

PRINTED FREQUENCY SELECTIVE SURFACES (FSS) FOR EMI
SHIELDING IN POLYMER MATRIX COMPOSITES

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ABSTRACT

PRINTED FREQUENCY SELECTIVE SURFACES (FSS) FOR EMI SHIELDING IN POLYMER MATRIX COMPOSITES

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Frequency selective surfaces (FSS), periodic metallic patterns on radiotransparent materials, are used to decrease radar cross section (RCS) of a radiating structure by allowing the transmittance of a signal at the desired frequency band. This study investigates the methodology and application of frequency selective surfaces (FSS) to be used in structural polymer matrix composites to provide electromagnetic interference (EMI) shielding in desired electromagnetic (EM) bands. Motivation of this work comes from the increased use of FSS layers in structural radome applications and the deficits of generally used manufacturing routes. Modelling and processing of suitable FSS patterns on glass fiber woven fabric surface with proper conductive paste materials by screen-printing method is the main research interest of this work to provide both structural characteristic and selective transmittance properties to multilayer radome composites. In the scope of this study, FSS design to provide desired EM performance, printing techniques of conductive patterns on fiber woven fabric materials, surface treatment of glass fiber and printed conductive paste surfaces, manufacturing of multilayered thermoset matrix composites and

composite characterizations have been investigated for a generic FSS design. Microstructural characterization in pattern level, electrical characterization in both fabric level and composite level as well as mechanical characterization in composite level have been performed. Target performance of the FSS composite material was determined as minimum -10 dB reflection loss and -2 dB insertion loss in 8-9 GHz frequency range. In conclusion, a selectively transmitting multilayer FSS composite material containing the modeled, validated and screen-printed conductive FSS pattern with selected conductive paste material showing the target performance has been demonstrated.

Keywords: Frequency Selective Surface (FSS), Electromagnetic Functionalized Fabric, Electromagnetic Interference (EMI) Shielding, Polymer Matrix Composites

ÖZ

POLİMER MATRİS KOMPOZİTLERDE ELEKTROMANYETİK GİRİŞİMİN KALKANLANMASI İÇİN BASKI YÖNTEMLERİ İLE ÜRETİLMİŞ FREKANS SEÇİCİ YÜZEYLERİN (FSY) KULLANILMASI

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Frekans Seçici Yüzeyler (FSY) yayın yapan aygıtların önündeki elektromanyetik pencerelerin sadece istenen frekans aralıklarında geçirgen olmasını, diğer frekans aralıklarındaysa elektromanyetik girişimin kalkanlamasını sağlayarak söz konusu yapıların radar kesit alanını (RKA) azaltan periyodik metalik desenlerdir. Bu tez kapsamında hedeflenen frekans bandında elektromanyetik girişim kalkanlamasını sağlamak için yapısal kompozitlerde entegre şekilde kullanılacak frekans seçici yüzeylerin (FSS) metodolojisi ve uygulaması araştırılmıştır. Bu çalışmanın motivasyonu, FSS katmanlarının yapısal anten radomlarında artan kullanımından ve daha önce bahsedilen genel üretim uygulamalarının proses dezavantajlarından kaynaklanmaktadır. Hedeflenen frekans bandı için FSY desenlerinin modellenmesi, cam elyaf kumaş yüzeyine iletken mürekkep kullanarak serigrafi yöntemiyle uygulanması ve hem yapısal hem de elektromanyetik seçici geçirgen özellik gösteren çok katmanlı radom kompozitinin elde edilmesi tezin ana araştırma konusudur. Bu çalışma kapsamında, hedeflenen elektromanyetik performans için FSY tasarlanması, iletken mürekkep analizi, tasarlanan FSY desenlerinin serigrafi baskı yöntemi ile

cam elyaf yüzeyine uygulanması sürecinin optimizasyonu, cam elyaf yüzeyinin ve iletken baskı yüzeyinin modifikasyonu, çok katmanlı termoset matris kompozitin üretilmesi ve karakterize edilmesi aşamaları ele alınmıştır. Çalışma boyunca desen seviyesi morfolojik analizler, hem desen hem kompozit panel seviyesi elektromanyetik ölçümler ve kompozit panel seviyesi mekanik karakterizasyon testleri uygulanmıştır. Sonuç olarak, 8-9 GHz frekans aralığında hedeflenen minimum -10 dB yansıma kaybı ve -2 dB geçirme kaybı performansını sağlayan, FSU baskı içeren, modellenmiş ve doğrulanmış yapısal çok katmanlı lamine kompozit gösterimi yapılmıştır.

Anahtar Kelimeler: Frekans Seçici Yüzey (FSU), Elektromanyetik Fonksiyonlandırılmış Kumaş, Elektromanyetik Girişim Kalkanlama, Polimer Matris Kompozitler



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LIST OF ABBREVIATIONS

ABBREVIATIONS

1D	: One-dimensional
2D	: Two-dimensional
3D	: Three-dimensional
BSE	: Boresight Error
BSES	: Boresight Error Slope
CAS	: Chemical Abstracts Service
CNT	: Carbon Nanotube
DC	: Direct Current
EHD	: Electrohydrodynamic
EM	: Electromagnetic
EMI	: Electromagnetic Interference
FSS	: Frequency Selective Surface
FTIR	: Fourier Transform Infrared
GSM	: Grams per square meter
IL	: Insertion Loss
ILSS	: Interlaminar Shear Strength
PE	: Printed Electronics
PVD	: Physical Vapor Deposition
R2R	: Roll-to-roll
RCS	: Radar Cross Section
RF	: Radar Frequency
RT	: Room Temperature
SE	: Shielding Efficiency
SEM	: Scanning Electron Microscope
TDS	: Technical Datasheet
TGA	: Thermogravimetric Analysis

UV : Ultraviolet
VNA : Vector Network Analyzer
XPS : X-ray Photoelectron Spectroscopy



CHAPTER 1

INTRODUCTION

Stealth (avoiding detection) technology encompasses methods aimed at concealing friendly weapon systems from detection by enemy surveillance systems. This technology, including radar, infrared, and acoustic stealth, is composed of an integrated system utilizing diverse techniques.

Radar stealth technology is very important among all stealth technologies. Radar systems detect reflections of intense electromagnetic waves transmitted from the radar to the target, providing precise data on various target parameters like azimuth, altitude, distance, and vector. To minimize the detection by radar, radar stealth technology involves absorbing or scattering electromagnetic waves, thereby minimizing reflected signals [1].

The effectiveness of radar stealth depends on the reduced Radar Cross Section (RCS), which denotes the apparent size of an object on radar. RCS is influenced by factors such as incident wave polarization, angle of incidence and observation, target geometry, surface condition, electrical properties, and operating frequency. Enhancing radar stealth often entails employing frequency-selective stealth radomes to decrease the RCS of a vehicle.

A radome, a blend of "Radar" and "Dome," is a protective enclosure placed over antennas to shield the radiating element (Radar Antenna) from environmental factors [2]. Composed of a material that minimally degrades antenna performance and transparent to radio frequencies, radomes are extensively utilized across diverse systems, including ground, maritime, vehicle, aircraft, airborne, and missile applications [3], [4].

Unlike conventional stealth methods aimed at absorbing or scattering electromagnetic waves, stealth radomes necessitate a distinct electromagnetic performance. Encapsulating with internal antennas, stealth radomes must allow transmission of the internal antenna's communication frequency while absorbing or reflecting other frequencies. This selective transmission is enabled by frequency-selective surfaces, ensuring optimal antenna functionality while preserving stealth characteristics Figure 1.1.

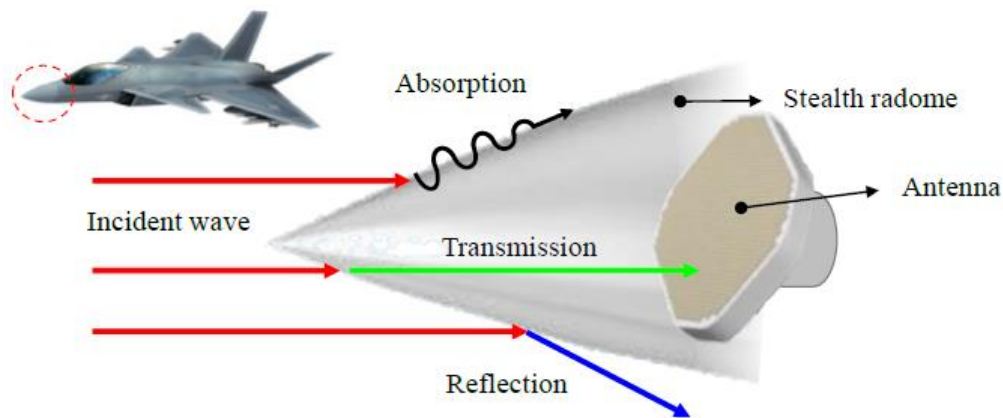


Figure 1.1. Electromagnetic properties of stealth radome [5].

To meet the requirements of both electromagnetic characteristics and mechanical performance, a stealth radome of an aircraft must be robust enough to withstand the stresses encountered in flight environments. Thus, the design of a stealth radome necessitates consideration not only of its electromagnetic properties but also its structural integrity. To fulfill mechanical performance criteria, the stealth radome is typically engineered with a composite material that includes a frequency-selective surface (FSS) in its multilayered structure.

The concept of FSS is described as a periodic surface which contains repetitive identical elements of infinite arrays in one or two dimensions [6]. Frequency

Selective Surfaces (FSSs) are used to filter through which electromagnetic fields are transmitted or reflected within the specified band of frequency [7].

FSSs are particularly used to reduce the radar cross section of emitting structures (i.e. antennas) where the transmission properties can be tuned as desired. Fiber woven fabric reinforced thermoset composites are among the most common materials used in structures, and it is important to embed FSS patterns into such structures rather than printing them on the surface due to durability concerns. This requires printing the FSS pattern on the fiber woven fabric first and then manufacturing prepregs from this intermediate product to achieve high quality structures such as radomes with FSS function.

The inherent problem with such approach is related with the topography of the fabric and the fine details of the FSS pattern, as a result of which printed structures are different from the design to some degree [8]. There are several methods to overcome these issues including the change of FSS fabricating method from conductive paste printing to knitting/embroidery [9] or defining a new surface between conductive paste and textile substrate by applying a polymer layer to avoid non-controlled penetration of conductive particles [8]. However, in case of glass fiber woven fabrics, it is hard to apply embroidery without degrading the weave of the fabric, and surface modification by polymer layer is not applicable, since the polymer layer will have a negative impact on the mechanical properties of the final composite structure. Therefore, an alternative approach composed of directly patterning the glass fiber woven fabric surface by the FSS array printed using a conductive paste has been developed in this study. The effect of conductive particle size of the commercially available conductive paste products on the performance of the printed FSS structure has been considered in a parametric manner.

Several factors affect the performance of FSS structures, such as type, shape, dimensions, electrical conductivity etc., of the periodic elements as well as the electrical properties of the substrate material. Therefore, there can be numerous

combinations of various parameters for the optimal solution for this specific problem.

The main objective of this study is to obtain an FSS composite material which transmits the incoming RF wave in 8 – 12 GHz (X-band) range and reflects the rest without decreasing its mechanical properties. For this purpose, first, glass fiber woven fabric with the required FSS design was patterned with screen-printing method to obtain FSS fabric. Then, FSS fabric was impregnated with epoxy resin to produce FSS prepreg which can be utilized in multilayer FSS composite.

In this thesis, a fairly simple design has been used, where the focus was on the materials and processing rather than the electromagnetic (EM) solution. Two different types of silver-based pastes having different conductive particle size and geometries were used to print an X-band FSS pattern on glass fiber woven fabric by screen printing method. It was shown that printing with smaller particles caused the surface conductivity to deteriorate as a result of penetration into the substrate material, and also caused frequency shifts in the FSS behavior as a result of the substrate material appearing on the surface. FSS printed glass fabrics were impregnated with thermoset resin to obtain FSS prepregs as to be utilized in multilayer composite structure. Figure 1.2 schematically presents the scope of this thesis study in the form of a graphical abstract. In the end, it was revealed that the required electromagnetic performance of the multilayer FSS composite could be achieved by screen-printing method.

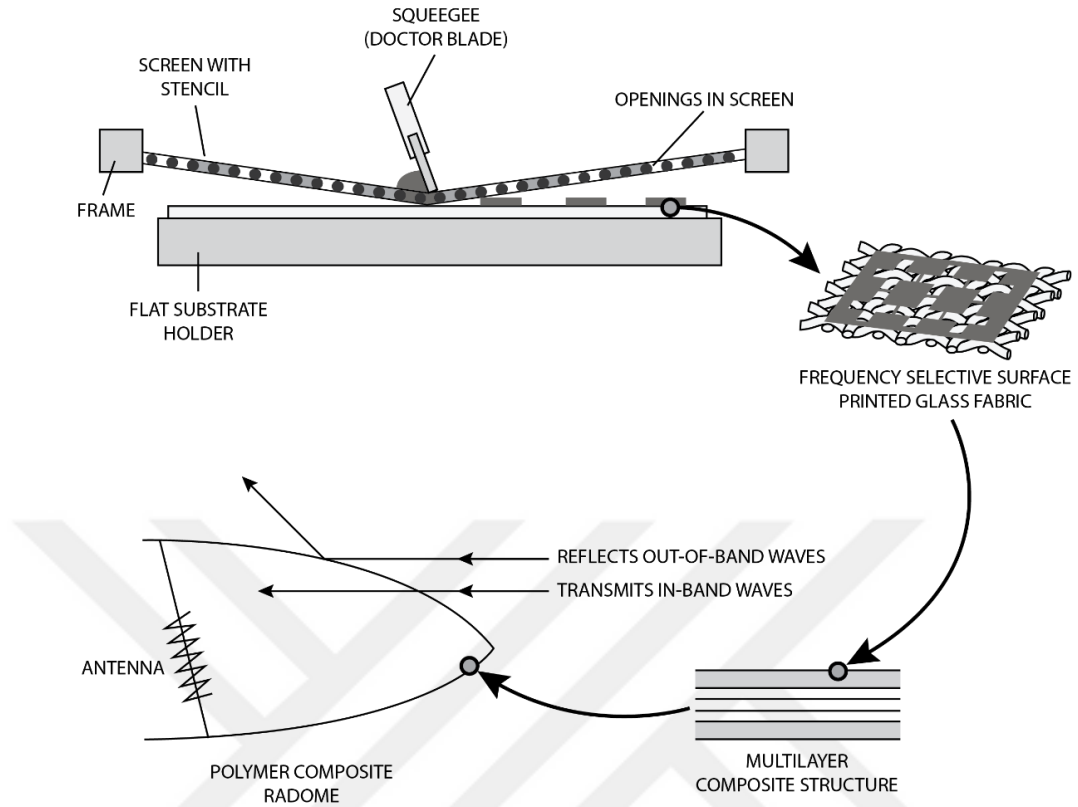


Figure 1.2. Schematic representation of the scope of this thesis.

This Ph.D. thesis includes five chapters designed to provide comprehensive information about the development of a novel method for FSS manufacturing to be utilized in multilayer polymer composites. In Chapter 2, literature review starting from the stealth concept to the printing applications, covering the overall theoretical background that leads to the scope of this study was given. In Chapter 3, the principles of the production methods and the characterization procedures utilized were given in detail. Chapter 4 contains experimental results and their discussions with respect to electromagnetic and structural approaches. Finally, Chapter 5 summarizes the thesis, covering overall findings and suggestions for outlook.

CHAPTER 2

LITERATURE REVIEW

2.1 Electromagnetic Theory

This section will briefly explain the electromagnetic (EM) spectrum and electromagnetic waves, exploring their diverse applications in broadband technologies and their interactions with materials. Specifically, the focus will be on understanding the material interactions of electromagnetic waves, with a particular emphasis on electromagnetic loss mechanisms.

2.1.1 Electromagnetic Spectrum and Electromagnetic Waves

The term "electromagnetic spectrum" encompasses electromagnetic radiation across all frequencies, with electromagnetic radiation arising from the motion of photons, which possess energy and exhibit both wave-like and particle-like behavior[10]. The initial discovery of electromagnetic radiation is attributed to William Herschel, while Michael Faraday established a correlation between electromagnetic radiation and electromagnetism. Subsequently, James Clerk Maxwell formulated the fundamental laws of electromagnetism, providing mathematical expressions known as Maxwell's equations. These equations include Gauss' law, Faraday's law, and Ampere's law. Maxwell's equations suggest that varying electric fields induce changes in magnetic fields in free space, and vice versa, with these changes occurring perpendicular to each other [11]. Furthermore, Maxwell speculated that EM waves should propagate at the speed of light based on his analysis of the speed of variations in electric and magnetic fields. Heinrich Hertz's experiments supported this notion, leading to the well-known equation:

$$c = \lambda f \quad (1)$$

the formula, where (c) represents the known speed of light $3,00 \times 10^8$ m/s, (f) denotes frequency, and (λ) signifies wavelength, is applied to all frequencies, yielding the electromagnetic spectrum.

In free space, electromagnetic waves transport energy through associated both magnetic and electric fields. This energy is conveyed by photons, and the energy (E) of photons can be expressed using Equation 1, where (h) represents Planck's constant $6,63 \times 10^{-34}$ J.s.

$$E = hc/\lambda \quad (2)$$

This equation illustrates that electromagnetic waves with shorter wavelengths carry higher energy, or conversely, EM waves with lower frequencies possess lower energy. As each EM wave carries a specific amount of photon energy, wavelength of this wave can be determined using Equation 2. Subsequently, each EM wave can be categorized into one of various regions of the EM spectrum according to its frequency or wavelength. The classification of the EM spectrum is depicted in Figure 2.1.

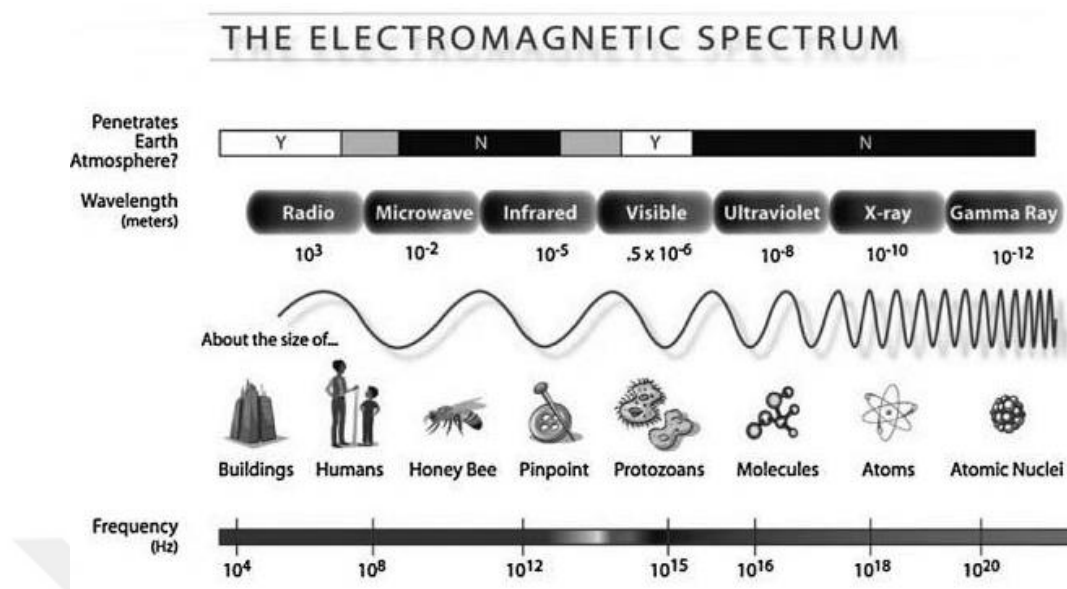


Figure 2.1. Electromagnetic spectrum [10].

The speed of light being constant, Equation (1) indicates that frequency and wavelength of a wave are inversely proportional; thus, an increase in frequency corresponds to a decrease in wavelength. Additionally, according to Equation (2), waves with lower wavelengths exhibit higher photon energy [12]. These relationships between photon energy, wavelength, and frequency are visually apparent in the electromagnetic spectrum, as depicted in Figure 2.1.

Electromagnetic waves are typically classified as radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays based on their increasing frequencies. There are no precise boundaries separating these regions, and they often coincide at certain frequencies.

Radio waves, with the lowest frequencies and longest wavelengths (ranging from 0.1 m to 1 km), are produced by the acceleration of charged particles and find extensive applications in communication and broadcasting systems such as TV, radio, and cell phones.

Microwaves, with wavelengths ranging from 0.3 m to 10^{-4} m, are utilized in radar applications and are generated similarly to radio waves. Since the practice subject of microwaves includes radar applications, further information will be given in the following parts of the thesis.

Infrared waves, with wavelengths from 1 mm to 700 nm, contribute to the heating effect of the Sun and are emitted by objects and molecules at room temperature. They are readily absorbed by the skin, resulting in the sensation of heat.

Visible light, with wavelengths between 350 to 700 nm, is the only electromagnetic wave detectable by the human eye.

Ultraviolet waves, with shorter wavelengths and higher energy than visible light, range from 10^{-7} to 10^{-10} m and can cause skin disturbances when exposed to sunlight. They find applications in sterilization and security measures.

X-rays, with wavelengths between 10^{-8} and 10^{-12} m, are commonly generated by accelerating free electrons and are employed in medical diagnostics and materials analysis.

Gamma rays, with wavelengths ranging from 10^{-10} to 10^{-14} m, possess extremely high energy and originate from nuclear reactions. They are utilized in medical imaging and industrial applications but can be harmful to human tissues [13].

Electromagnetic waves can be generated by various sources, including electronic devices, nuclear phenomena, and solar radiation, and propagate through space for communication and information transfer. However, in the Earth's atmosphere, interactions with atmospheric gases result in absorption of certain wavelengths, rendering the atmosphere opaque to many electromagnetic radiations. This atmospheric absorption varies with wavelength, influencing the design and operation of electronic systems on Earth [14]. Figure 2.2 illustrates the percentage of atmospheric opacity with respect to wavelength and the wavelengths blocked by the atmosphere.

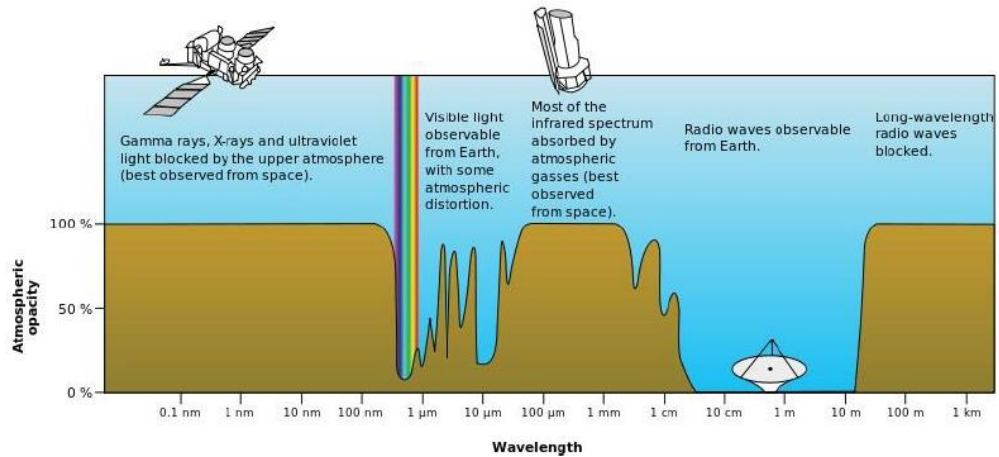


Figure 2.2. Atmospheric opacity [14].

2.1.2 Microwave Frequencies

Microwave frequencies span the range from 300 MHz to 300 GHz, falling between radio waves and infrared waves. The wavelengths of microwave radiation range between 1 mm and 1 m [13]. Due to objects resonating with microwave frequencies of the same wavelength, microwave frequencies encompass numerous molecular and atomic resonance frequencies.

Various applications operate within the microwave frequency range, including wireless devices, radars, medical applications, navigation systems, mobile phones, military applications, satellites, and processing applications. Table 2.1 illustrates the primary application areas of microwaves, which predominantly correspond to radar applications across specific frequency and band regions [13].

Table 2.1. Microwave frequencies and corresponding bands [13].

Band	Frequency Range	General Usage
L	1 – 2 GHz	Long Range Surveillance Enroute Traffic Control
S	2 – 4 GHz	Moderate Range Surveillance Terminal Traffic Control, Long Range Weather
C	4 – 8 GHz	Long Range Tracking Airbone Weather Detection
X	8 – 12 GHz	Short Range Tracking Mapping, Marine Radar, Airborne Intercept
Ku	12 – 18 GHz	High Resolution Mapping, Satellite Altimetry
K	18 – 27 GHz	Little Used (Water Vapor Absorption)
Ka	27 – 40 GHz	Very High Resolution Mapping Airport Surveillance
mm	40 – 100+ GHz	Experimental

The extensive use of electronic devices operating within the microwave frequency range has led to an increase in unwanted radiation pollution. Consequently, there is a growing demand for electromagnetic (EM) wave shielding and/or absorbing solutions to mitigate this issue. In this study, an electromagnetic interference (EMI) shielding solution targeting the X-band frequency range (8-12 GHz) is presented.

2.1.3 EM Wave – Material Interactions

EM radiation arises from the interplay between electrical and magnetic fields and traverses through free space or a medium. During propagation, it may interact with other waves in a constructive or destructive manner, resonate with objects whose size matches the wavelength of the radiation, or encounter elementary particles like electrons.

When electromagnetic waves interact with matter, they exhibit three primary behaviors: reflection (R), transmission (T), or absorption (A). These interactions

result in a decrease in the energy of the wave, with the lost energy being transferred to reflected, transmitted, or absorbed waves. Based on the law of energy conservation, the final energy of the system must equal the initial energy of the system. Thus, in accordance with Equation (3), the power fractions of reflected (P_R), absorbed (P_A), and transmitted (P_T) waves with respect to the power of the incident wave (P_0) must sum up to one [10].

$$1 = \frac{P_R}{P_0} + \frac{P_A}{P_0} + \frac{P_T}{P_0} \quad (3)$$

Materials can be categorized based on their response to electromagnetic waves:

1. **Opaque Materials:** These materials are considered opaque to electromagnetic waves if the waves are reflected from their surface. Opaque materials are typically conductors, as reflection occurs when the material contains mobile charge carriers, such as electrons.
2. **Transparent Materials:** Transparent materials allow electromagnetic waves to pass through them without significant attenuation. These materials are typically insulators or have low dielectric loss properties.
3. **Absorbing Materials:** Absorbing materials have the ability to absorb incident electromagnetic power and generate both magnetic and electric dipoles for absorption. Several mechanisms contribute to absorption, including polarization of dipoles (dielectric loss), rotation of magnetic domains (magnetic loss), and free electron flow (conductance loss) [15]. Figure 2.3 illustrates the interaction of electromagnetic waves with these three classes of materials.

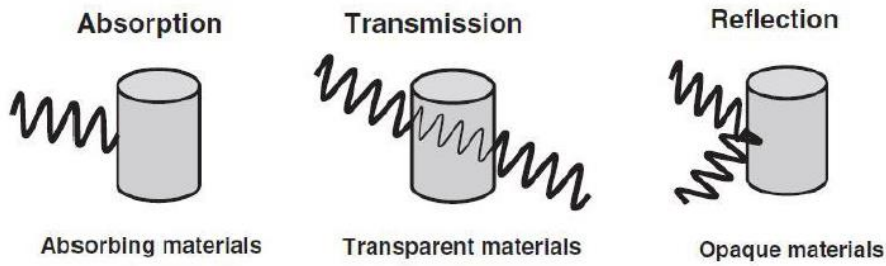


Figure 2.3. Material classification based on their interaction with the electromagnetic wave [15].

2.1.4 Electromagnetic Interference (EMI) Shielding

With the continuous improvement of technology, the proliferation and usage of electronic devices have expanded significantly. As discussed earlier, many of these devices function at microwave frequencies, generating EM fields that can propagate into the surrounding environment. Such electromagnetic fields have the potential to interact with other electronic devices, leading to damage and operational failures. This scenario underscores the importance of electromagnetic shielding to mitigate the spread of harmful and undesirable radiation from electronic devices. The primary objective of electromagnetic (EM) shielding is to safeguard electronic and electrical parts and systems from external electromagnetic fields or prevent the emission of EM fields by these components and systems [16].

EM waves can interact with matter in three primary ways: reflection, transmission, and absorption. Among these, reflection and absorption are the leading mechanisms accountable for shielding EM waves. Figure 2.4 illustrates the mechanisms resulting from the interaction between EM waves and shielding materials [17].

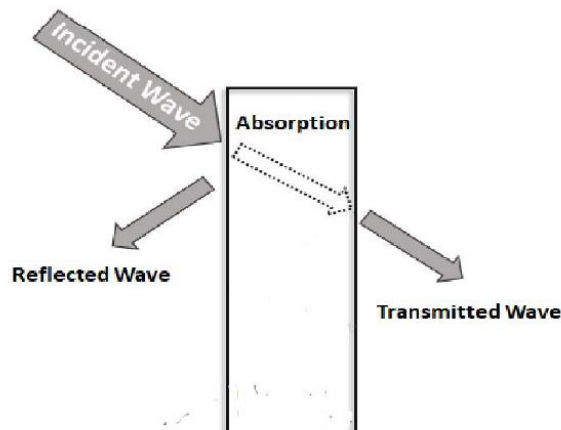


Figure 2.4. Electromagnetic wave – material interaction [17].

Reflection serves as the primary mechanism for electromagnetic (EM) shielding, arising from the interaction between EM waves and mobile charge carriers, such as electrons and holes. While high conductivity is not the sole requirement for effective shielding, materials with high conductivity facilitate increased reflection of electromagnetic waves. Consequently, metals are commonly chosen for their high reflectivity, making them suitable for EM shielding applications.

Absorption represents the second important mechanism for electromagnetic shielding. For absorption to occur, either the electrical or magnetic field parts of the electromagnetic wave must interact with electrical or magnetic dipoles present in the shielding material. Thus, shielding materials must possess magnetic or electrical dipoles to reduce the incoming radiation energy by trapping this loss in energy within its structure [18].

Shielding effectiveness (SE) is another crucial consideration. SE refers to the ability of a material to function as a shield in contradiction of outside and inside EM fields, thereby mitigating the harmful effects of these radiations. Numerous parameters influence shielding effectiveness, as outlined in Figure 2.5.

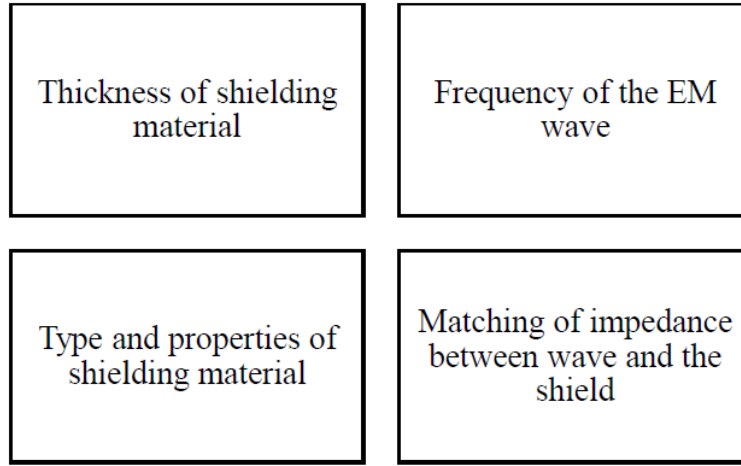


Figure 2.5. Shielding effectiveness parameters [19].

Shielding effectiveness (SE), typically expressed in decibels (dB), can be linked to the electromagnetic shielding mechanisms discussed earlier. The absorbed portion of the incoming wave is termed absorption loss (A_{loss}), while the reflected portion is termed reflection loss (R_{loss}). SE is determined by summing these terms.

$$SE(dB) = A_{loss} + R_{loss} \quad (4)$$

Another approach to state shielding effectiveness (SE) is to calculate the logarithm of the ratio of the initial and final electrical and magnetic fields. Equations 5 and 6 illustrate the relationship between shielding effectiveness and electrical and magnetic fields, respectively.

$$SE = 20 \times \log \left(\frac{E_f}{E_i} \right) \quad (5)$$

$$SE = 20 \times \log \left(\frac{H_f}{H_i} \right) \quad (6)$$

2.2 Frequency Selective Surfaces (FSSs)

A Frequency Selective Surface (FSS) is a periodic structure comprised of identical unit cells, such as patches and/or loops, arranged on a dielectric substrate [20]. This structure possesses the ability to selectively reflect, transmit, or absorb electromagnetic waves. While these unit cells are commonly arranged in a two-dimensional (2D) geometry, examples of one-dimensional (1D) and three-dimensional (3D) configurations can also be found in the literature [21], [22].

FSSs find widespread use as free-standing two-dimensional beam-splitters due to their inherent frequency response characteristics. These characteristics can be tailored to exhibit various spectral filtering behaviors, including low-pass, high-pass, bandstop, or bandpass filtering, as depicted in the figure below [6].

Single-layer Frequency Selective Surface (FSS) designs, along with their corresponding analog circuit representations and filter response characteristics, are illustrated in the provided images. The darker colors in the images represent the conductive areas within the FSS structures. These designs and their analog circuit equivalents allow for the analysis of the electromagnetic behavior and filtering properties of the FSS structures.

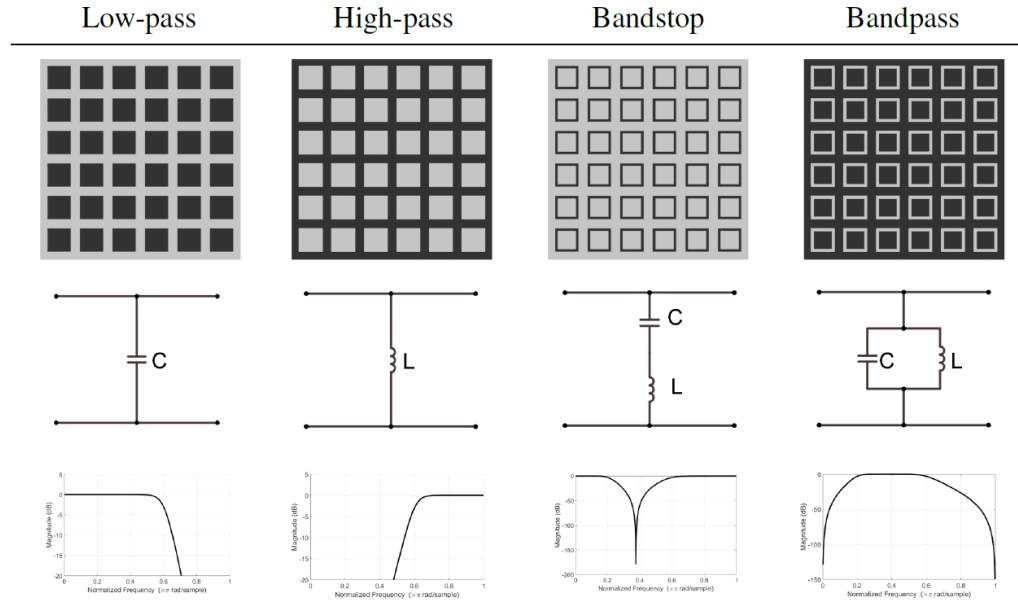


Figure 2.6. Single-layer Frequency Selective Surface (FSS) designs, along with their corresponding analog circuit representations and filter response characteristics [7].

The images displayed in Figure 2.6 depict typical unit cell arrangements utilized to create the periodic structure of Frequency Selective Surfaces (FSS). These unit cells can be fabricated using various patch or slot shapes, each imparting specific frequency response characteristics. The choice of FSS type depends on the design requirements. For instance, a low-pass FSS can be constructed using an array of square patches, as shown in Figure 2.6. Figure 2.6. Single-layer Frequency Selective Surface (FSS) designs, along with their corresponding analog circuit representations and filter response characteristics or using hexagonal [23] or circular [24] patches with a solid interior. In [6], Munk presents a diverse range of different designs (Figure 1.6), while in [25], the authors demonstrate the equivalent circuit for the simplified modeling of more complex FSS unit cell configurations (Figure 2.7).

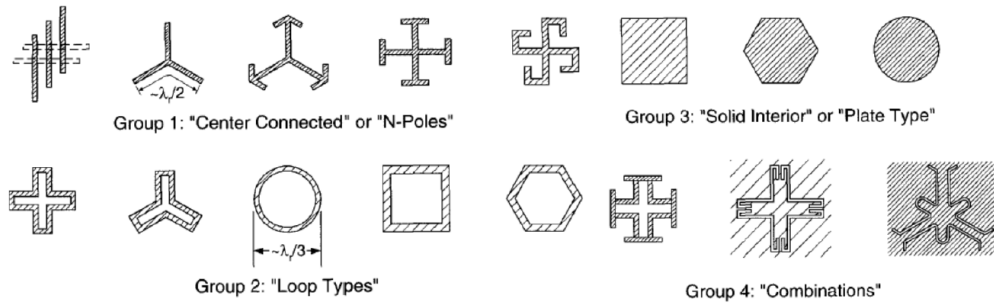


Figure 2.7. Examples of FSS unit cell designs [6].

In Figure 2.7, Munk divides the design into four distinct groups [6]:

1. Centre Connected Unit Cells: These unit cells consist of thin lines connected at the center.
2. Loop-Type Elements: This group includes square, circular, or hexagonal ring structures, which may be nested for broadband applications [26].
3. Solid Interior: These unit cells feature a solid interior and typically exhibit a low-pass filter response. When used for designing absorbers, this arrangement offers several advantages over loop-type FSS, particularly depending on the thickness [27].
4. Combination of Loop Types and Centre Connected: This category involves a combination of loop-type and center-connected elements and is sometimes utilized to create more compact designs [28], [29].

Each group offers unique characteristics and advantages, catering to different requirements and applications in Frequency Selective Surface (FSS) design (Figure 2.8).

S. No	FSS	Circuit	Equivalent Circuit
1	Single Square Loop		
2	Double Square Loop		
3	Triple Square Loop		
4	Cross Dipole		
5	Jerusalem Cross Array		

Figure 2.8. Equivalent circuit diagram for different FSS [25].

Patch elements, also known as dipole FSSs, are engineered to function as stopband filters for incoming plane waves. They operate as highly reflective surfaces within a narrow band of frequencies, effectively blocking or reflecting electromagnetic waves. In contrast, aperture elements, referred to as slot FSSs, exhibit passband characteristics [30]. This means they act as transparent surfaces to incident EM waves within their operating frequency range, allowing the waves to pass through with minimal attenuation. However, conventional FSSs face limitations in meeting

the functional requirements of various electromagnetic applications. These limitations include inadequate filter response, low angular stability, and narrow bandwidth. As a result, their utility is often restricted in practical applications.

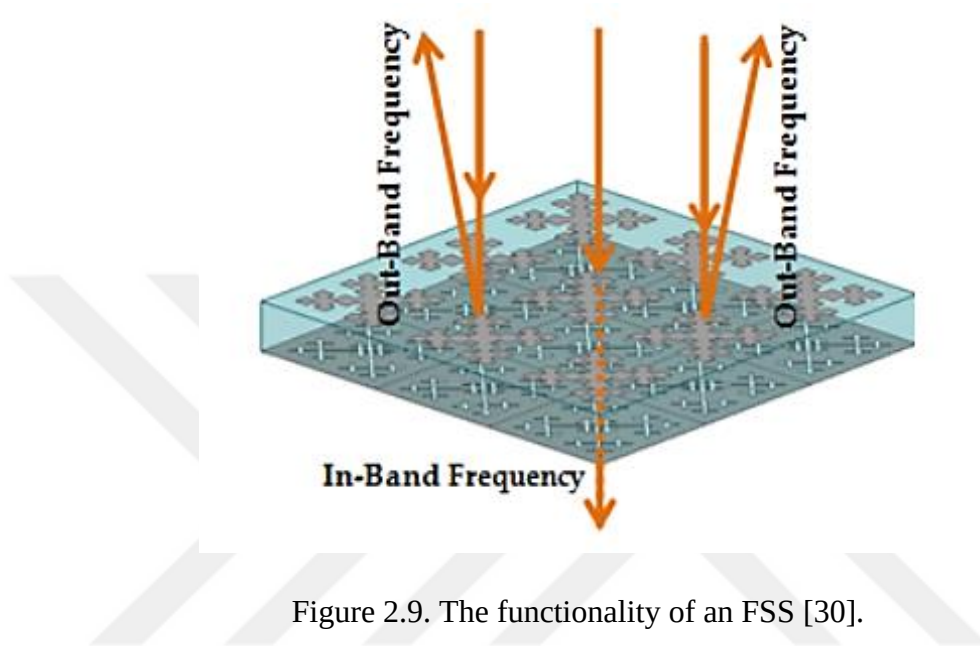


Figure 2.9. The functionality of an FSS [30].

2.3 Printing Technologies

Printing is the process of fabricating a writing or an image on paper or other substrates utilizing a machinery system [31].

Printed electronics (PE) production is usually described as an automated, additive process involving a small number of processing steps, as depicted in Figure 2.10. The typical printing process flow comprises three main steps: (i) pre-treatment of the substrate surface, (ii) the actual printing application, and (iii) post-process application, which may contain drying and curing/sintering procedures. However, in several applications, substrate surface may not require pre-treatment, and there are

available inks which do not require curing further reduces the number of processing steps needed.



Figure 2.10. Schematic presentation of a printing process including pre-treatment of surface, printing and post-processing [31].

Currently, there are five prominent printing application technologies utilized in printed electronics (PE) manufacturing, with screen printing being the most prevalent in the commercial market, as depicted in Figure 2.11. This dominance is primarily attributed to efficient mass production and high process stability derived from graphic printing techniques. In particular, web presses allow printing on substrates in rolls, rather than individual sheets, enhancing productivity. Additionally, screen-printed metallic inks offer high achievable conductivity, further solidifying screen printing's position [32].

While high-speed roll-to-roll (R2R) methods such as gravure and flexographic printing hold promise for large-scale PE production, factors like ink fluid dynamics significantly influence material interactions and printing outcomes, necessitating careful control [33]. Inkjet printing, although primarily utilized in research and development settings, is increasingly considered for commercial PE applications due to advancements in multi-nozzle configurations and compatibility with R2R processing.

Coating techniques, along with screen printing, find commercial use in fabricating organic solar cells [34]. Apart from these prevalent printing technologies, numerous emerging methods are either being developed or used in niche areas for PE fabrication.

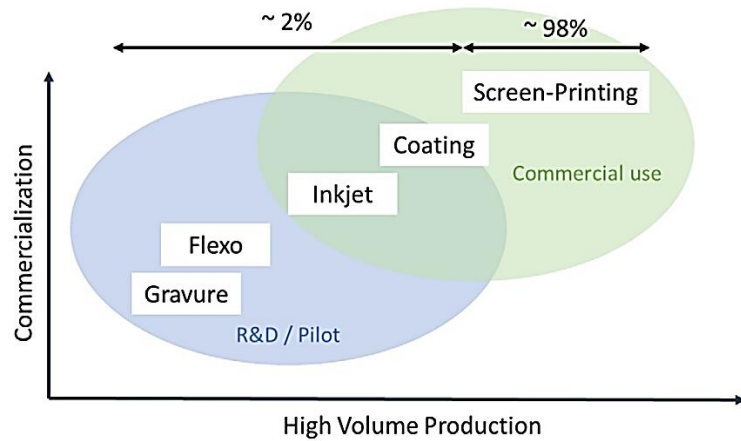


Figure 2.11. Commercial use of state-of-the-art printing technologies for PE manufacturing [31].

The key parameters for characterizing and directly comparing printing methods include achievable resolution (printable line width), layer thickness, optimum ink viscosity, and printing velocity. Table 2.2 offers an overview of various printing technologies and their characteristic properties.

Table 2.2. Overview of the properties of several printing technologies used in the fabrication of printed flexible sensors [31].

Printing Method	Ink Viscosity (cP)	Line Width (μm)	Thickness (μm)	Speed (mm/min)
Aerosol Jet	0.7 – 2500	$10 - 10^3$	0.01 – 10	6
Flexo	50 – 500	7 – 100	0.17 – 8	10 – 18
Gravure	100 – 1100	2 – 100	0.02 – 12	0.5 – 18
Inkjet	2 – 100	30 – 50	0.1 – 20	1 – 2
Screen	500 – 5000	30 – 100	3 – 100	1 – 10

In general, there exists a trade-off between resolution and processing velocity across all printing technologies. Lower scale methods like EHD and laser-induced forward transfer tend to offer the highest resolution, while scalable roll-to-roll (R2R) methods such as screen printing and gravure printing achieve the highest speeds. However, compared to graphic printing like newspaper printing, R2R fabrication of printed electronics (PE) tends to be slower, as higher speeds can lead to incomplete and inaccurate ink transfer. An exception to this rule is nanoimprinting, which allows for high-resolution printing at high speeds, although it is not an additive process like the other methods presented.

Printing technologies can be broadly classified into two major groups; contact and non-contact methods. In contact printing, as in screen printing, flexo printing, or gravure printing, the deposition equipment (e.g., roller or stamp) directly touches the substrate surfaces. Contact printing methods generally offer high throughput at low costs, enabling true R2R manufacturing. However, most contact methods require a primary template, increasing initial costs and reducing flexibility for design changes.

On the other hand, non-contact methods like inkjet printing, EHD, and aerosol jet printing deposit inks without touching the substrate surfaces [35]. This can be advantageous for depositing functional materials on uneven, 3D, or highly sensitive substrates. Moreover, many non-contact printing methods, such as inkjet printing and aerosol jet printing, do not require a primary template or stencil, enhancing design flexibility as changes can be applied instantaneously (Figure 2.12).

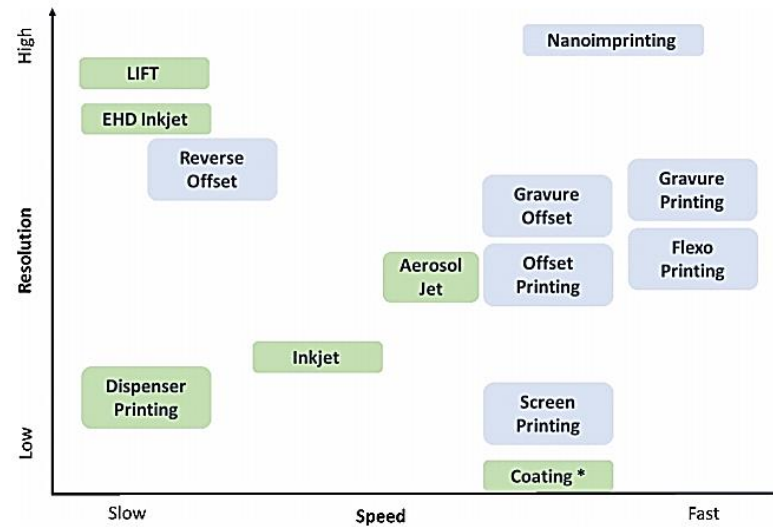


Figure 2.12. Printing application speed vs. resolution for different printing processes where contact printing technologies are indicated in blue and non-contact technologies are indicated in green.

2.3.1 Screen Printing

Screen printing currently stands as the main method for commercially producing printed electronics (PE) [36]. Its popularity stems from its compatibility with a wide range of functional inks and substrates, along with its high processing throughput. In the screen-printing process, ink is forced through a patterned stencil using a squeegee, also known as a doctor blade, at velocities reaching several centimeters per second.

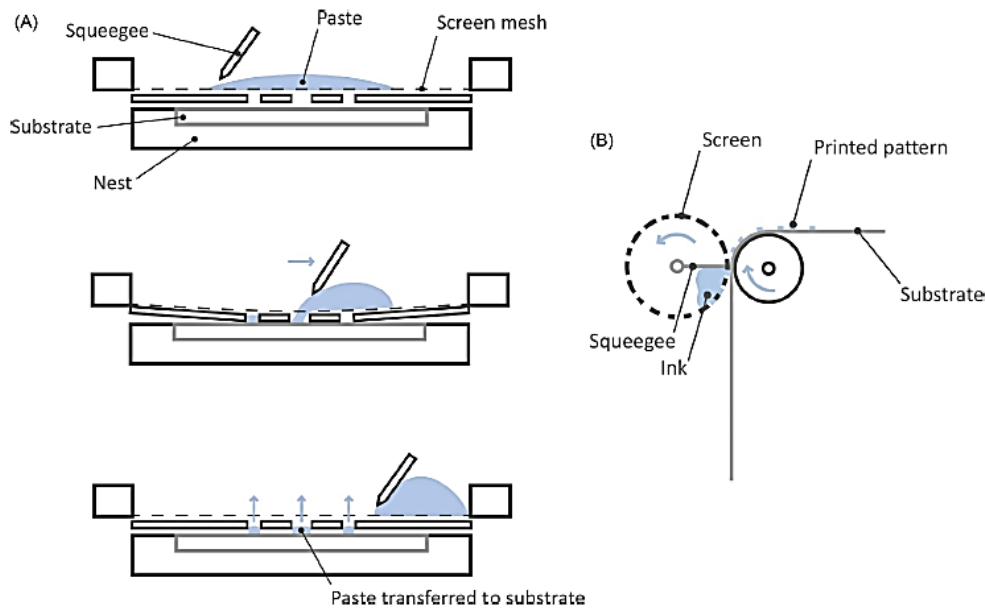


Figure 2.13. Schematic presentation of (A) flat-bed screen printing; (B) rotary screen printing [36].

In the screen-printing process for printed electronics, a relatively high viscosity ink ranging between 500 and 5000 cP is typically required. This viscosity range allows for smooth flow through the stencil while maintaining thixotropic behavior, which ensures quick recovery of viscosity after shear stress is released. However, this viscosity range contributes to a limited resolution of 30–100 μm in commercial applications [37].

Conventionally, a screen printer comprises a flat screen and a flat substrate holder, where sheets are processed one by one (flat-bed screen printing). For roll-to-roll (R2R) multilayer printing and increased throughput, rotary screens are available. The screen mask consists of a frame, a stencil, and a screen fabric (Figure 2.13) [36].

The screen fabric mesh is typically made of natural silk, plastic, or metal fibers and the stencil pattern is prepared using photolithography, requiring light-sensitive materials. The printing resolution is constrained by the resolution of the screen mask, which in turn depends on the quality of the screen manufacturing process [31].

Although screen printing is generally believed to be a low-resolution technique, narrow lines with widths of less than 10 μm have been reported in laboratory conditions [38].

2.4 Conductive Pastes and Related Properties

The choice of conductive ink plays a crucial role in achieving the desired patterns with the required conductivity and quality in screen-printed electronics. Typically, conductive pastes include essentially inorganic particles (as the conductive part), binder material (as the insulator part), solvents, and additives. The composition and conductivity of the ink can vary depending on the printing technique employed [39].

The conductive material, composition of the ink, and the applied amount of ink on surface significantly impact the final conductivity of the printed pattern. Properties such as the conductor material, particle morphology and the solid content of the ink influence both the electrical and mechanical properties of printed patterns. Additionally, the viscosity of the ink has an effect on its transfer onto the substrate. In cases where the substrate surface is rough related to the required conductive ink layer thickness, differences in the thickness may arise, causing increased resistance. The curing temperature of the ink is also an important parameter to consider [40].

In recent years, there has been a surge in the development and use of nanomaterials as conductive inks, including metallic micro/nano particles, conductive polymers, graphene, carbon nanotubes (CNTs), etc. These materials, especially conductive polymers, graphene, and CNTs, are widely utilized for printing integrated circuits. However, their conductivity still has room for improvement. As a result, ink formulations based on metallic micro/nano particles, particularly silver, are often chosen as strong candidates due to their desirable conductivities. Silver is currently the most used material for conductive ink and is widely used in industrial applications, as the use of copper presents challenges due to oxidation, and gold is relatively expensive [41].

2.5 Polymer Matrix Composite Radomes

A radome, a combination of "radar" and "dome," serves as a protective shell for radar or communication antennas, shielding them from environmental elements. Its primary function is to maintain transparency to electromagnetic energy, akin to a glass window's role in the optical spectrum. In addition to weather protection, radomes obscure antenna electronic equipment from external observers, offering a layer of security. They also facilitate the use of antenna systems and minimize mechanical design requirements, leading to cost savings by shielding antennas from harsh external conditions [42].

Radomes come in various shapes, including spherical, geodesic, and planar, tailored to specific applications. They are constructed using diverse materials such as fiberglass, quartz, PTFE-coated fabric, closed-cell foam, and honeycomb. These versatile structures find applications in aircraft, ships, cars, and ground-based installations. For high-speed platforms like aircraft, considerations include the radome's streamlined shape to mitigate drag forces.

The principal electrical parameters influencing radome performance include:

- Insertion Loss (IL) arising from the radome's presence.
- Elevated levels of antenna sidelobes in the radiation pattern.
- Amplification of depolarization in the radiation pattern.
- Boresight Error (BSE) and Boresight Error Slope (BSES).

Insertion loss refers to the decrease in signal strength experienced as an electromagnetic wave traverses the radome wall. This loss is attributed partially to reflections from the air/dielectric interface, with additional losses stemming from internal and external diffraction, refraction effects, and polarization shifts. The remaining loss is due to dissipation within the dielectric layers [2].

In high-frequency electric fields, the electrical properties of dielectric materials are dictated by their dielectric constant (ϵ_r) and dielectric loss tangent ($\tan \delta$), both of

which vary significantly with factors such as moisture content, material temperature, and radio wave frequency [43]. Moisture contamination poses a significant degradation source due to the high dielectric constant of water and the polymeric matrix's propensity to absorb it. As temperature rises, moisture absorption increases, facilitated by temperature acting as a diffusion activator in radome materials [44].

Over time, water absorption can alter the dielectric constant of the radome material, leading to performance degradation. However, the impact of surface water on transmission characteristics is minimal due to the hydrophobic nature of the materials used on the outer surface and the high airflow around the radome structure.

During radome design, it is crucial to recognize that dielectric property data is specific to the fabrication process. Therefore, caution must be exercised when applying known high-frequency dielectric properties of composite materials. Assuming that the dielectric constant and dielectric loss remain constant during radome design, even small changes in the dielectric constant can alter the electrical thickness of the radome, potentially exacerbating transmission characteristics.

Table 2.3 List of material properties optimized for radome fabrication [43].

MECHANICAL	ELECTRICAL	THERMAL	ENVIRONMENTAL
• Young's modulus • Tensile strength • Shear modulus • Impact strength • Fatigue • Creep	• ϵ with temperature • ϵ with frequency • ϵ with humidity • $\tan\delta$ with temperature • $\tan\delta$ with frequency • $\tan\delta$ with humidity	• Specific heat • Thermal conductivity • Thermal shock resistance • Thermal expansion • Flammability	• Radiation exposure • Rain erosion • Water absorption • Chemical resistance

Individual materials often fail to meet all the requirements for radomes outlined in Table 2.3. Therefore, composite materials offer an optimal solution by combining various properties. Polymer matrix composites, in particular, demonstrate exceptional fatigue and corrosion resistance, alongside stiffness and strength to withstand aerodynamic stresses. The ability to mold large laminate shapes efficiently while maintaining dimensional and alignment stability has led to extensive adoption

of composites in the aerospace industry. This, in turn, has resulted in significant weight reduction of up to 30–35%, thereby enhancing fuel efficiency and range [45], [46]. Moreover, composites offer benefits such as low dielectric constant and minimal loss, ensuring radar transparency while retaining high strength. However, despite these advantages, composites suffer from drawbacks like poor interfacial properties, susceptibility to failure from impacts and delamination, and high-water absorption. Over time, these issues can degrade the mechanical and electrical properties of radomes.

The configurations of radomes, as depicted in Figure 2.14, are typically determined by a combination of mechanical and electrical factors specific to the operational environment of the radome and aircraft.

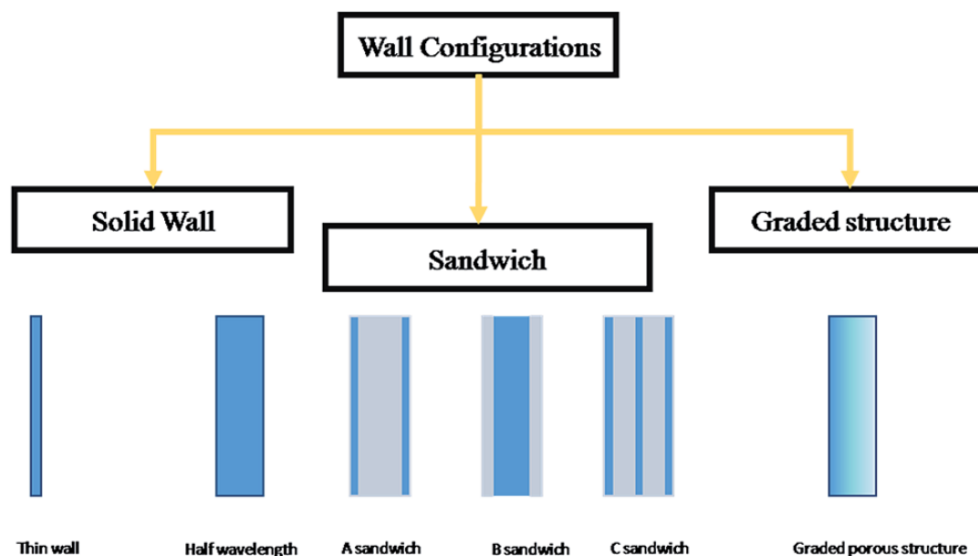


Figure 2.14. Wall configurations of modern radome [43].

Radome materials, falling into the three categories outlined, face significant challenges due to the scarcity of materials capable of simultaneously meeting the necessary structural and electromagnetic criteria in the demanding aerial context.

Often, there exists a trade-off between the electrical and mechanical properties of a material, necessitating designers to accept a compromised solution. In sandwich radomes, laminates offer structural integrity, while core materials contribute to a low dielectric constant and provide flexural strength. The subsequent sections delve into the specific materials utilized for radome construction.

The majority of radome laminates used in aircraft construction are composed of composites. These materials offer a high strength-to-weight ratio and the ability to customize mechanical and electrical properties, making them well-suited for radome fabrication. Composites are carefully chosen to meet specific radome requirements, with key components including fibers such as E-glass, S-glass, D-glass, aramid fibers, and quartz (Table 2.4). These fibers are typically embedded in polyester or epoxy resins. E glass, characterized by its low alkali content and comprising SiO_2 , Al_2O_3 , CaO , B_2O_3 , and MgO , is widely utilized in the electronics industry due to its ready availability and superior strength [47].

Table 2.4 Properties of fiber materials measured at ambient temperatures [48], [49].

MATERIAL	DIELECTRIC CONSTANT	LOSS TANGENT	ELASTIC MODULUS (GPa)	TENSILE STRENGTH (MPa)	DENSITY (g/cm ³)
E Glass	6.30	0.003	73.5	3500	2.54
S Glass	5.10	0.0068	86.8	4660	2.49
D Glass	4.00	0.0026	52.5	2450	2.16
Kevlar-49	3.85	0.019	112.4	3600	1.44

In addition to material characteristics, the orientation of fibers and interfacial properties play crucial roles in determining the properties of composite laminates. Fiber orientation dictates whether the properties of the laminate are isotropic or anisotropic; for example, a continuous arrangement of parallel fibers provides the highest unidirectional strength. Various types of weaves are employed for fibers in radome fabrication, with plain weave and satin weaves being the most common, as illustrated in Figure 2.15. Interfacial properties are also significant factors in the selection criteria; therefore, high-grade polyester or epoxy resin is typically used for

laminate fabrication. To enhance adhesion between the reactive groups of the resin and the fiber surface, a silane coupling agent is often employed. This results in improved resistance against operational factors and higher mechanical strength [50], [51].

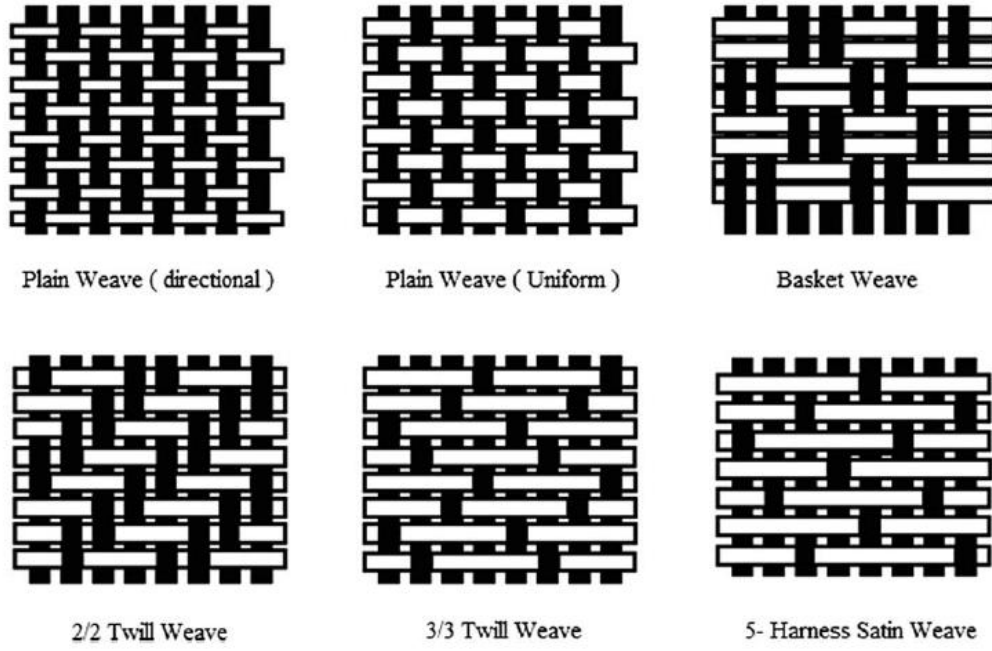


Figure 2.15 Types of weaves [43].

For fiber-reinforced laminates, the dielectric constant (ϵ) can be predicted using the following equation [52]:

$$\log \epsilon_m = V_f \log \epsilon_f + (1 - V_f) \log \epsilon_r \quad (7)$$

where:

- V_f is the volume fraction of fibers,
- ϵ_f is the dielectric constant of fibers, and
- ϵ_r is the dielectric constant of the resin.

The primary role of core materials is to increase thickness without significantly increasing weight, thereby leading to a substantial enhancement in flexural properties. This increase in thickness is crucial, as flexural properties depend on the cube of thickness in sandwich structures. Core materials are selected based on various properties, including low density, dielectric constant, thermal insulation, high shear modulus, compressive modulus, and stiffness. These materials are generally categorized into two main groups: foam and honeycomb structures.

Foam materials, particularly rigid foams with closed cells, are well-suited for serving as core materials in sandwich radomes. These materials allow for the precise molding of intricate shapes, either through foaming in place or thermoforming methods. In the foaming process, the foam can be positioned between inner and exterior laminates by softening it through heating, followed by the pressing of the exterior laminate over the foam. One of the advantages of foam materials is their closed-cell structure, which reduces moisture penetration.

Commonly used foam materials for sandwich-type radomes include polyvinyl chloride (PVC), polymethyl methacrylamide (PMI), polyetheramide, and polyurethanes. Among these, polyetheramide foams, such as Airex R82, demonstrate stability at high temperatures compared to other foam materials. However, they are susceptible to moisture absorption and exhibit relatively poorer mechanical properties. On the other hand, foams composed of polyurethane (e.g., Airex PXc 320) and polymethacrylimide (e.g., Rohacell IG) offer high strength at low densities.

Table 2.5 provides a summary of the properties of materials commonly used as foam materials for radome construction.

Table 2.5. Properties of foam materials for radome construction, measured at room temperature [53].

MATERIAL	DENSITY (g/cm ³)	COMPRESSIVE MODULUS (MPa)	SHEAR MODULUS (MPa)	THERMAL CONDUCTIVITY (W/mK)
Airex R82.80	0.05-0.07	52	18	0.040
Airex C71	0.06	70	20	0.036
Rohacell IG	0.11	167	50	-
Airex PXc 320	0.32	179	122	-

Honeycomb core materials offer exceptional transmission characteristics and mechanical properties, including favorable stiffness-to-weight and strength-to-weight ratios, as well as excellent resistance to acoustic shock. Moreover, they provide the potential for customized properties tailored to specific requirements. Typically, honeycomb materials feature a hexagonal cell structure, with cell sizes ranging from 1/800 to 1/200. However, more flexible flexicore cells can also be utilized for radomes with complex structures.

Various materials are suitable for radome fabrication, including Nomex (e.g., Plascore PN2), aramid (e.g., Plascore PK2 Kevlar), and glass-reinforced resins (e.g., Hexweb HRH-10, HRH-327, HFT). The mechanical properties of honeycomb structures exhibit directional dependence, as outlined in Table 2.5. A comparison between honeycomb structures and foam materials is provided in Figure 2.16.

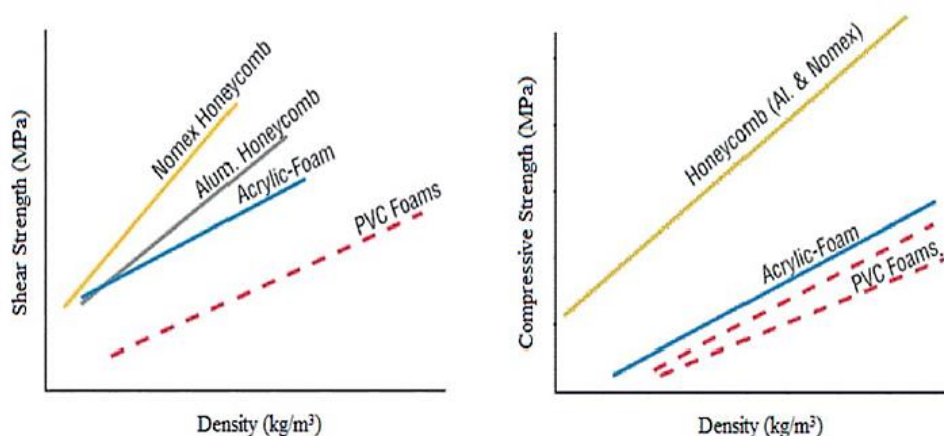


Figure 2.16. Strength comparison of honeycomb and foam materials[48], [54].

Among the array of techniques available for radome fabrication, the hand lay-up technique stands out as one of the most common and straightforward methods. In this approach, layers of fiber and resin are systematically stacked onto a mold until the desired thickness is attained. Excess resin is then removed using a roller. While this method is labor-intensive and tends to yield products with lower surface finish, it excels in casting intricate shapes [48].

To streamline the laborious process of resin application onto fabrics, manufacturers have turned to pre-impregnated laminate sheets, known as prepregs [54]. These prepregs are cured using an autoclave through two distinct methods. The first method involves curing the prepregs separately on different autoclave schedules and subsequently joining them with core material to form the sandwich structure. The second method entails assembling the sandwich structure on a fixture and curing it as a single unit, thereby saving energy and accelerating the production of radomes.

However, when fabricating sandwich structures with thin prepregs, there is a risk of the prepregs being pressed into the honeycomb structure by the autoclave pressure, resulting in surface defects known as the telegraphing phenomenon. Additionally, the two different autoclave methods yield different bonding mechanisms between the layers, leading to variations in the mechanical strengths of the final products [55].

2.6 Prepreg Manufacturing Techniques

The objective of this study is to fabricate a polymer matrix composite laminate incorporating frequency selective surfaces (FSS). The next step in this research involves wetting patterned dry fibers with a suitable resin to assess the compatibility between FSS patterns and polymer resin. Therefore, the initial phase of this endeavor is the manufacturing of prepreg.

Prepreg manufacturing has been chosen over wet lay-up due to its ability to offer better control over resin content. Resin content plays a critical role in the mechanical performance of the final laminate; therefore, it must be precisely controlled.

Ensuring that all layers have similar resin content within a small tolerance range is essential for maintaining the balance of the laminate.

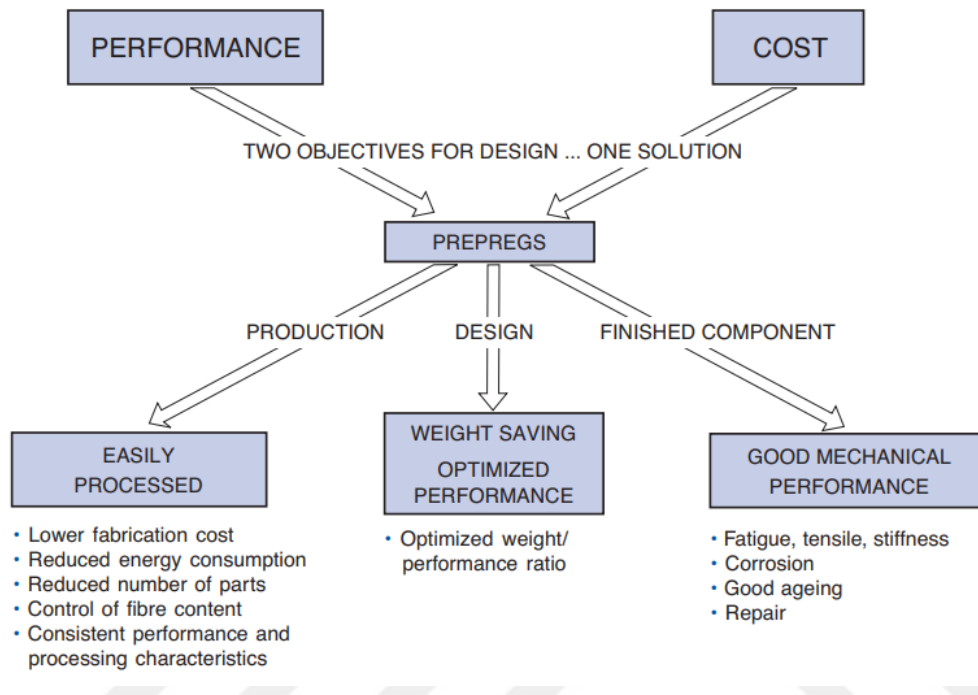


Figure 2.17. Advantages of prepreg route.

Prepreg can be produced through two different routes, depending on the viscosity of the polymer resin. One method is the solution route, which is employed for low viscosity resins. In this process, the fiber is simply dipped into a resin bath and impregnated.

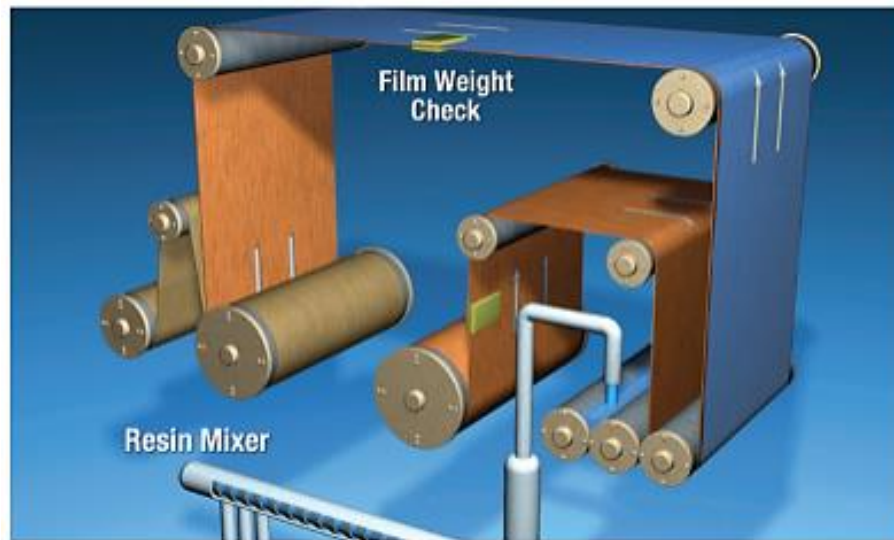


Figure 2.18. Schematic of film manufacture.

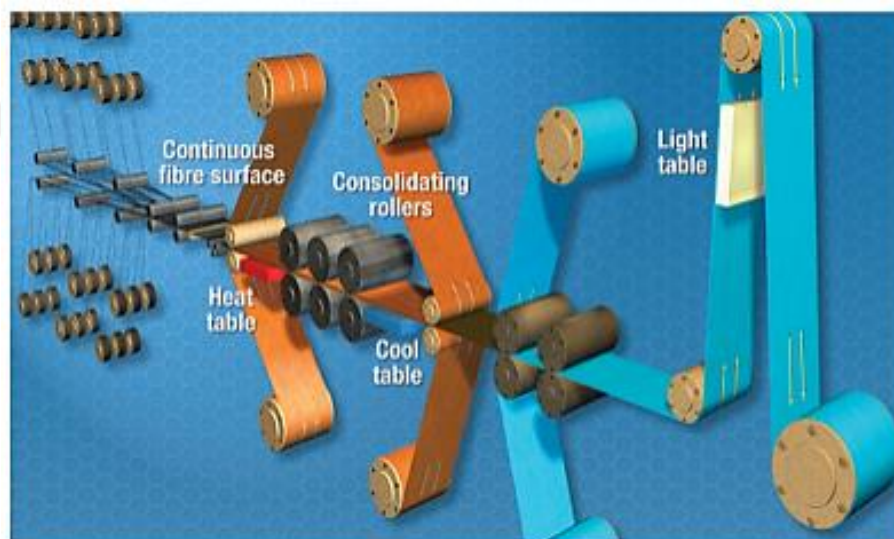


Figure 2.19. Schematic of film transfer.

The other route is film transfer, which is more suitable for high viscosity resins and provides better resin control. In this method, the resin is first turned into a film layer with a certain thickness, and then the fiber is impregnated with the resin layer under

pressure or through mandrels. The parameters of this process depend on the properties of the resin and fiber.

The figures above depict schematic representations of industrial production lines for the film transfer route. However, in our case, a simpler approach is employed. The film layer is produced using tape cast equipment, with the thickness of the resin film calculated and its weight controlled for a specific area. Once the film layer is produced, it is combined with dry fabric and pressed together using a simple lamination tool. This method allows for the production of prepreg including the FSS layer with controlled resin content.

2.7 Electromagnetic Characterization Methods

There are various methods available for investigating the electromagnetic properties of materials, such as shielding effectiveness (SE) and absorbing behavior. The choice of the most suitable characterization method depends on significant parameters of the material, such as its shape, thickness, and form. Materials can exist in the form of panels, thin sheets, or bulk.

Some of the important electromagnetic characterization methods include the coaxial probe method, parallel plate method, transmission line method, surface waveguide method, shielded box method, and free space method. In Figure 2.20, these EM characterization methods are located according to the loss behavior of the material and the frequency region [56].

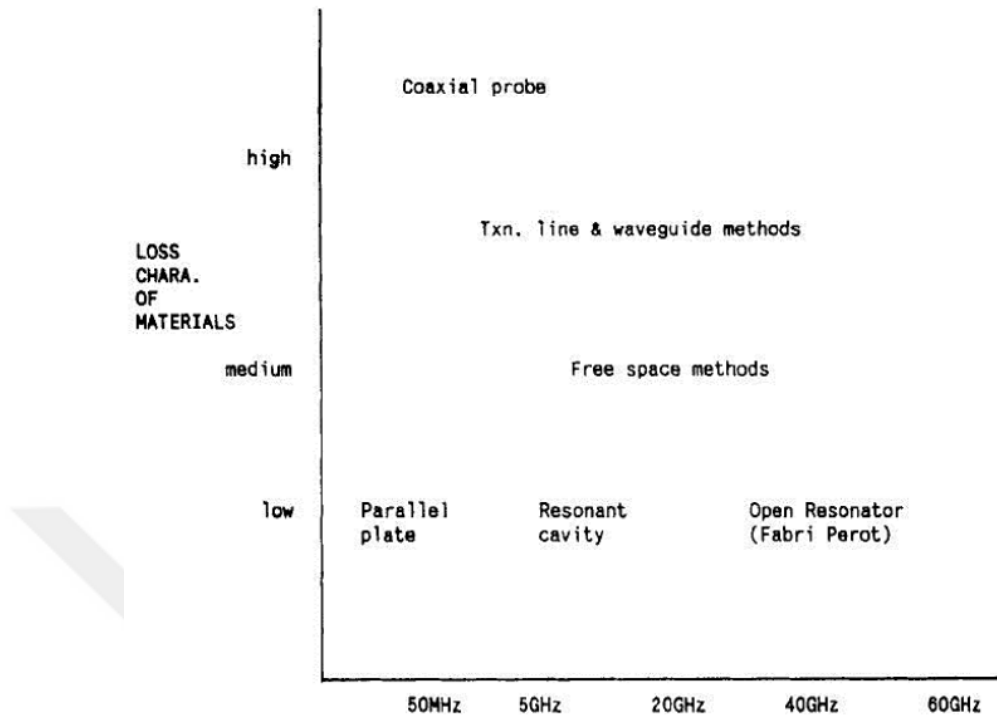


Figure 2.20. The suitable EM characterization method selection [56].

In this study, the free space method was selected as the most suitable approach to characterize the electromagnetic properties of FSS printed glass fiber woven fabric. This method is specifically chosen for its capability to assess the reflection and transmission behavior of materials. Moreover, it enables the characterization of electromagnetic properties for inhomogeneous materials. Additionally, considering Figure 2.16, the free space method aligns well with the frequency range and the loss characteristics of the material under investigation in this study.

2.7.1 Free-Space Method

The free space method is a widely employed non-destructive technique, relying on the reflection and transmission behavior of the media under investigation. This measurement setup typically comprises two horn antennas positioned opposite each

other, with power generated by a vector network analyzer transmitted through coaxial cables to these antennas. Subsequently, electromagnetic waves are emitted from the horn antennas and focused onto the surface of the specimen via lenses. Figure 2.21 illustrates a schematic diagram of the free space setup [57].

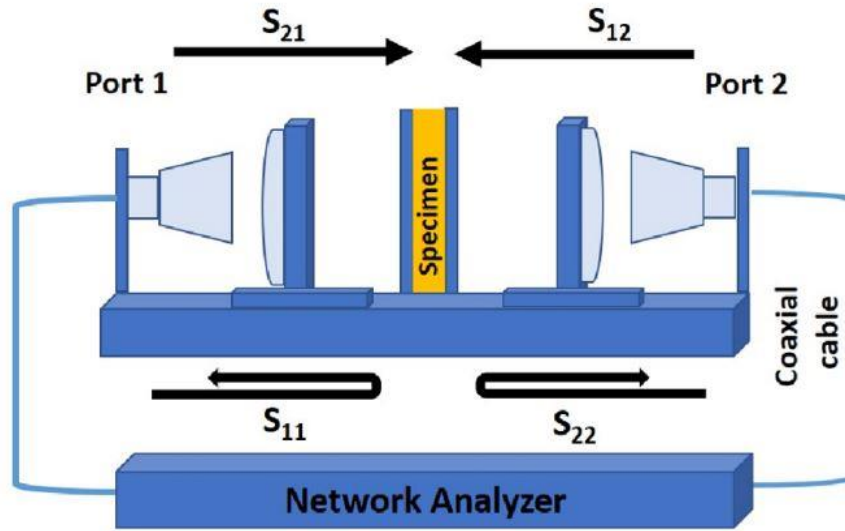


Figure 2.21. Schematic representation of the home-designed and built free space setup [58].

In the preceding sections, the primary mechanisms of interaction between electromagnetic (EM) waves and matter have been defined as reflection loss and absorption loss. When utilizing the free space method, measurements are conducted to determine the reflection and transmission coefficients in terms of phase (in dB) and magnitude (θ). The output is typically presented in the form of four S parameters: S_{11} , S_{12} , S_{22} , and S_{21} . In these parameters, the first number indicates the port receiving the EM wave, while the second number indicates the port transmitting the EM wave. For instance, when the incident wave originates from antenna 1 and is reflected back to antenna 1 after interacting with the sample, this is represented by

the reflection coefficient as S11. Conversely, if the incident wave from antenna 1 is transmitted to antenna 2, it is denoted by the transmission coefficient as S12. The opposite scenarios are labeled as S22 and S21 [12].

Reflection (R) and transmission (T) loss in decibels can be expressed as the logarithm of the ratio of reflected and transmitted power to the incident power. When the vector network analyzer outputs the results in power units, the multiplication factor is 10. However, when the outputs are in voltage units, the multiplication factor becomes 20. Equations 8 and 9 depict the formulation for reflection and transmission loss in both voltage and power forms [59].

$$R(S_{22}) = 10 \log \frac{P_R}{P_0} = 20 \log \frac{V_R}{V_0} \quad (8)$$

$$T(S_{22}) = 10 \log \frac{P_T}{P_0} = 20 \log \frac{V_T}{V_0} \quad (9)$$

CHAPTER 3

EXPERIMENTAL PROCEDURE

This chapter presents experimental procedures and techniques utilized in screen-printing process preparation, optimization and printed FSS pattern characterization steps.

3.1 Materials

The aim of this work was to coat glass fabric (E-glass) in a certain pattern with conductive paste by screen printing method. There are several parameters affecting printing quality such as ink rheology, interface between ink and substrate, surface roughness, screen parameters, etc. Therefore, properties of glass fiber woven fabric used as a substrate and the conductive pastes were significant and must be taken into consideration in all aspects.

3.1.1 The Reinforcement – Glass Fiber Woven Fabric

E-Glass fiber were chosen as the substrate materials since they are suitable for FSS applications due to their dielectric properties. Composition of E-glass fiber is given in Table 3.1.

Table 3.1. Composition of E-glass fiber type by weight %.

SiO ₂	Al ₂ O ₃	B ₂ O ₃	CaO	MgO	Na ₂ O	TiO ₂	Fe ₂ O ₃	K ₂ O
52-56	12-16	5-10	16-25	0-5	0-1	0.2-0.5	0.2-0.4	trace

The mechanical properties of the resulting glass fiber reinforced composite material depend heavily on the nature of the fiber – matrix interface. A strong interface generally leads to the best composite properties and many effective interfacial coupling agents that can form strong interface have been identified for single component polymer matrices.

Properties of glass fiber such as their weave types, areal weight and topographical behaviors are important parameters since the surface roughness of substrate directly affects the printing resolution and resulting EM performance. There are several weave types and corresponding areal weights for E-glass fabrics. Plain weave type 0.10 mm thick fabric (schematically shown in Figure 3.1), with 110 GSM (g/m^2) areal weight and silane sizing was chosen in this study due to its quasi-isotropic behavior. The areal weight of the glass fabric has been optimized through trials, and the 110 GSM thickness was selected as to provide a rigid enough structure to withstand deformations during screen-printing and handling such that a smooth enough topography could be printed with high fidelity patterns. Dielectric properties of selected bare glass fabric were analyzed beforehand by using free-space set-up, and dielectric constant of the fabric was found as 3.75 where loss tangent was 0.01 at 10 GHz.

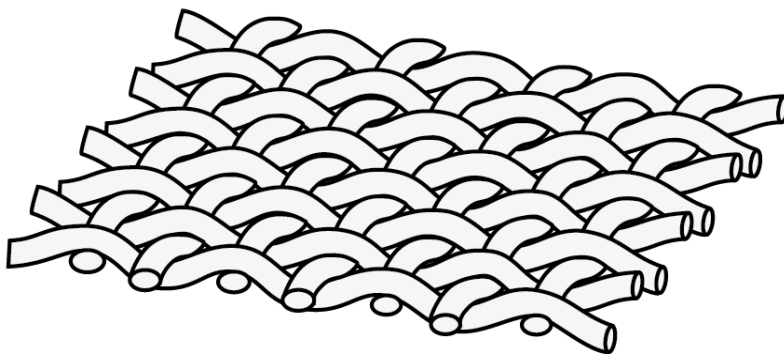


Figure 3.1 Schematic of plain weave glass fabric.

Properties of glass fiber used in experimental studies are given in Table 3.2.

Table 3.2. Properties of glass fiber.

E-Glass Fabric	
Mass per unit area (GSM)	110 ± 5
Weave Type	Plain
Sizing Type	Silane
Thickness (mm)	0.10

3.1.2 The Conductive Paste

Conductive paste is one of the most critical factors to fabricate the desired surface patterns with required conductivity and resolution in screen printed electronics. Composition of the conductive paste (ratios of conductive part, binder, solvents, additives, etc.) and the geometries of the conductive particles have significant effect on the final conductivity of the printed pattern [60].

Type and shape of the particles (material, size, amount, shape, distribution, and orientation) directly affect the electrical properties. Currently, silver is the most frequently reported material for conductive pastes being the most widely utilized in industrial applications, while the alternatives such as copper-based and gold-based pastes are either low in oxidation resistance or high in price, respectively [61]. There were three main criteria for selection of conductive paste in this study. First, two different particles sizes were selected to observe the printing quality and EM performance. The second one was the curing temperature which should be as low as possible to preserve the surface chemistry of glass fabric throughout the application for the composite manufacturing process to follow. Finally, the viscosity of the paste should be compatible with the specific screen printing equipment and process to achieve the best pattern resolution. Consequently, two different types of commercially available silver-based conductive pastes were used in this study. The properties of these pastes are summarized in Table 3.3.

Parameters for drying processes taken from technical datasheets of related conductive pastes are given in Table 3.4.

Table 3.3. Properties of silver pastes used in this study (derived from TDS documents).

Trade Name of The Paste	Loctite EDAG 725A	Loctite ECI 1011
Paste Referred in The Text as	Ag-120 or Type-1 Paste	Ag-150 or Type-2 Paste
Pigment Type	Silver	Silver
Drying Temperature	120°C	150°C
Av. Particle Size	100nm < & <1mm	<2µm
Density (g/mL)	2.14	3.00
Viscosity (cP)	12500	2800
Solid Content (%)	60.0	75.6
Sheet Resistance (Ω /sq/25µm)	≤ 0.015	≤ 0.005

Table 3.4. Typical (recommended) curing cycles of silver pastes.

	Ag-120	Ag-150
DRYING CYCLE	15 min @120°C (Box oven)	10 min @150°C (Box oven)

3.1.3 The Resin

In this study DA100 epoxy resin, which is a commercial product of SPM Composite company, was used as the composite matrix material. DA100 is a high flow, 120 °C curing epoxy resin with good tack and drape. Post cure is not required for desired properties. This resin system is suitable with carbon, glass and aramid fabrics reinforcements. DA100 resin system is designed for autoclave applications; however, it can be successfully processed by hot press and vacuum bagging techniques. It is especially best for low to medium service temperature applications.

3.2 Electromagnetic Design of FSS Pattern and Simulation

The definitions and discussions about Frequency Selective Surfaces (FSS) phenomena are clearly elucidated by Munk, a prominent figure in FSS research [6]. The fundamental concept to grasp is the notion of a "Periodic Surface," as it forms the foundation of FSS structures. A periodic surface comprises identical elements arranged in infinite arrays, typically in one or two dimensions. Several factors influence the performance of FSS structures, including:

- Type of elements (patches vs. slots)
- Shape of elements
- Dimensions of elements
- Inter-element spacing
- Array configuration (e.g., rectangular, triangular, hexagonal)
- Alignment of elements in multi-layer structures.

Additionally, the electrical characteristics of the substrate material play a crucial role in FSS performance. As a result, numerous combinations of parameters are explored to achieve an optimal solution for specific applications. This thesis focuses on developing and analyzing FSS structures for conformal bodies using ANSYS HFSS®, beginning with planar unit cell models tailored to different specifications.

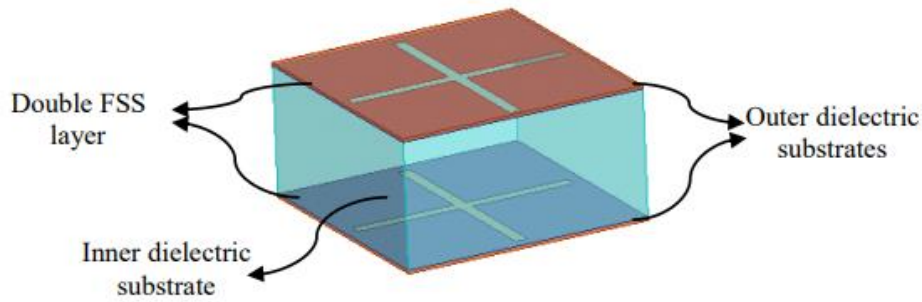


Figure 3.2. Stack-up configuration.

The hybrid FSS model exhibits improved transmission response in both band-pass flatness and bandwidth compared to a single metallic layer of crossed dipole aperture FSS [62]. Thus, this thesis intends to utilize the hybrid FSS model. Patch-type FSS patterns exhibit band-stop behavior, blocking the transmission of specific frequency waves across the entire frequency range. In contrast, aperture-type FSS patterns provide band-pass characteristics, allowing the transmission of only a specific frequency wave while blocking others. Material properties used in HFSS simulation are given in Table 3.5.

Table 3.5. Material properties used in HFSS simulation.

	Relative Permittivity (@10 GHz)	Dielectric Tangent Loss (@10 GHz)	Thickness (mm)
110 GSM Glass Fabric	3.30	0.007	0.09
110 GSM Glass Prepreg	3.75	0.01	0.1
280 GSM Glass Prepreg	4.10	0.011	0.25
ROHACELL	1.07	0.001	3.5

3.2.1 Single Layer FSS Design

FSS design starts with “unit cell” approach and due to periodic nature of FSS structures infinite array approximations are applicable [62]. Unit cell method employs the periodic solution of an FSS model.

In this study, the performance of the FSS structure under the infinite array conditions was determined using HFSS® module of ANSYS software starting from the planar unit cell models. Design parameters were analyzed for the targeted 9.8 GHz frequency (in X-band) and the dimensions (x, y, t and d values shown in Figure 3.3) of the FSS geometry were chosen through parametric sweep studies (Figure 3.3). Resulting FSS dimensions through EM simulation targeting band-pass behavior at 9.8 GHz is given in Figure 3.5. FSS coating thickness was taken as 20 mμ due to limitations resulting from screen-printing method and the material was assumed pure silver as an excellent electric conductor in simulation. The expected EM performance (reflection and transmission loss) of the single layer FSS structure with the repeating crossed dipole unit cell geometry based on the simulation is given in Figure 3.6. As it is seen in the simulation result, the FSS structure shows a notch in the reflection response at 9.8 GHz as designed.

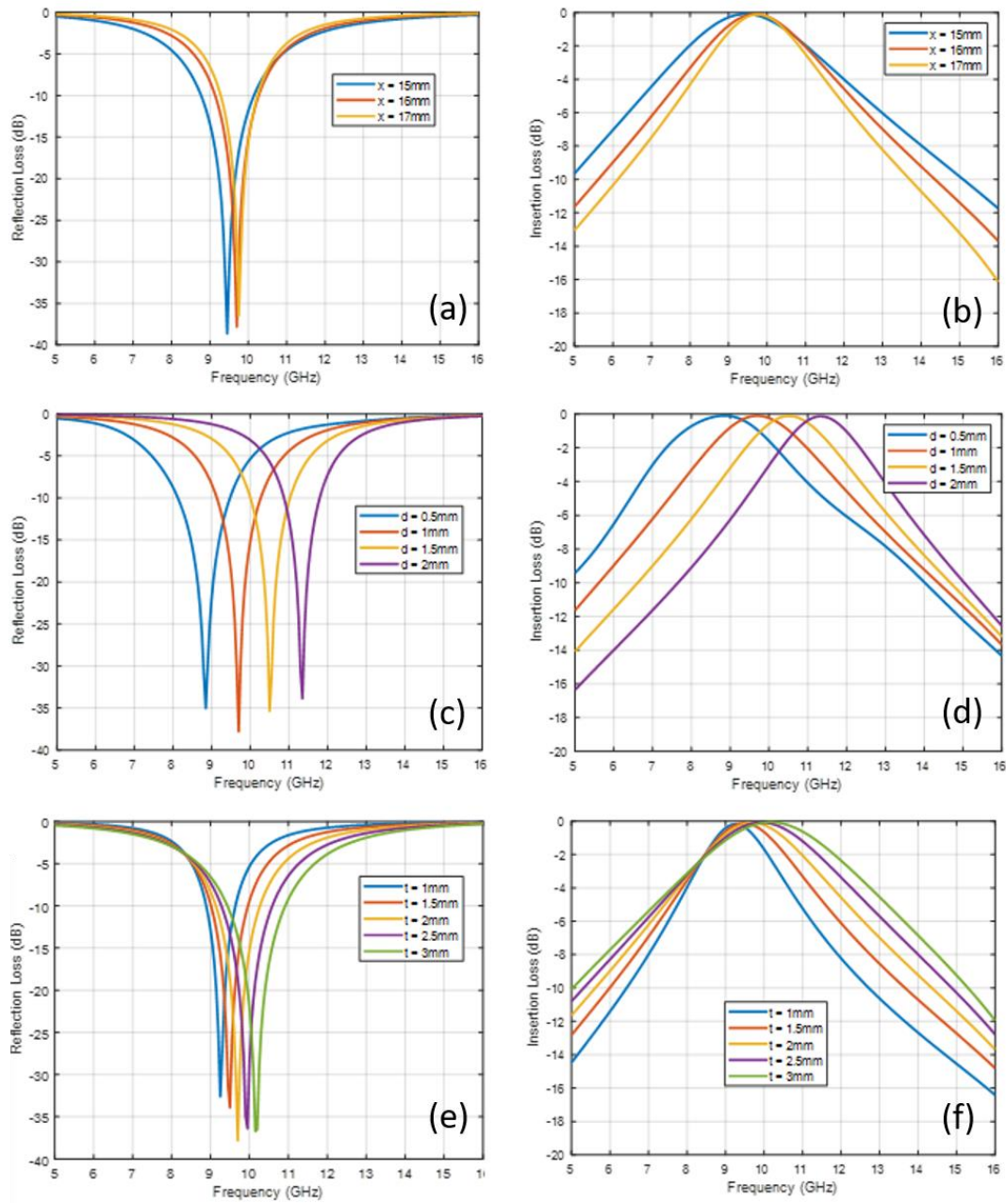


Figure 3.3. Parametric sweep analysis of FSS unit cell (a)-(f).

Later, pure silver properties were replaced with the properties of silver based conductive paste having $25\text{ }\mu\text{m}$ thickness cured on a smooth surface which has a sheet resistance of around $0.015\text{ }\Omega/\text{sq.}$ (according to supplier's technical datasheet), and it was seen that the deviation from pure silver properties has an insignificant

effect on target frequency, where it only affects the amount of insertion loss at the frequency of interest (Figure 3.4). This study has been also repeated for different conductive paste thicknesses, and the result was similar with the change in resistivity case. As the conductive layer thickness increases, conductivity decreases for the same sheet resistance value, causing minimum insertion loss to increase without leading to any change in target frequency.

The sensitivity of the reflection against conductor's thickness and hence related resistivity is given in Figure 3.4. Conductivity values of different coating thicknesses were calculated according to the Eq.10, assuming the sheet resistance is the same. The effect of conductive coating thickness on minimum insertion loss of the printed FSS layer was analyzed by using Table 3.6 and the result of the analysis is given on Figure 3.4.

$$\text{Sheet Resist. at DC } (\Omega/sq) = \frac{1}{\text{Conductivity } (S/m) * \text{Thickness } (m)} \quad (10)$$

Table 3.6 Calculated conductivity values for different coating thicknesses for the same sheet resistance.

COATING THICKNESS (μm)	5	10	15	20	25	30	35	40	45	50
CONDUCTIVITY ($10^6 \times S/m$)	13.3	6.67	4.44	3.33	2.67	2.22	1.90	1.67	1.48	1.33

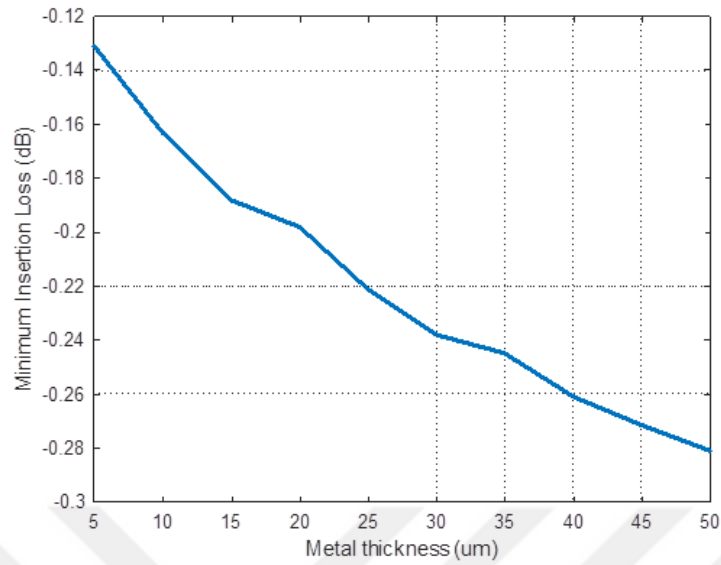
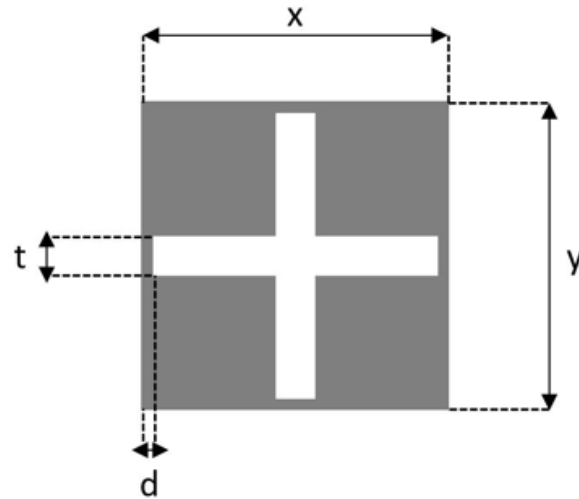


Figure 3.4 Effect of coating thickness on minimum insertion loss of FSS layer.

3.2.1.1 Single Layer FSS Design for Sandwich Structure

Unit cell implies one period of the FSS where the geometry used in this study in sandwich composite structure is shown in Figure 3.5.



	x	y	t	d
Size (mm)	16	16	2	1

Figure 3.5. Unit cell of a crossed dipole aperture FSS model of sandwich structure and its dimensions.

In this study, the performance of the FSS structure under the infinite array conditions was determined using HFSS® module of ANSYS software starting from the planar unit cell models. Design parameters were estimated for the targeted 9.8 GHz frequency (in X-band), and dimensions of the FSS geometry were chosen through EM simulation as given in Figure 3.5.

The expected EM performance (reflection and transmission loss) of the single layer FSS structure of sandwich design with the repeating crossed dipole unit cell geometry based on the simulation is given in Figure 3.6. As it is seen in the simulation result, the FSS layer shows a notch in the reflection response at 9.8 GHz as designed.

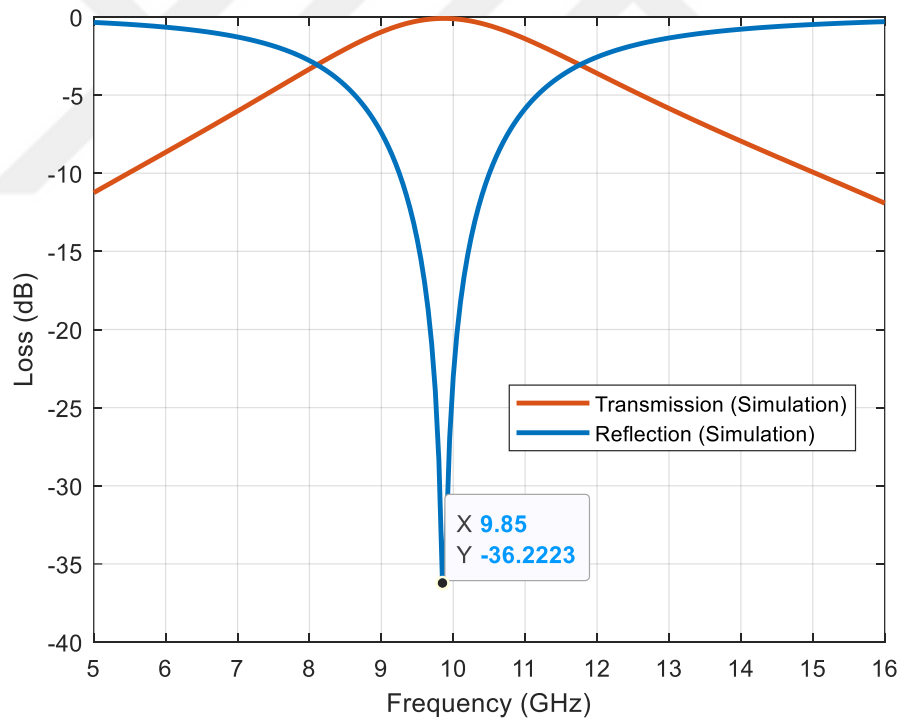


Figure 3.6 The expected reflection and transmission performance of single layer FSS structure of sandwich design.

3.2.1.2 Single Layer FSS Design for Monolithic Structure

Unit cell implies one period of the FSS where the geometry used in this study in monolithic composite structure is shown in Figure 3.7.

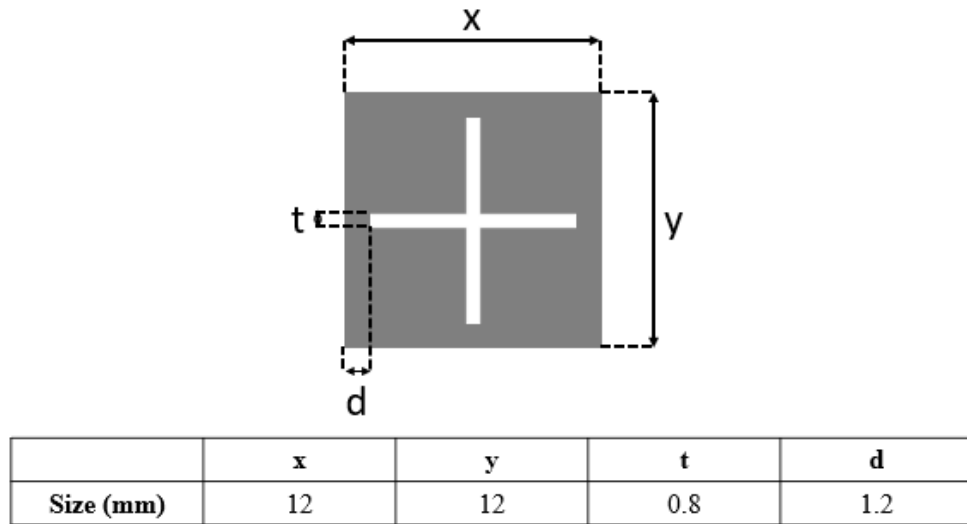


Figure 3.7. Unit cell of a crossed dipole aperture FSS model of monolithic structure and its dimensions.

The expected EM performance (reflection and transmission loss) of the single layer FSS structure of monolithic design with the repeating crossed dipole unit cell geometry based on the simulation is given in Figure 3.8. As it is seen in the simulation result, the FSS layer shows a notch in the reflection response at 13.25 GHz as designed.

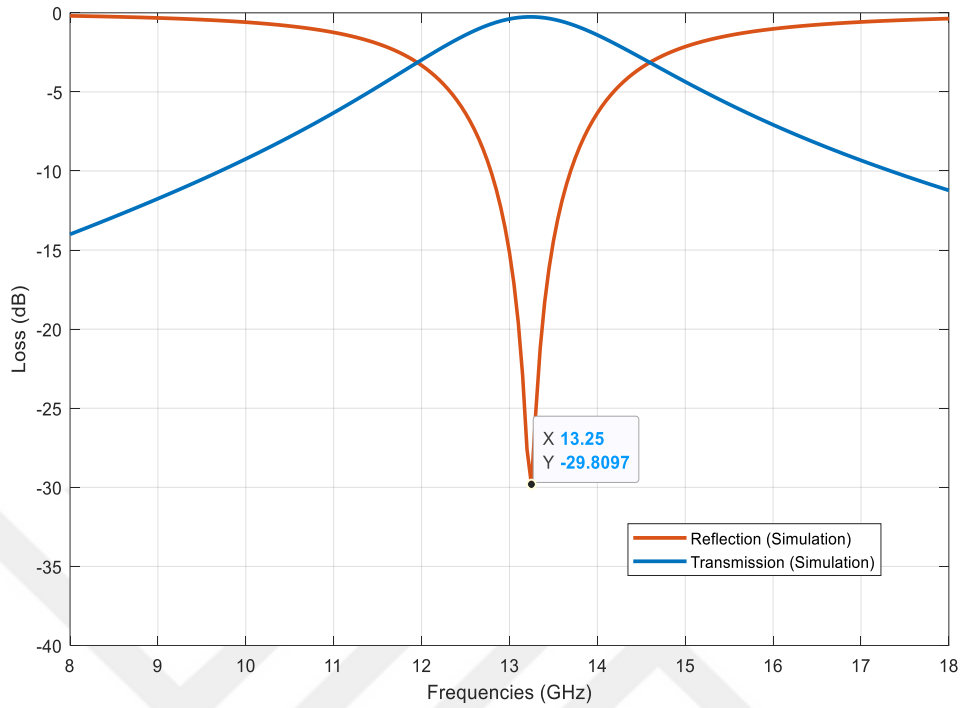


Figure 3.8. The expected reflection and transmission performance of single layer FSS structure of monolithic design.

3.2.2 Multilayer FSS Composite Design

Multilayer FSS composite contains FSS printed prepreg layers together with dielectric spacing layers which are empty glass preregs or core structures such as Rohacell or honeycomb depending on the application. In case of monolithic composite configuration, empty glass preregs were used as spacing media between FSS printed prepreg layers where in sandwich composite configuration, spacing media was chosen as Rohacell in this study. Details of these configurations and expected EM performances are explained in following chapters. Schematic stack-up of final composite structure is given in Figure 3.9.

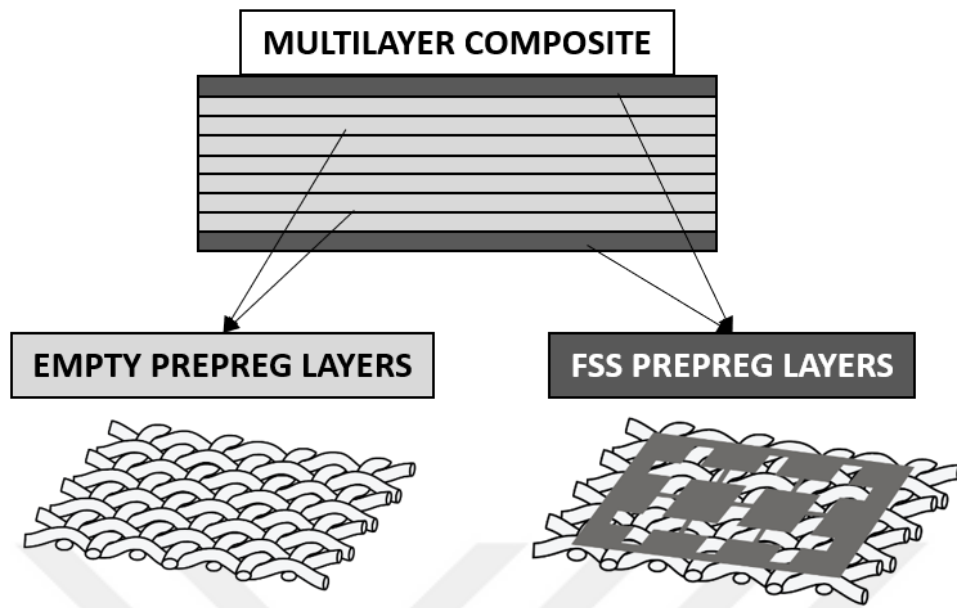


Figure 3.9. Schematic of multilayer composite stack-up.

3.2.2.1 Sandwich FSS Composite Design

Sandwich composite design in this study includes two FSS printed prepregs, two double layered 280 GSM glass prepregs and one 3.5 mm thick Rohacell core layer in the middle. The schematic representation of sandwich composite design is given in Figure 3.10.

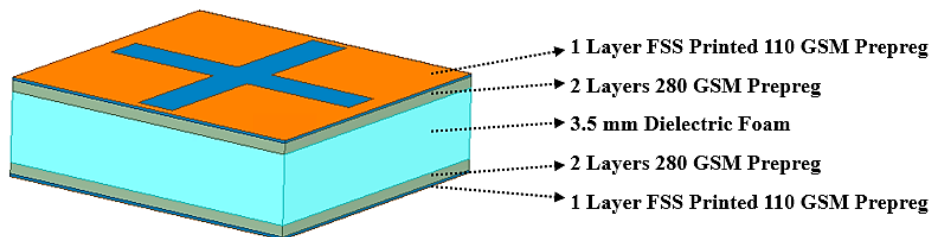


Figure 3.10. Multilayer Sandwich Composite Stack-up.

EM simulation of multilayer composite was also conducted through HFSS® module of ANSYS software (Figure 3.11).

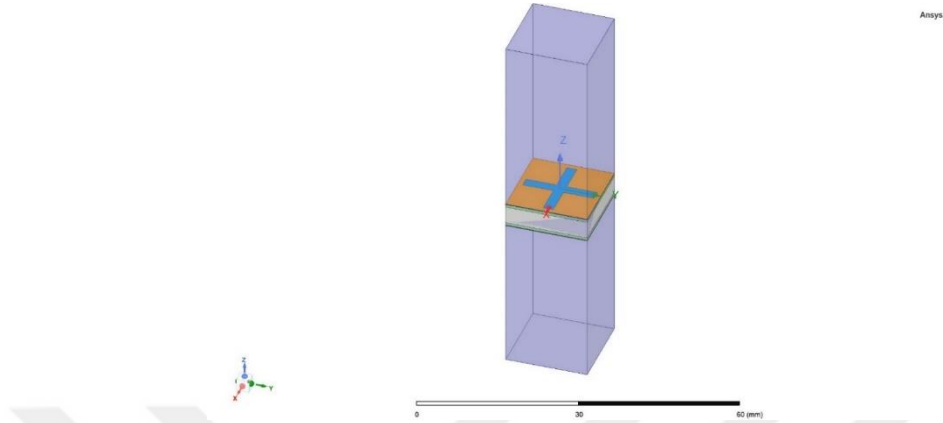


Figure 3.11. A unit cell FSS of sandwich composite in HFSS module.

Expected EM performance of related sandwich composite design is given in Figure 3.12.

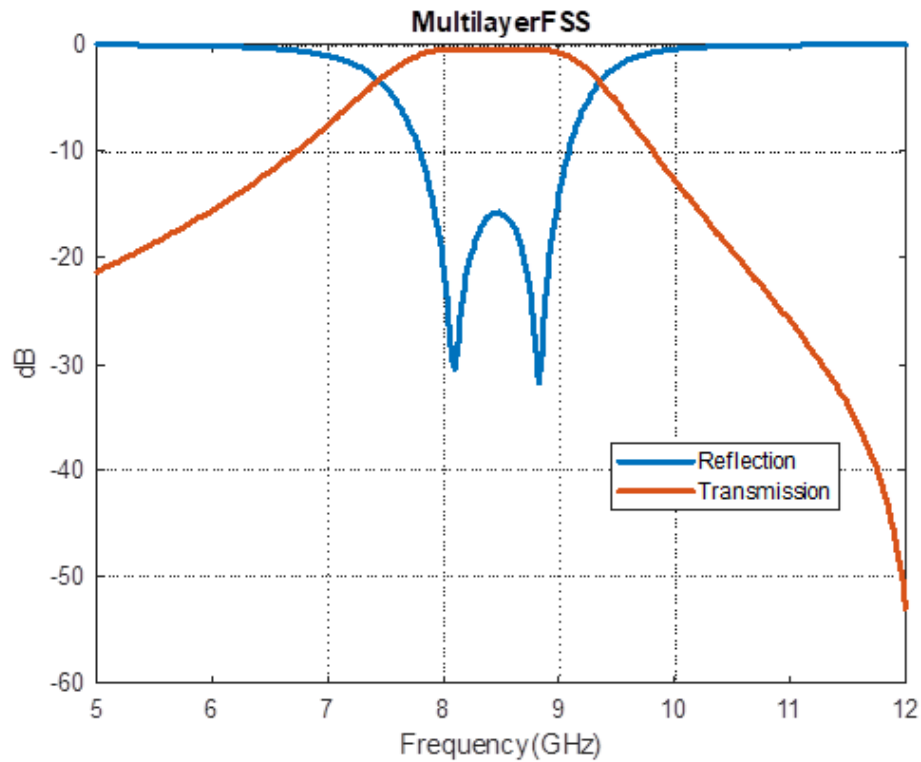


Figure 3.12. The expected reflection and transmission performance of FSS sandwich composite design.

3.2.2.2 Monolithic FSS Composite Design

Monolithic composite design in this study includes two FSS printed prepregs and five layers of 280 GSM glass prepregs in the middle. The schematic representation of monolithic composite design is given in Figure 3.13.

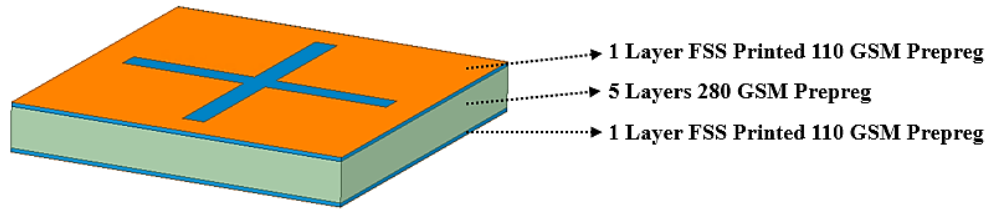


Figure 3.13. Multilayer monolithic composite stack-up.

EM simulation of multilayer composite was also conducted through HFSS® module of ANSYS software (Figure 3.14).

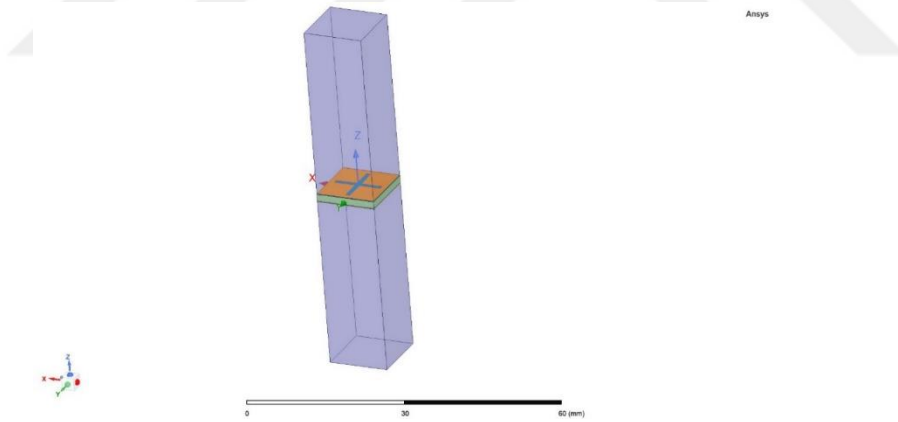


Figure 3.14 A unit cell FSS of monolithic composite in HFSS module.

Expected EM performance of related monolithic composite design is given in Figure 3.15.

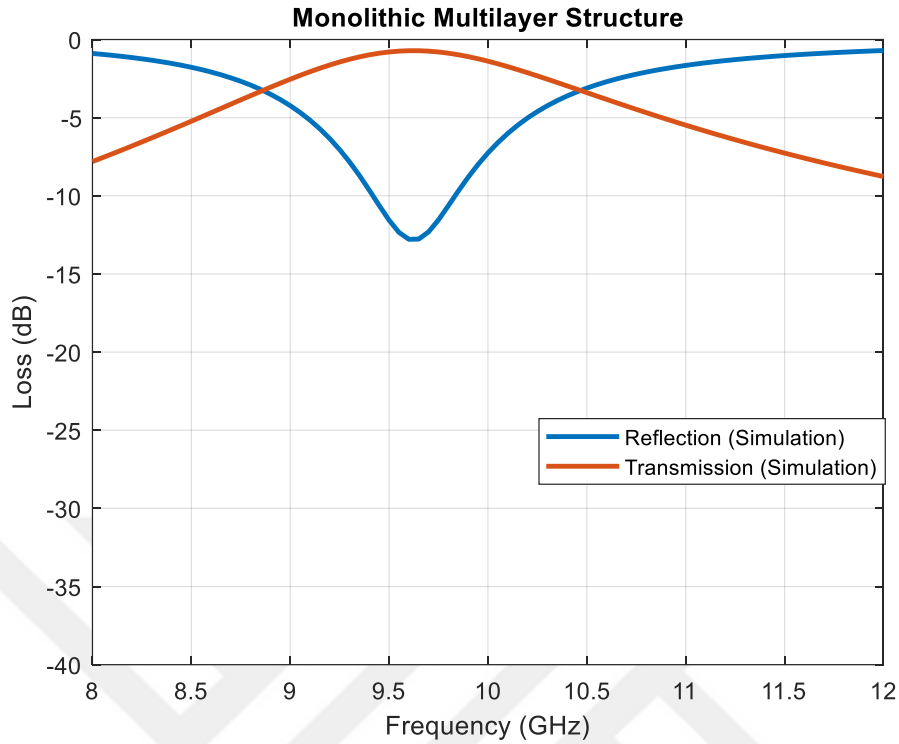


Figure 3.15 The expected reflection and transmission performance of FSS monolithic composite design.

3.3 Screen Printing of FSS Layer on Glass Fabric

Screen printing applications have several parameters which affect the quality of printed FSS patterns. Therefore, preparation of screens and the parameters used in this application are of high importance.

One of the key points in screen printing quality is to obtain a printed pattern on a substrate having the same dimensions as pattern on the screen mesh. The fidelity and quality of the pattern on the screen mesh, the viscoelastic behavior of the paste and the mechanical behavior of the screen-squeegee couple are among the most important factors which directly affect the printing quality. As the intended and actual pattern dimensions get close to each other, the printing quality improves, and

the agreement between the simulated EM properties and the actual measurements increases.

The thickness of the resulting pattern on the substrate should be close to the initial design thickness and must have minimum variation over the surface for best EM performance. Two different types of FSS were covered in scope of this thesis (Figure 3.16).

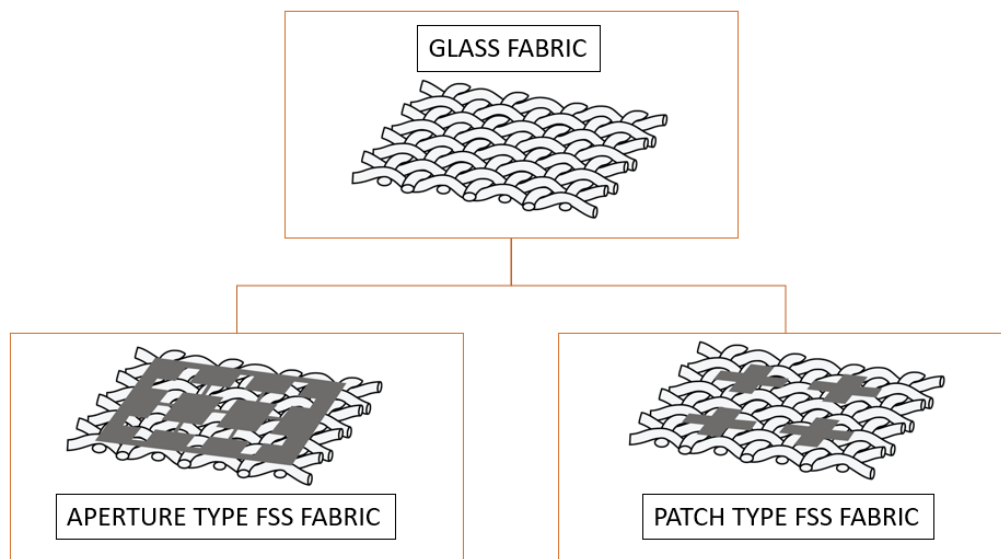


Figure 3.16. Schematic of FSS printed glass fabrics in aperture type and patch type.

3.3.1 Screen Mask Preparation

Depending on the paste type (containing metallic particle) and the substrate properties (glass fabric), white colored polyester screen having 120 mesh size (with a 34% opening ratio) was used.

First, white colored polyester mesh was stretched to aluminum frames at certain tension values. It was important to have a tight mesh for better quality printing application.

There are several colors for polyester mesh fabrics. The difference between these fabrics is the resolution of imprinted patterns during UV curing. For example, yellow colored mesh provides better resolution and suitability for complex and thin geometries. However, since the patterns used in this study were coarse, it was not necessary to use yellow color, it was decided to continue with white colored mesh.

Then, the screen was manufactured by using water-based UV curing emulsion applied on this mesh fabric. Emulsion was solidified by drying application before UV curing. Drying step was repeated until the required thickness of emulsion was achieved (Figure 3.17, Figure 3.18, Figure 3.19).

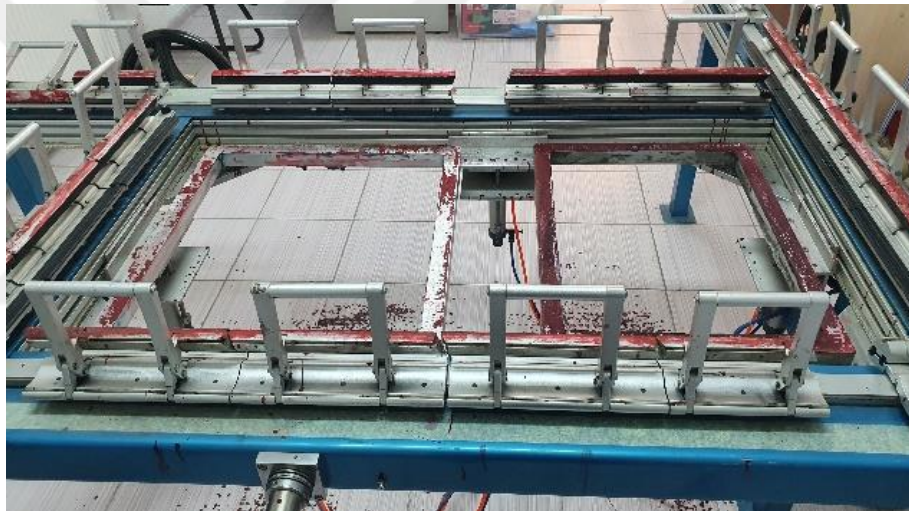


Figure 3.17. Screen frames.



Figure 3.18. Mesh fabric stretching to frames.

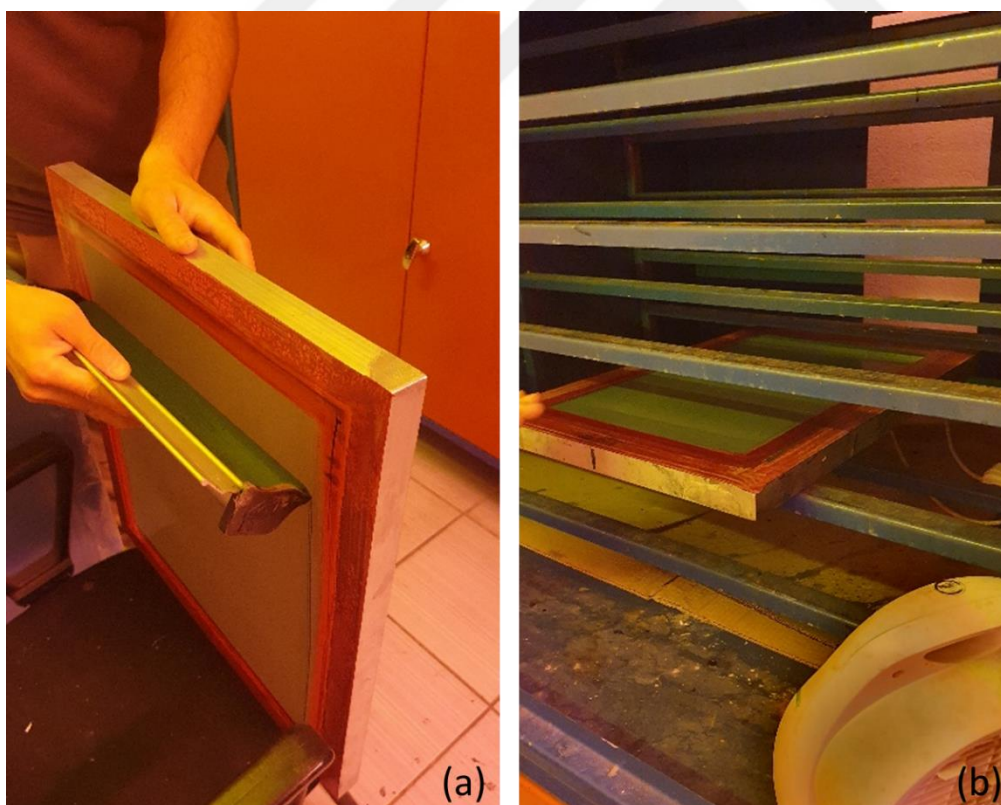


Figure 3.19. Emulsion coating (a) and drying of emulsion (b).

After this step, to obtain the FSS pattern on screen, high power (3000 Watt) UV lamp was applied for 120 seconds. This curing time was dependent on the properties of emulsion material. After curing, areas exposed to UV light were stabilized where areas behind the black FSS pattern remained uncured. In the end, to obtain the final FSS pattern printed screen, the screen was washed with high pressure water and the removal of excess uncured emulsion from the surface was achieved (Figure 3.20).

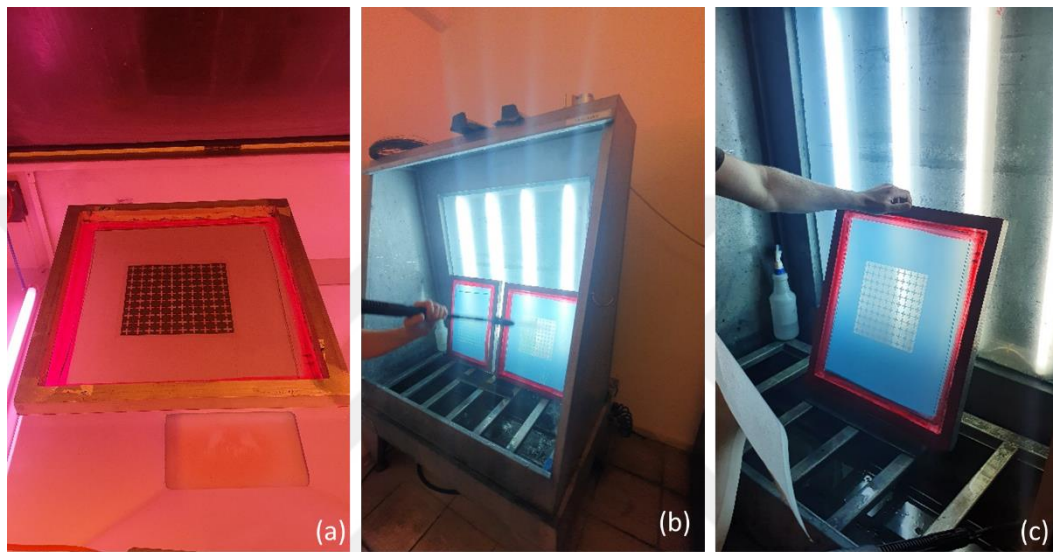


Figure 3.20. UV curing of emulsion (a), washing excess emulsion (b) and pat drying (c).

3.3.2 Screen Printing Application

After the screen was prepared, it was attached to the application platform. Normally, for flat substrates, vacuum was applied to hold and to control the substrate throughout the printing application. However, since the substrate was air permeable, adhesive tape was used to fasten it on the application table. The fastening of the substrate material on application table was very important since printing quality was affected by the time spent until the screen and substrate were separated from each other. If the substrate sticks to the screen, printing quality would be affected negatively (Figure 3.21).

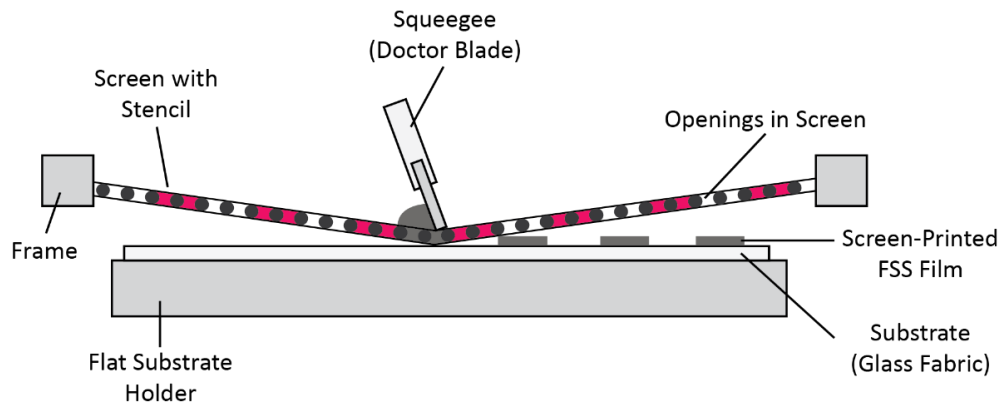


Figure 3.21. Schematic operation of screen-printing method.

When the substrate and the screen were ready, conductive paste was applied on screen surface. The patterns were printed by the two-stroke method, i.e., first round to distribute the paste throughout the surface and the second round to print the paste on the substrate as shown in figure below (Figure 3.22, Figure 3.23).

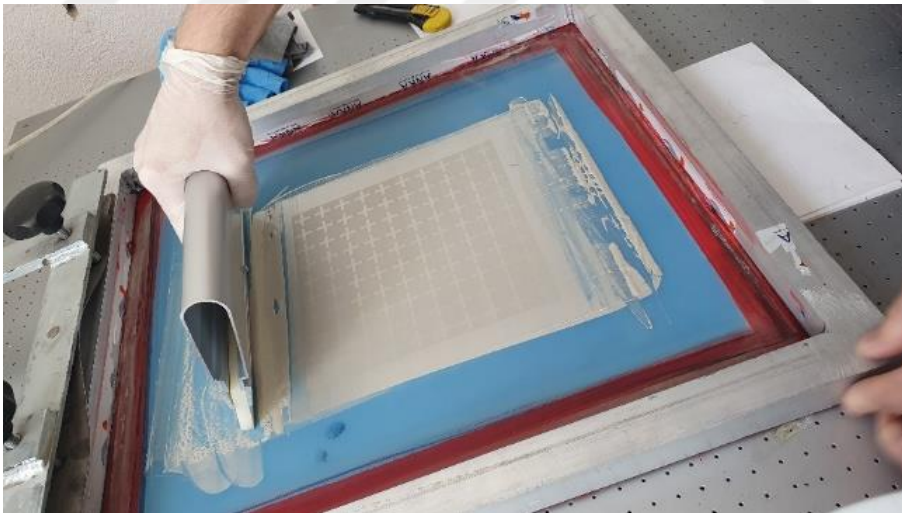


Figure 3.22. Distributing ink to surface.

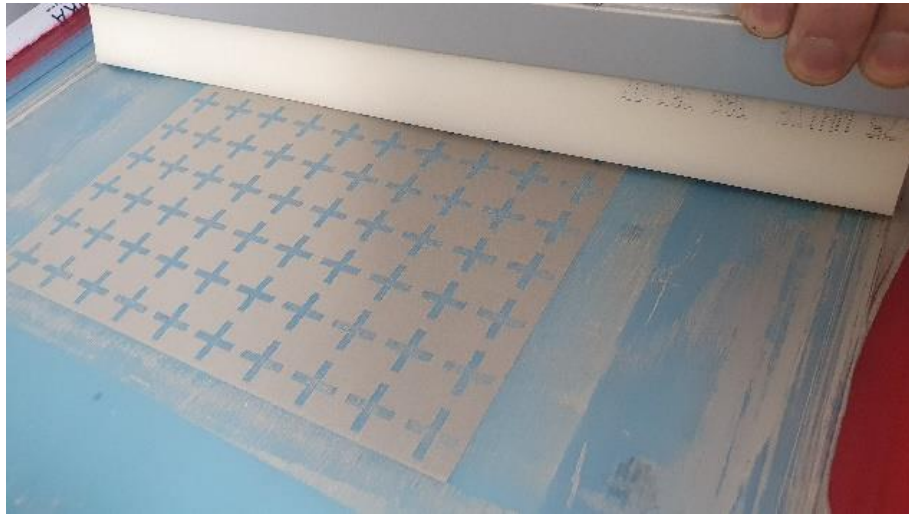


Figure 3.23. Screen printing application.

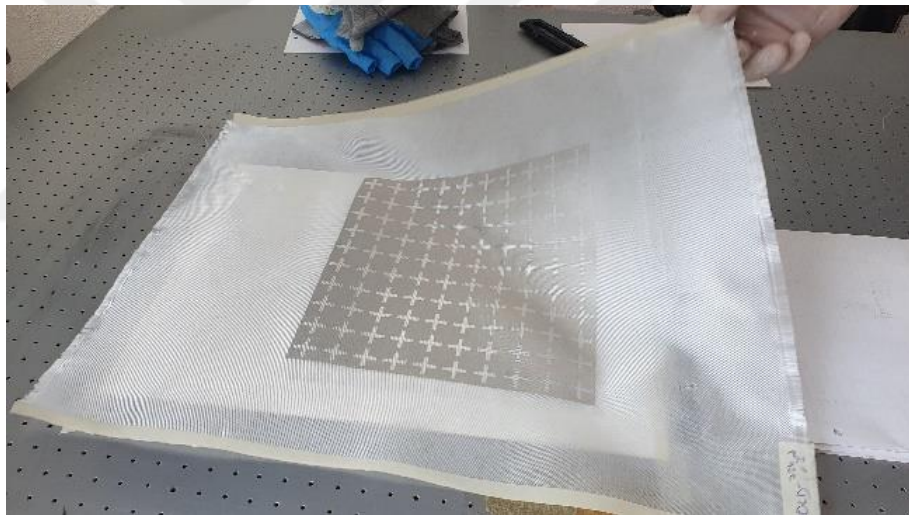


Figure 3.24. Screen printed surface.

After the FSS patterns were printed on the glass fabric surfaces, to obtain the final conductive patterns shown in Figure 3.24, curing of the printed patterns has been completed by blow drying at atmospheric conditions according to manufacturer's recommendations. Type-1 paste was cured at 120 °C for 15 minutes whereas Type-2 paste was cured at 150 °C for 10 minutes.

3.4 Surface Treatment of FSS Patterns

The mechanical properties of the resulting glass fiber reinforced composite material depend heavily on the nature of the fiber – matrix interface. A strong interface generally leads to the best composite properties and many effective interfacial coupling agents that are capable of forming strong interface have been identified for single component polymer matrices. However, in this case, glass fabric surface was patterned and the interface was altered with conductive paste. Therefore, surface modification is needed to enhance mechanical properties (especially shear strength) by improving chemical bonding between the conductive paste and the fiber surface.

In this study, surface modification was applied to enhance bonding between epoxy resin and printed FSS pattern surface. Surface was first treated with air plasma (Diener, Plasma Surface Technology, Plasmabeam PC) (Figure 3.25) and then coated with coupling agent solution by using brush (Figure 3.26).



Figure 3.25 Plasma Treatment of FSS Patterns.



Figure 3.26 Surface Modification of FSS Patterns.

Coupling agent solutions were prepared by mixing 1% coupling agent with dry toluene with magnetic stirrer. The solution was applied on surface with brush and surface modified fabrics were dried at 100°C for 1 hour in furnace. After drying step, surface was washed with dry toluene (Figure 3.27) to get rid of the excess coupling agent and the fabric was dried again by using the same condition.

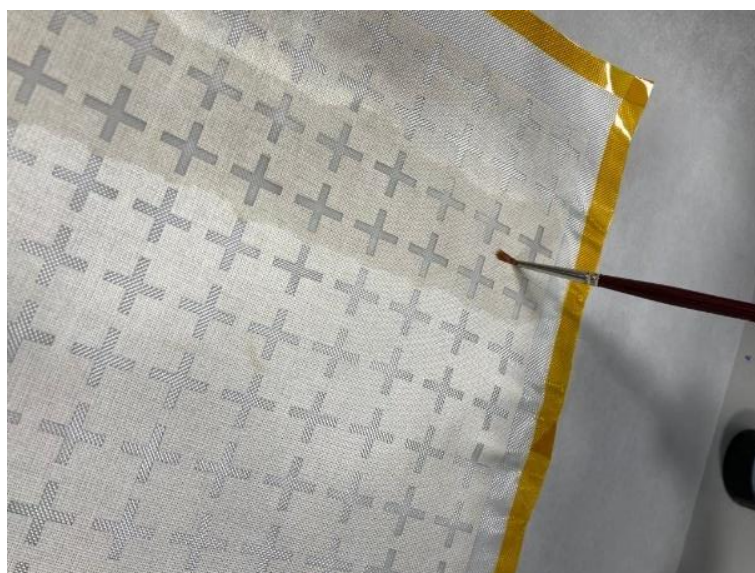
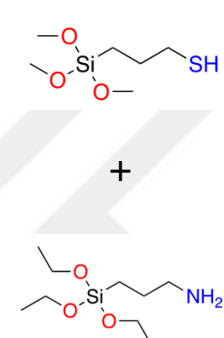
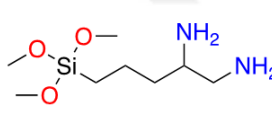
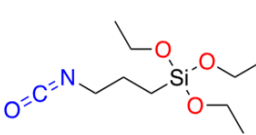
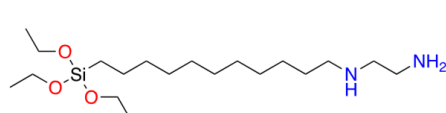
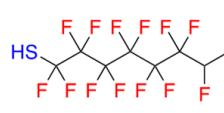


Figure 3.27 Removal of Excess Coupling Agent from Surface.

Selected coupling agents are given in Table 3.7.

In 1st sizing, coupling agents were chosen to ensure bonding between silver in printed pattern by thiol functional group. 2nd, 3rd and 4th sizings were chosen from available coupling agents to enhance bonding. 5th sizing was chosen to be used as a marker in XPS analysis.

Table 3.7 Coupling agents chosen for surface modification of FSS patterns.

1	(3-Mercaptopropyl)trimethoxysilane CAS #: 4420-74-0 + (3-Aminopropyl)triethoxysilane CAS #: 919-30-2	
2	(3-Trimethoxysilylpropyl)ethylenediamine CAS #:1760-24-3	
3	(3-Isocyanatopropyl)triethoxysilane CAS #:24801-88-5	
4	(2-Aminoethyl)-11-aminoundecyltriethoxysilane CAS #: 121772-92-7	
5	Tridecafluoro-1-octanethiol CAS #: 34451-26-8	

3.5 FSS Prepreg Manufacturing

After conductive paste has been printed on the fabric surface and dried, the following step is to manufacture a prepreg containing patterned fabric and polymer resin. In this study, prepreg epoxy with the trade name DA100 of SPM Composites company has been used.

3.5.1 Resin Impregnation

As mentioned in the Introduction, film-transfer route is applied for prepreg manufacturing. However, instead of industrial path, simple tape caster equipment (Figure 3.28) and lamination tool (Figure 3.29) have been used in the process.

First, resin film layer having 65 μm thickness was drawn on silicon coated paper by using tape caster. Since epoxy has very high viscosity at room temperature, both tape caster plate and epoxy resin were heated to 60 °C degrees. At this temperature, it was possible to produce continuous and homogeneous resin layer.

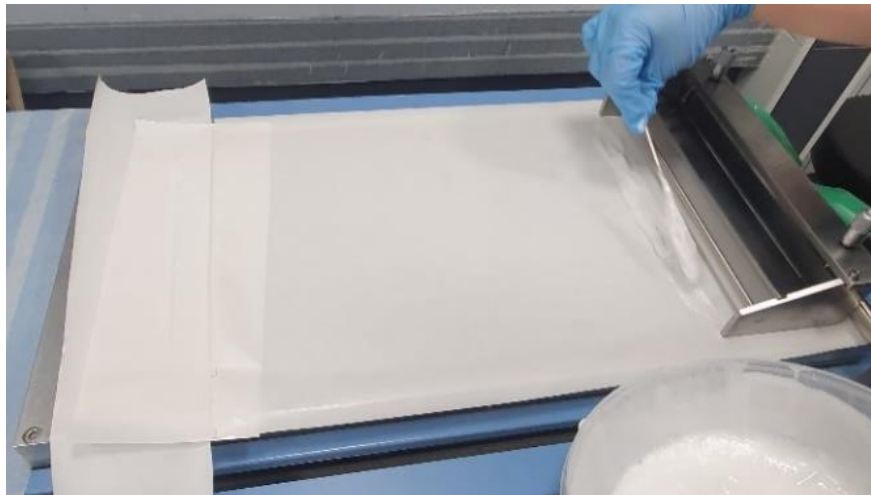


Figure 3.28. Resin film making via tape caster.



Figure 3.29. Film transfer via lamination tool.

After the resin layer has been obtained, it was combined with glass fabric and pressed through lamination tool. After lamination, which is called as film transfer step, epoxy layer was examined, and it is was seen that all epoxy was impregnated into fabric without excess (Figure 3.30, Figure 3.31).



Figure 3.30. Prepreg of Aperture Type FSS.



Figure 3.31. Prepreg of Patch Type FSS.

3.5.2 Curing of FSS Prepreg

FSS printed glass fabrics were impregnated with commercial DA100 resin, which is a product of SPM Composites company, via film transfer method and obtained prepregs were cured by vacuum bagging technique.

Vacuum bagging was conducted according to lay-up procedure given schematically in Figure 3.32.

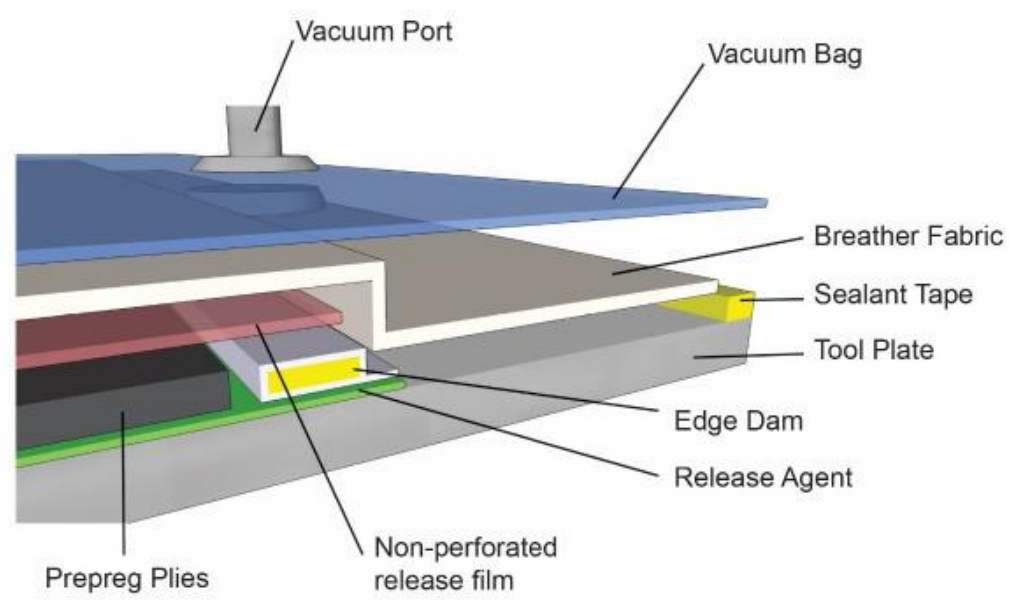


Figure 3.32. Vacuum bagging procedure.

Recommended curing cycle of DA100 resin was retrieved from TDS as shown in Figure 3.33.

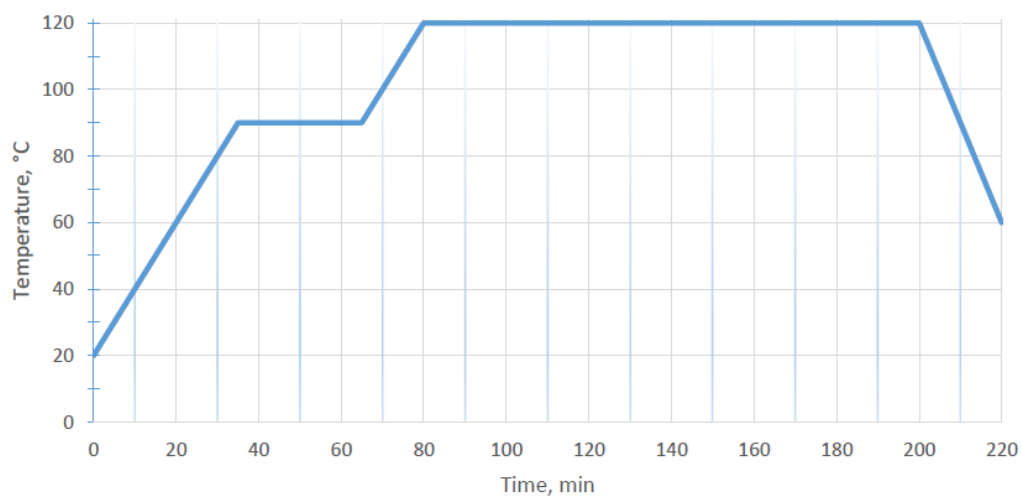


Figure 3.33. DA100 Cure Cycle.

120 °C curing temperature was applied for 120 minutes after 30 minutes dwell was conducted at 90 °C. There are other curing temperatures with different cure times for the same resin system, however in this study, recommended curing temperature and time have been used.

Single layer cured FSS preregs for both sandwich and monolithic configurations are given in Figure 3.34.

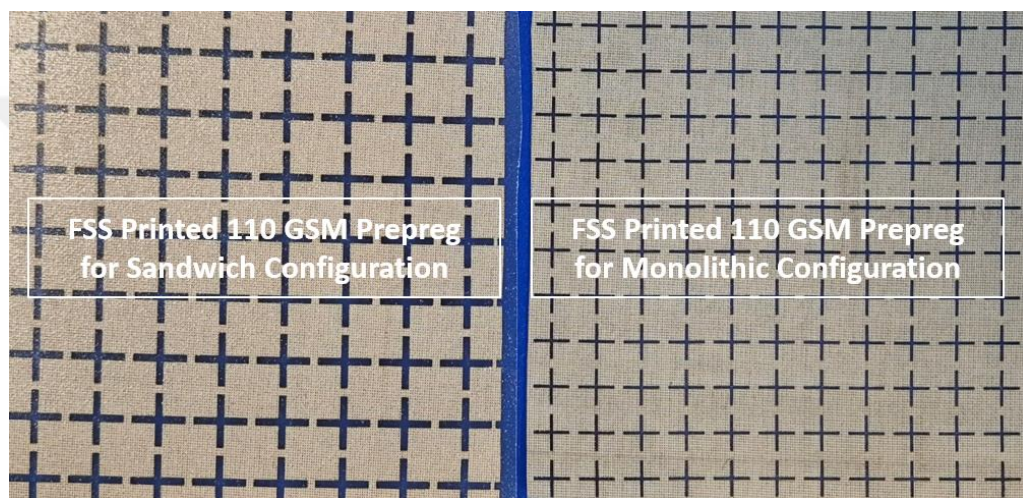


Figure 3.34 FSS printed 110 GSM cured preregs for sandwich and monolithic configurations.

3.6 Composite Panel Manufacturing

Composite coupons using FSS printed prepreg layers were manufactured for two main purposes. The first one was to characterize the EM performance of multilayer composites, and the second one was to use in mechanical testing.

Preregs were placed on glass mold according to their stack-up configurations. After the lay-up procedure was completed, a peel-ply layer was added on top for ILSS coupons. In case of EM coupons, peel-ply step was replaced with release film, since

composite thicknesses are very thin and tear-up could be observed when peeling (Figure 3.35). After the peel-ply layer, breather was placed, and whole structure was closed with vacuum bag (Figure 3.36, Figure 3.37). Open parts of vacuum bag were closed with sealant tape, and vacuum port was placed through the vacuum bag. Vacuum bagged composite coupons were cured in the vacuum oven at 120°C for 2 hours according to DA100 resin system's curing cycle (Figure 3.38).



Figure 3.35. Peel-ply layer on composite panels.



Figure 3.36. Breather layer.



Figure 3.37. Vacuum-bagging of all layers.



Figure 3.38. Curing in vacuum furnace.

3.6.1 Composite Manufacturing for EM Measurement

Related stack-up configurations of composite coupons of EM measurement were given in Figure 3.10 and Figure 3.13.

For monolithic configuration, FSS printed preregs on top and at bottom of composite panel were cured separately as single layer where five layers of 280 GSM preregs as spacing were co-cured. For EM measurement, separately cured preregs

were stacked together to ensure the alignment of FSS patterns according to each other. Each layer of cured prepregs and stack-up configurations of these layers are given in Figure 3.39.

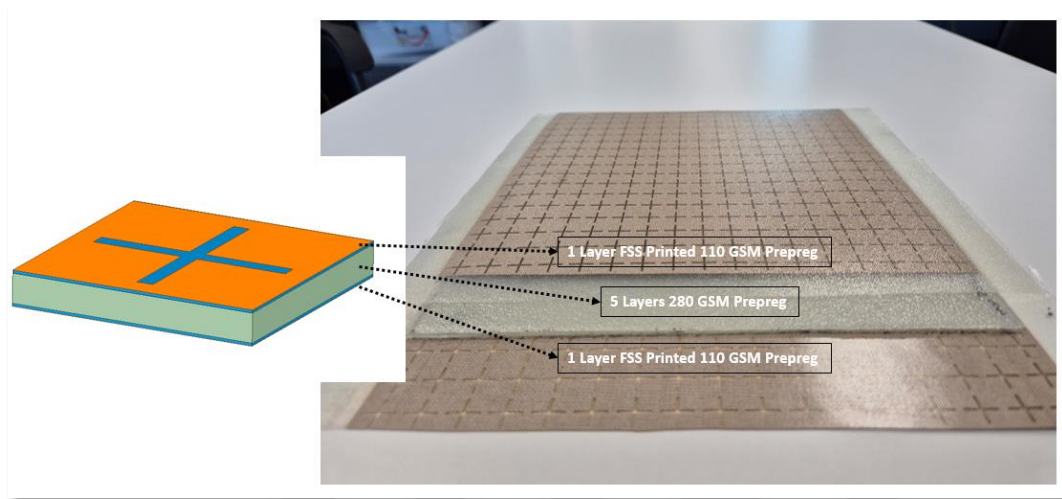


Figure 3.39. Multilayer monolithic composite stack-up.

Same approach was followed for sandwich multilayer structure. As in monolithic configuration, FSS printed prepregs and spacing parts were cured separately and combined together when measuring EM performance of the final composite panel. Each layer of cured prepregs and stack-up configurations of these layers are given in Figure 3.40.

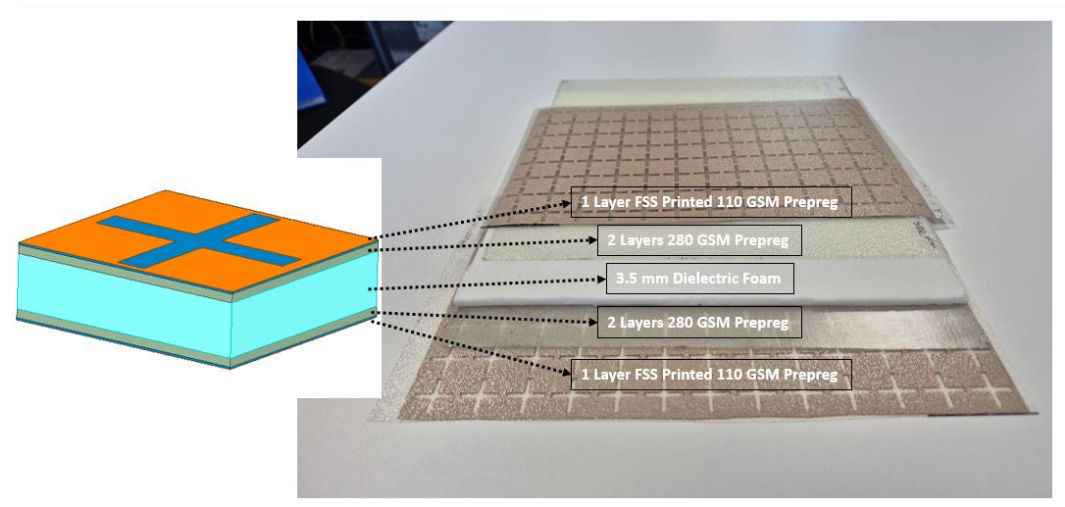


Figure 3.40. Multilayer sandwich composite stack-up.

3.6.2 Composite Manufacturing for Mechanical Characterization

Composite panels for mechanical test (interlaminar shear strength, ILSS) were prepared by vacuum bagging. To understand the effect of surface modification on the mechanical properties, ILSS test panels were manufactured by using 12 layers of 280 GSM glass prepreg and one-layer of FSS printed prepreg in the middle. Total thickness of the composite panel was aimed to be around 3 mm according to ILSS test standard requirement (Figure 3.41).

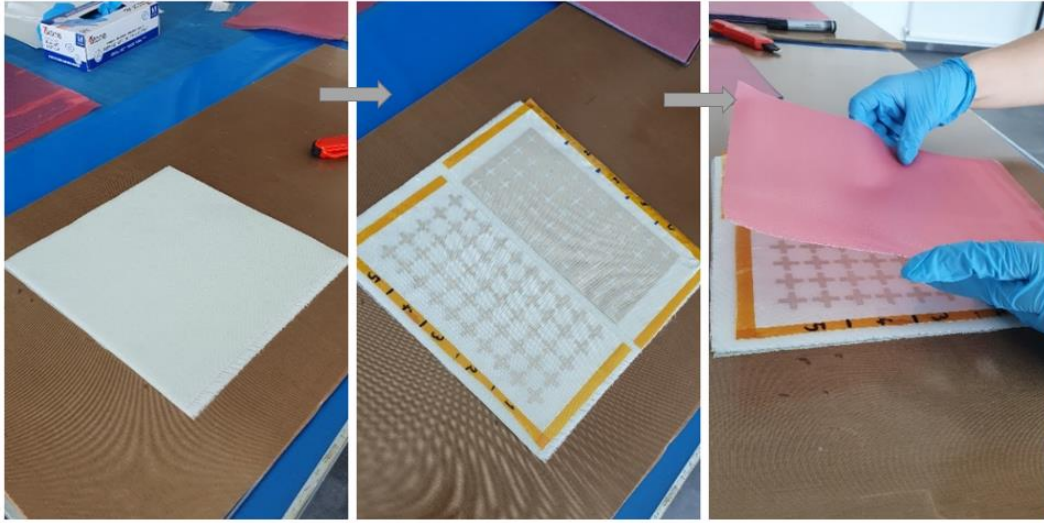


Figure 3.41. Composite test coupon preparation for ILSS test.

Same epoxy resin (DA100) was used for all layers to provide compatibility between prepreg layers. 20 cm × 20 cm composite panels were manufactured by vacuum bagging at 120 °C for 2 hours (Figure 3.42).

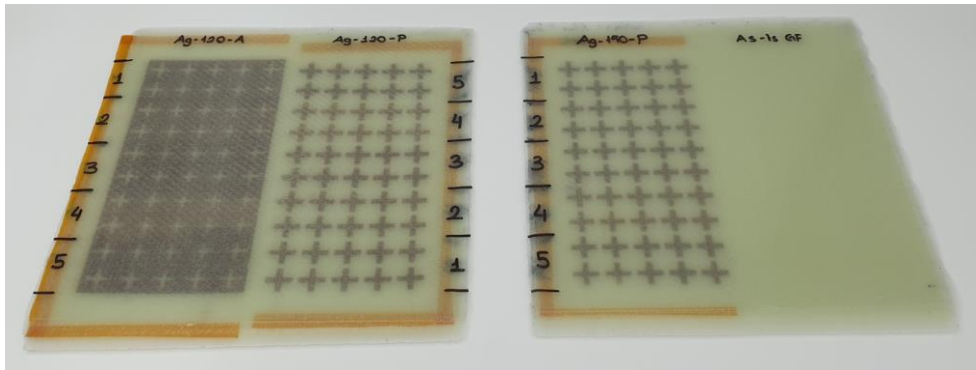


Figure 3.42. ILSS test panels after curing.

Two composite panels were manufactured for ILSS test. Three types of FSS printed prepreps were used to understand the effect of ink type, surface modification and conductive paste covered area according to FSS geometry (aperture versus patch

type). As-is glass fiber reinforced coupons were also manufactured in the same cycle to define a reference for mechanical properties. In case of as-is coupon, an empty 110 GSM glass prepreg layer was inserted rather than printed prepregs.

Sampling of ILSS test coupons was given in Figure 3.43.

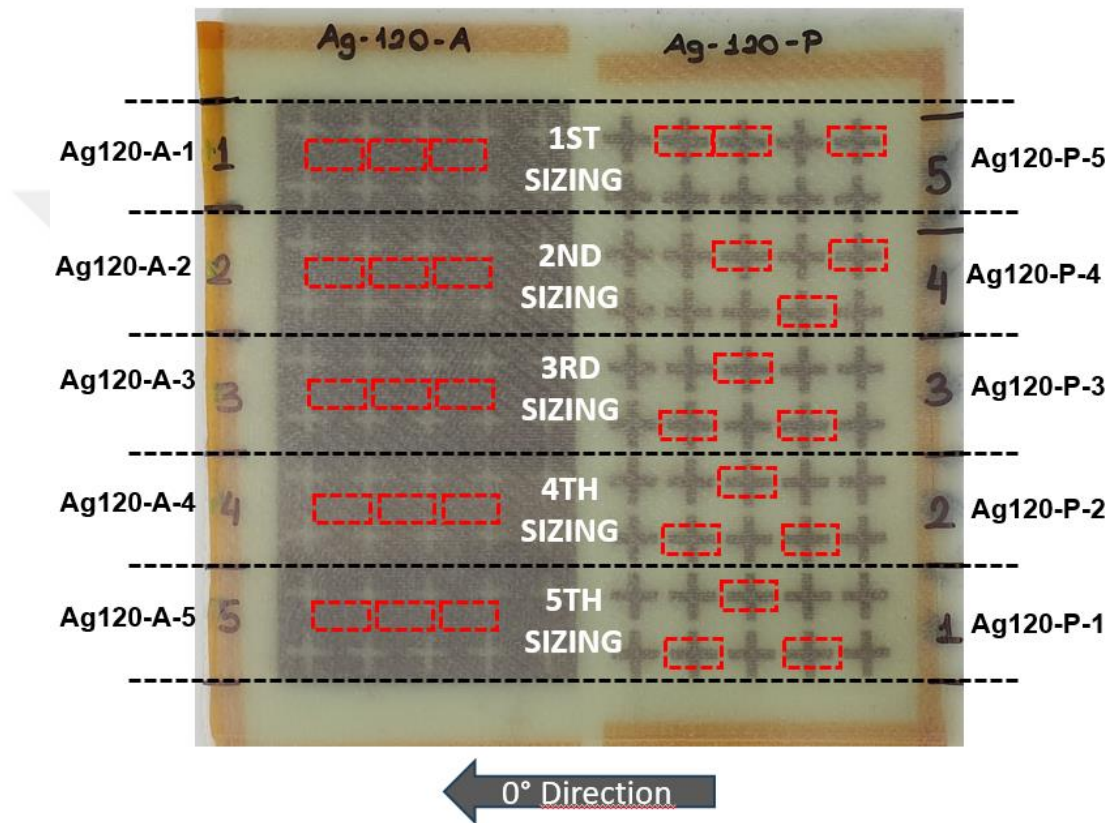


Figure 3.43. ILSS test coupon sampling.

According to the sampling given above, in aperture type ILSS coupons, 100% of interface area is covered with conductive paste. On the other hand, in terms of patch type ILSS coupons, only 44% of interface area is coated with conductive paste. Therefore, when these two coupons are compared, it could be possible to understand the effect of covered area on the ILSS properties of the final composite panels (Figure 3.44, Figure 3.45).

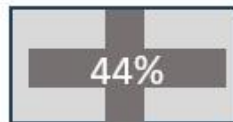
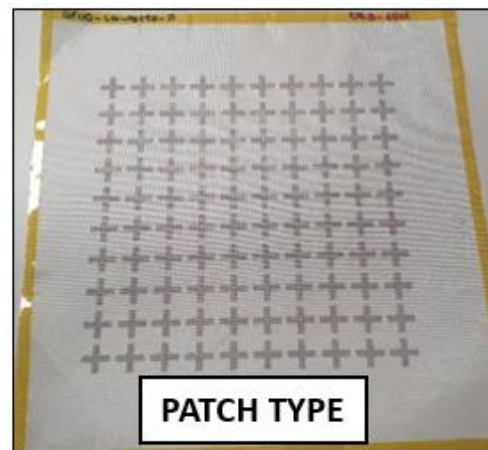


Figure 3.44. The schematic of patterned area in patch type ILSS samples.

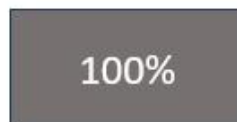
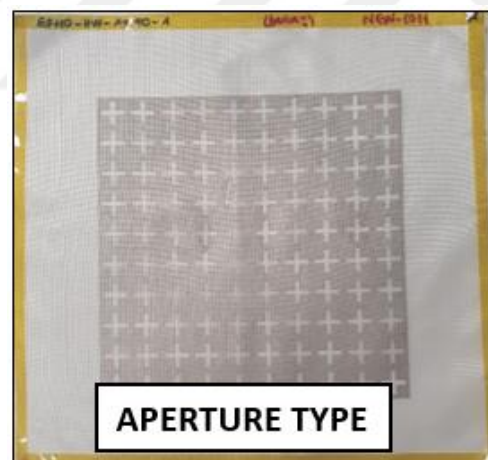


Figure 3.45. The schematic of patterned area in aperture type ILSS samples.

3.7 Characterization Methods

Three main characterization routes have been utilized in this study. First characterization route includes analyzing conductive pastes in terms of their particle size, solid content, binder formulation, etc. After conductive paste analyses have been completed, printed patterns on glass fiber woven fabric substrates were characterized in terms of their microstructure, electrical conductivity, electromagnetic performance, etc. Finally, resin impregnated FSS printed prepregs are cured according to their curing cycle have been analyzed through electromagnetic and mechanical testing approaches. Information about related test techniques has been given in detail for each step. Results and discussions about the outcomes of these tests were provided in the following chapter.

3.7.1 Conductive Paste Characterization

General information about conductive pastes was retrieved from their technical data sheets. However, to validate these properties and to understand the morphology of pastes further, several analyses have been applied. First, even though particle size and geometries of conductive pastes are given in their technical data sheets, to understand the particle size distribution throughout the pattern, SEM analysis (Phenom XL) was conducted. Samples were prepared by dripping several drops on coverglass after applying proper mixing. Drying step was not performed to observe as-is conductive particle morphologies (Figure 3.46).

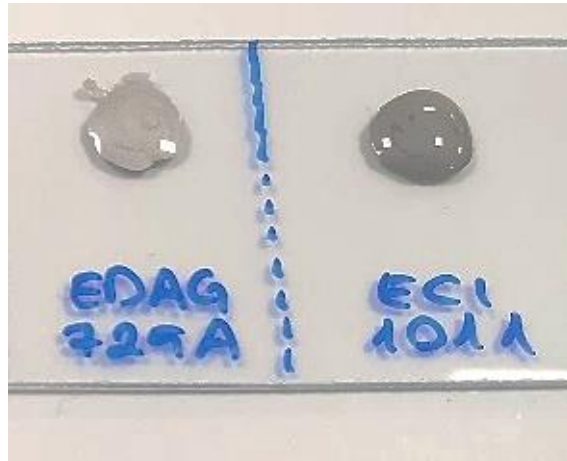


Figure 3.46. Droplets of Type-1 and Type-2 inks.

Moreover, to examine the binder of conductive paste, FTIR analysis (Thermo Scientific iS50 FT-IR) was applied. Finally, thermogravimetric analysis (TGA) (NETZSCH STA 449 F3 Jupiter) was performed to understand solid particle content of conductive pastes. Analyses were made from RT to 900°C with a heating rate of 10°C/min. Results of these tests and their related discussions have been given in the following chapter.

3.7.2 Characterization of FSS Patterned Glass Fabric

Microstructural characterization of the silver-based pastes applied on the glass fiber woven fabric surfaces has been conducted using scanning electron microscopy (SEM) to observe morphologies of the conductive silver particles and the accumulation behavior of these particles on the glass fabric surface. Moreover, band tape test according to ASTM D3359 – Adhesion by Tape Test standard was applied to printed and cured FSS patterns for both conductive pastes and the adhesion behaviors were compared with each other [11].

XPS analysis (Thermo Scientific K-Alpha) was conducted to observe the surface behavior of printed and dried conductive patterns. Printing surface was analyzed before and after ion bombardment (1000 eV Ar⁺ ion for 30 seconds).

Electrical resistance, R , values of the printed patterns were measured by two-point (four-wire (4W)) probe method utilizing probes designed with spring-loaded POGO pins with 1 mm contact point and 7 mm spacing between each other connected to an Agilent 34411A 6½-digit multimeter (Figure 3.47). Electrical resistance values of both conductive pastes were measured with the same method and the equipment. Therefore, comparison between both pastes were done accurately.

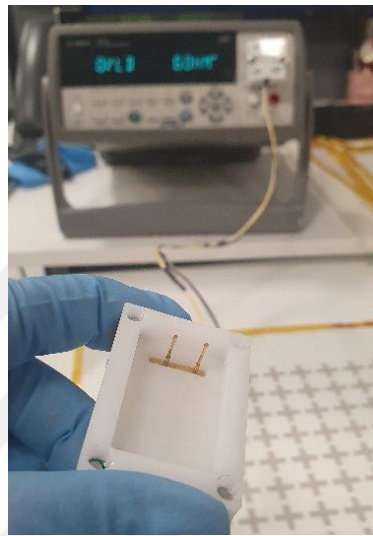


Figure 3.47. Two-point (4W) probe setup used in electrical resistance measurements.

Electromagnetic performance of the FSS patterns screen-printed using two different types of silver-based pastes have been measured by free space EM characterization setup. The patterned surface of the substrates was facing to Port 1 of the setup. To characterize the EM performance reflection (S_{11}) and transmission (S_{21}) loss values of the FSS patterned glass fiber woven fabrics were measured within 8-12 GHz range by the free space setup equipped with condensing lenses (Figure 3.48) connected to a vector network analyzer (VNA) (Agilent Technology Company 10 MHz-40 GHz N5230A PNA-L).

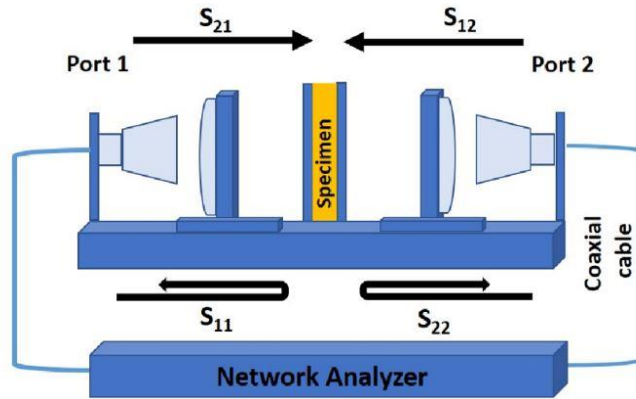


Figure 3.48. Schematic representation of the home-designed and built free space setup [58].

Screen-printed glass fabric was placed between two plexiglass frames to keep it wrinkle free and orthogonal to the signal (Figure 3.49). This method of handling avoids the deformation of the fabric and the FSS pattern (Figure 3.50). The specimen was placed between two horn antennas and reflection loss (S_{11}) and transmission loss (S_{21}) values of the patterns have been measured using the network analyzer at X-band (8-12 GHz frequency range). Measured loss values were compared with the simulated loss values of the initial design.

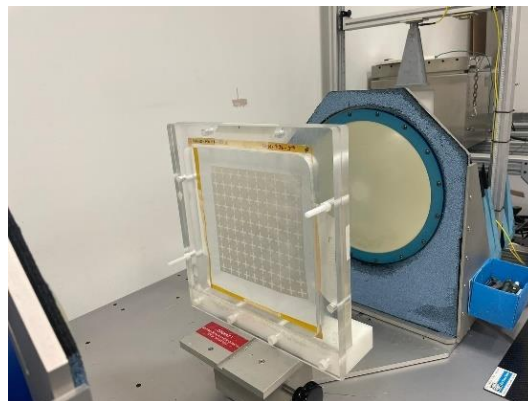


Figure 3.49. Free-space measurement specimen holder.

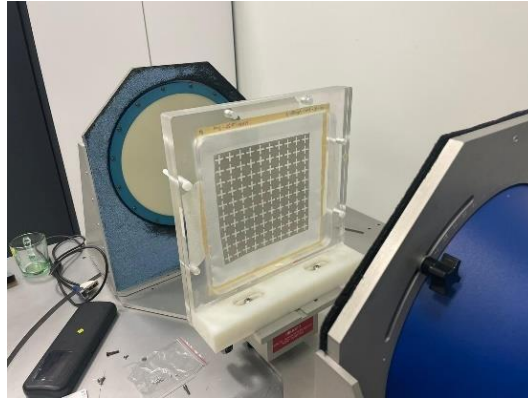


Figure 3.50 Free-space measurement specimen holder at the midpoint between the two horn antennas.

3.7.3 Characterization of FSS Composite

Electromagnetic characterization of multilayer FSS composites have been conducted the same way in FSS fabrics, the same free-space set-up was used for both cases.

EM measurement results were compared with those of the simulations, and deviations from target performance have been explained in detail in the following chapters.

Mechanical characterization plays an important role in this study since the main approach includes electromagnetic performance together with mechanical performance. Therefore, to observe the effect of FSS printing on the final mechanical properties, three-point bending test was applied to measure interlaminar shear strength.

The interlaminar shear strength of laminates with a brittle matrix, made of epoxy resin for example, is typically determined using a short beam shear test (SBS). This takes advantage of the fact that shear stress occurs in a flexure test. If the support span is small compared to the specimen thickness, the shear stresses that occur are very large compared to the normal stresses generated by the bending moment. In this

way, shear fracture can be generated in the brittle matrix materials, enabling measurement of the shear strength. Three-point bending test with EN2377 (Aerospace series; glass fibre reinforced plastics; test method; determination of apparent interlaminar shear strength (ILSS)) standard defines a method for the determination of the apparent interlaminar shear strength by delamination of glass fiber reinforced composite materials (GFRP). The beam flexure test is performed by placing the specimen symmetrical on the support fixture that is mounted either to a servohydraulic or an electromechanical testing machine (Figure 3.51, Figure 3.54). The load is applied to the specimen at mid-span until interlaminar shear failure occurs.

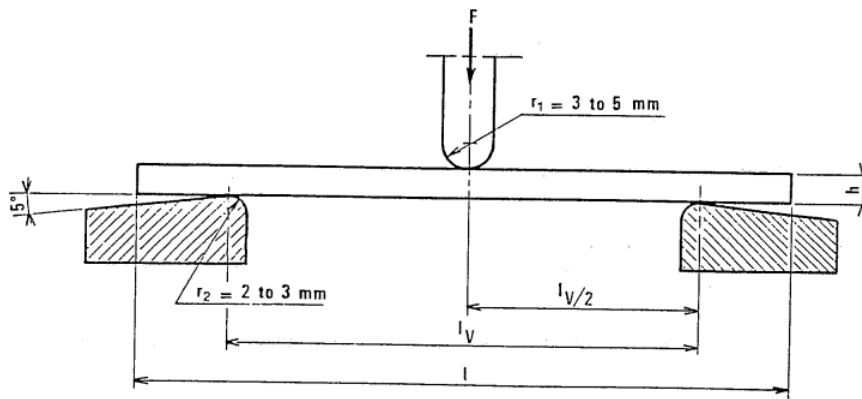


Figure 3.51. Schematic of the three-point bending test experimental set-up.

The shear strength of the matrix material or the behavior of the fiber-matrix bonding can be characterized depending on the failure type (Figure 3.52).

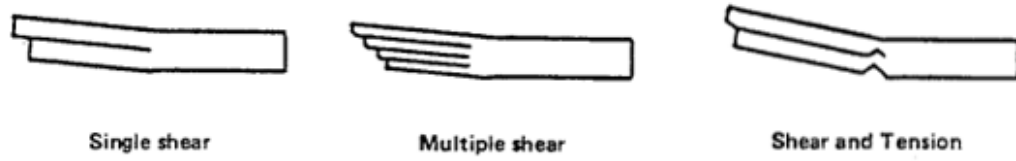


Figure 3.52. Failure modes of ILSS.

Shear stress can be calculated by using the formula below. However, to be able to use the equation below, specimen should fail in horizontal shear at neutral fiber axis.

$$\tau = \frac{3}{4} \times \frac{F}{b \times h} \quad (11)$$

Test specimens were prepared according to EN 2374, and standard specimen dimensions are given in Table 3.8 and Figure 3.53. Three important parameters were analyzed through this test to determine the effect of the covered area, conductive paste type and surface modification on the interlaminar behavior. For every condition three samples were tested, and for 16 different combinations 48 samples were tested in total.

Table 3.8. Standard Specimen Dimensions for EN2377 Test.

LENGTH (L)	20 ± 0.5 mm
WIDTH (b)	10 ± 0.2 mm
THICKNESS (h)	3 ± 0.2 mm

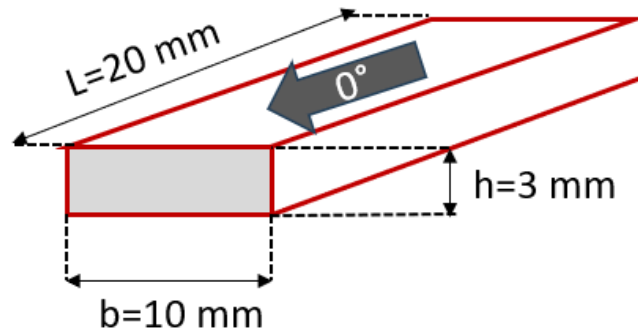


Figure 3.53. Coupon size for ILSS test specimen.

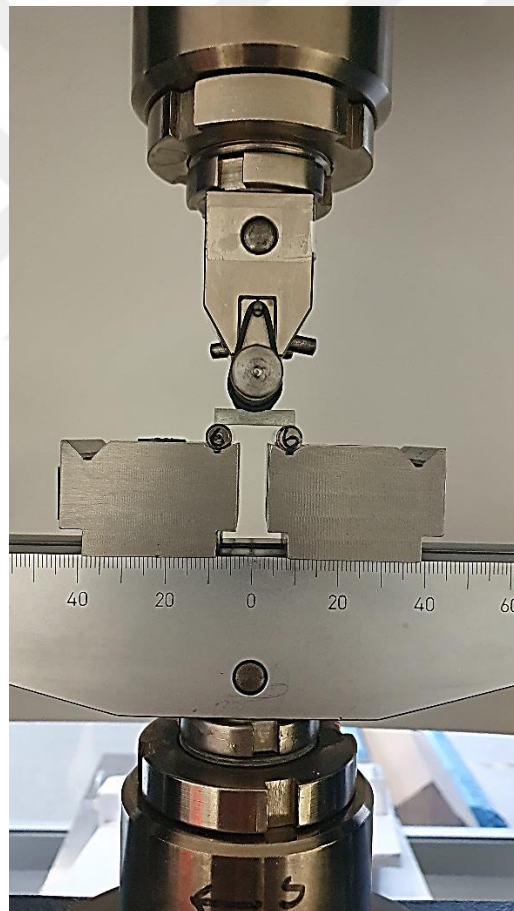


Figure 3.54 ILSS test set-up.

CHAPTER 4

RESULTS & DISCUSSION

In this chapter, experimental findings including microstructural evaluations, electromagnetic characterizations and mechanical property examinations and related discussions have been presented in detail.

4.1 Conductive Paste Properties

Even though particle size of conductive pastes was given in their technical data sheets, to understand the particle size distribution throughout the pattern, SEM analysis was made. SEM images of related conductive pastes are given in Figure 4.1 and Figure 4.2.

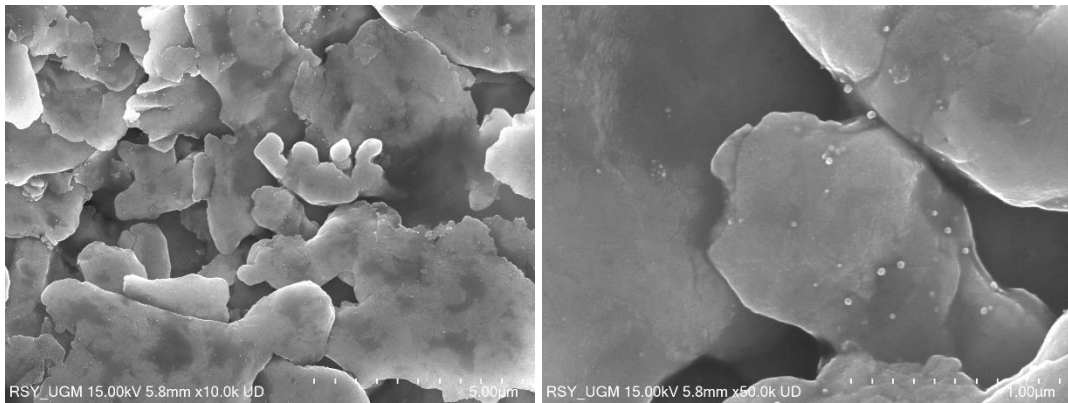


Figure 4.1. SEM images of as-is Ag-120 paste.

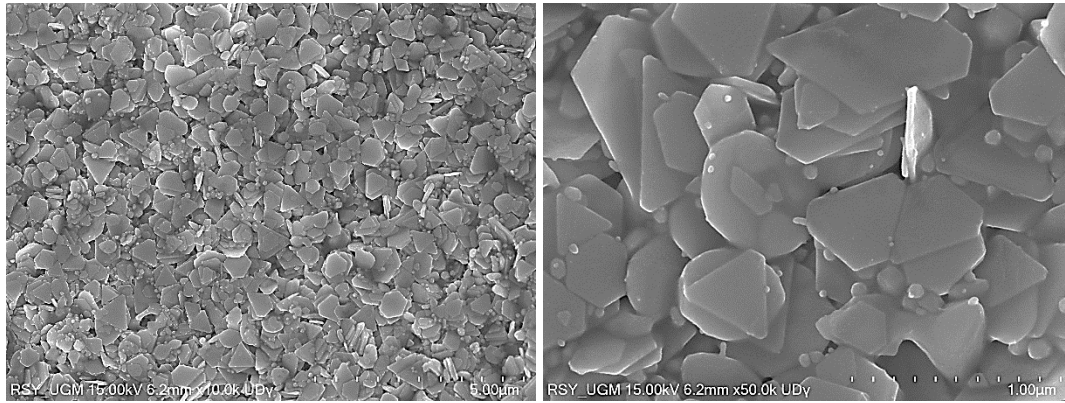


Figure 4.2. SEM images of as-is Ag-150 Paste.

It is seen from the images that Type-1 paste has 2D flake-like silver particles where they have varying sizes. On the other hand, Type-2 paste has smaller silver particles which are in several 2D and 3D shapes such as nanospheres, nanotriangles, etc (Table 4.1).

Table 4.1 Properties of metallic particles in conductive pastes.

	Type-1 (Ag-120)	Type-2 (Ag-150)
Metallic Particle	Silver	Silver
Particle Geometry	Flake-like (2D)	Combined (2D & 3D)

It is known that 2D (flake like) structures have higher aspect ratio than 3D (spherical) ones. It is also known that, as the aspect ratio of metallic particles increases, the percolation threshold for electrical conductivity can be obtained at lower concentrations. For that reason, even though Type-1 paste has lower solid content, it may be possible to obtain similar or higher electrical conductivity result for the same coating as Type-2 paste.

Other than solid content and metallic particles, other components such as solvent, monomer, oligomer, etc. were critical in case of printing applications. According to their TDS, conductive pastes have an acrylic base. Thus, FTIR analysis was made to understand the organic content of conductive pastes. FTIR results are given in Figure 4.3 and Figure 4.4. It is seen from the FTIR spectrum of the conductive pastes that the best matching results were similar to TDS.

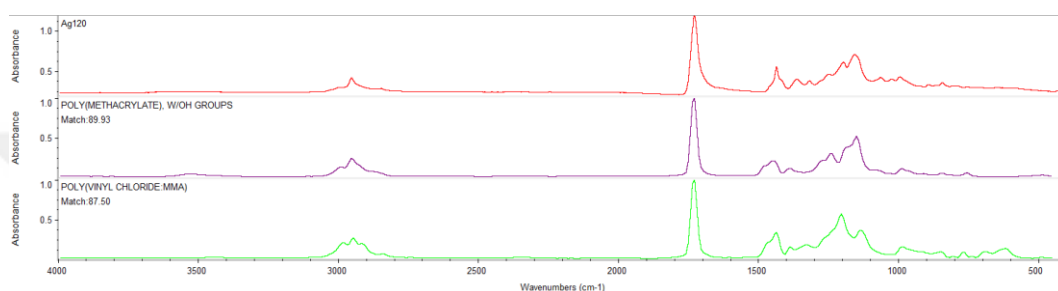


Figure 4.3. FTIR analysis result of Ag-120 paste.

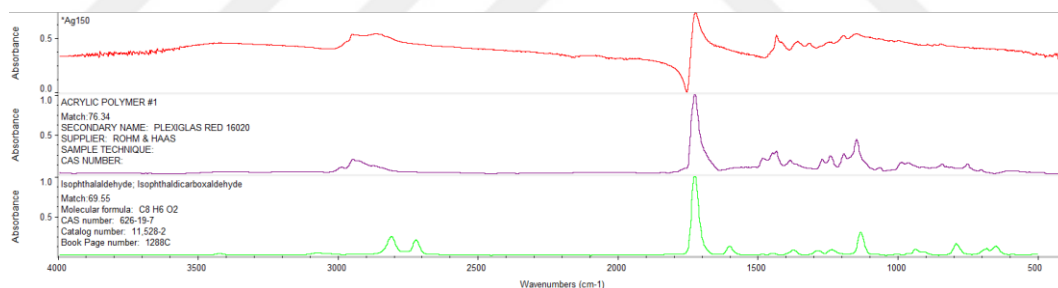


Figure 4.4 FTIR analysis result of Ag-150 paste.

To understand the temperature behavior of the constituents in paste, thermogravimetric analysis was made. It was understood from the TGA results that both conductive pastes contain a certain number of solvents which can be removed at a temperature around 150°C (Figure 4.5).

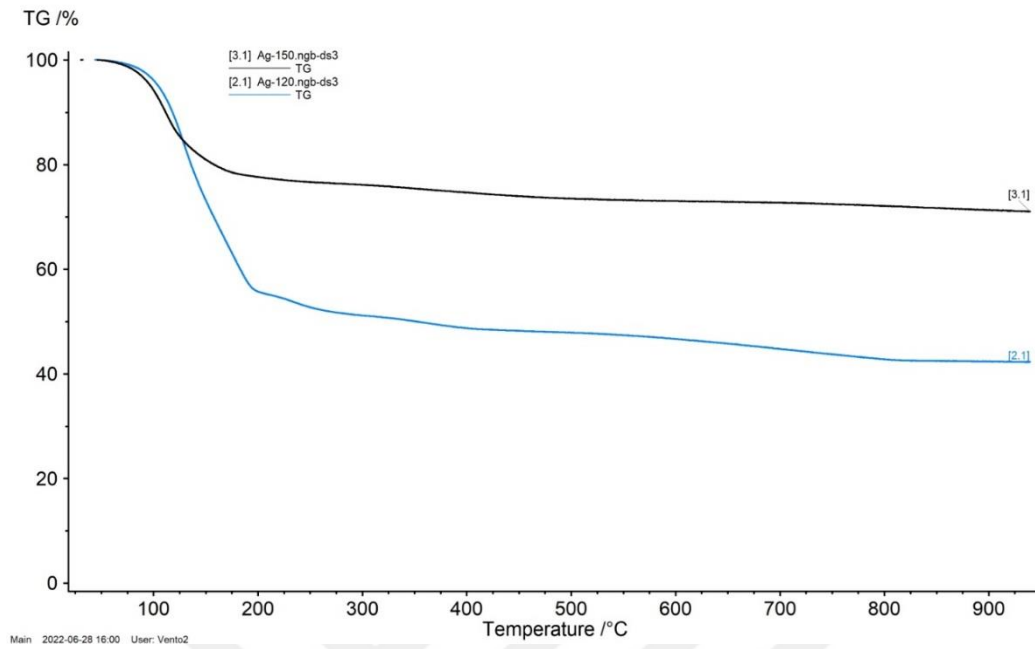


Figure 4.5 Thermogravimetric Analysis result of both conductive pastes.

Recommended drying parameters given in pastes' technical datasheet are given in table below. It is also checked from the TGA results that these drying temperatures are enough to remove solvents and to dry conductive pastes. Consequently, parameters for drying applications are used as given in TDS.

4.2 Microstructural Analysis of Printed FSS Patterns

Normally, when a typical paste is applied on non-porous solid surface, it is easy to obtain a connecting network structure between conducting particles. However, in case of porous surfaces such as the glass woven fabric used in this study, conducting particles tend to penetrate the openings of the glass fiber bundles, making it more difficult to obtain an electrically conductive network. SEM images of the two types of pastes printed on the glass fiber woven fabric surfaces as well as their cross-sections are shown in Figure 4.6 (a)-(d).

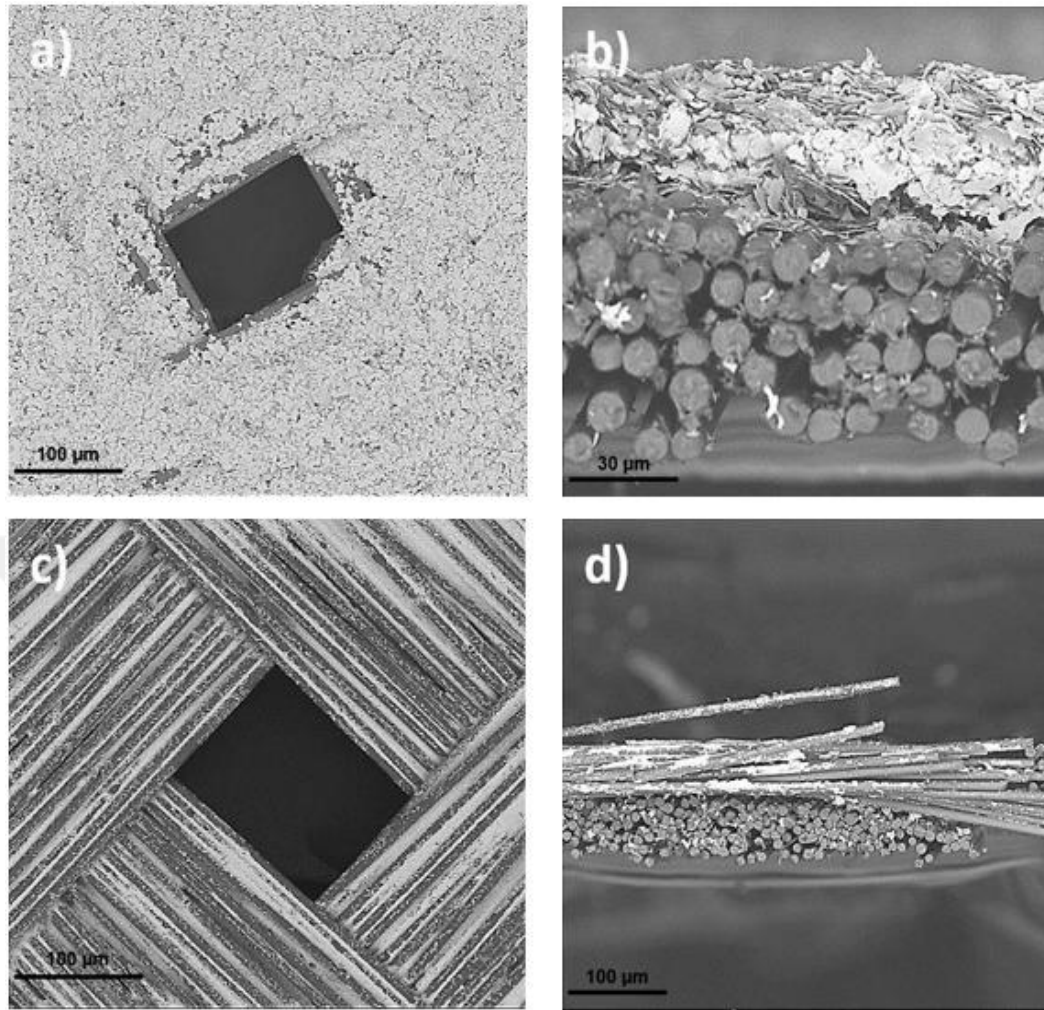


Figure 4.6. SEM images of printed FSS patterns on glass fiber woven fabric with a) Type-1 paste (top view), b) Type-1 paste (cross section view), c) Type-2 paste (top view) and d) Type-2 paste (cross section view).

As it is observed in the SEM images, the conductive paste having smaller sized, 2D/3D shaped combined metallic particles (Type-2) tends to penetrate into the fabric (Figure 4.6 (c)-(d)), whereas Type-1 paste with larger sized flake-like particles remains on top of the fabric (Figure 4.6 (a)-(b)). Schematic representations of metallic particles in both conductive pastes showing different accumulation behavior on the glass fabric surface are given in Figure 4.7.



Figure 4.7. Schematic representation of a) larger conductive particles accumulating on the fabric surface and b) smaller conductive particles penetrating the fabric.

In addition to the printing behavior difference between 2D/3D combined smaller particles and 2D larger flakes, the effect of drying temperature on morphologies of the printed patterns was also observed by the SEM imaging.

By the application of the curing treatment at elevated temperature, coalescence of the metallic particles with each other is expected, which has been observed in the SEM images. Especially in case of nano-sized spherical particles in Type-2 paste, necking has been observed clearly (Figure 4.8 (b)). For flake-like particles in Type-1 paste, it is seen that smaller particles act as connecting units, and they are sintered with larger particles around them (Figure 4.8 (a)).

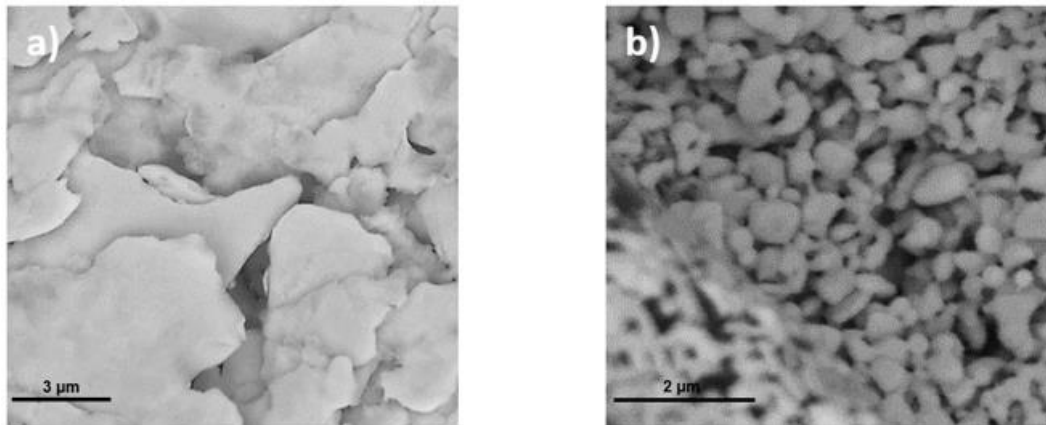


Figure 4.8. SEM image of a) Type-1 paste cured at 120°C and b) Type-2 paste cured at 150°C.

4.3 Surface Characterization of Printed FSS Patterns

In earlier studies, XPS measurement was applied to observe surface properties of printed FSS patterns. The red line shows oxygen on the surface before ion bombardment (1000 eV Ar⁺ ion for 30 sec) where the green line is after bombardment. It was seen that there is a huge amount on oxygen on surface, but it can be removed with ion bombardment (1000 eV Ar⁺ ion for 30 sec) which implies that oxygen is only on surface (Figure 4.9).

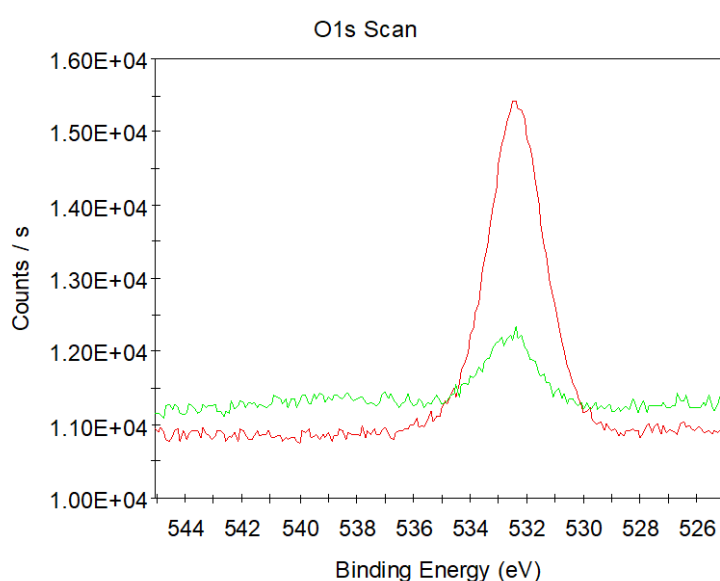


Figure 4.9. O1s region of the XPS spectra of as-is FSS pattern.

Oxidation of silver is a significant problem and should be avoided as much as possible before continuing with the surface modification. Therefore, plasma treatment was used to reduce the presence of oxygen on printed ink surface as a first step of surface modification. The effect of plasma treatment on the surface was examined through XPS analysis and the XPS results of plasma treated printed silver pastes are given in Figure 4.10. According to O1s region of the XPS spectra, it is seen that oxygen level remains similar after ion bombardment (1000 eV Ar⁺ ion for 30 sec) which implies that the adsorbent layer on the surface was successfully

reduced with plasma application. As the results are compared with as-is printed silver surface (Figure 4.9), one can say that the oxygen was reduced from the surface by plasma treatment. Moreover, as conductive paste does not fully cover the fabric surface, some information from the glass fibers was also observed.

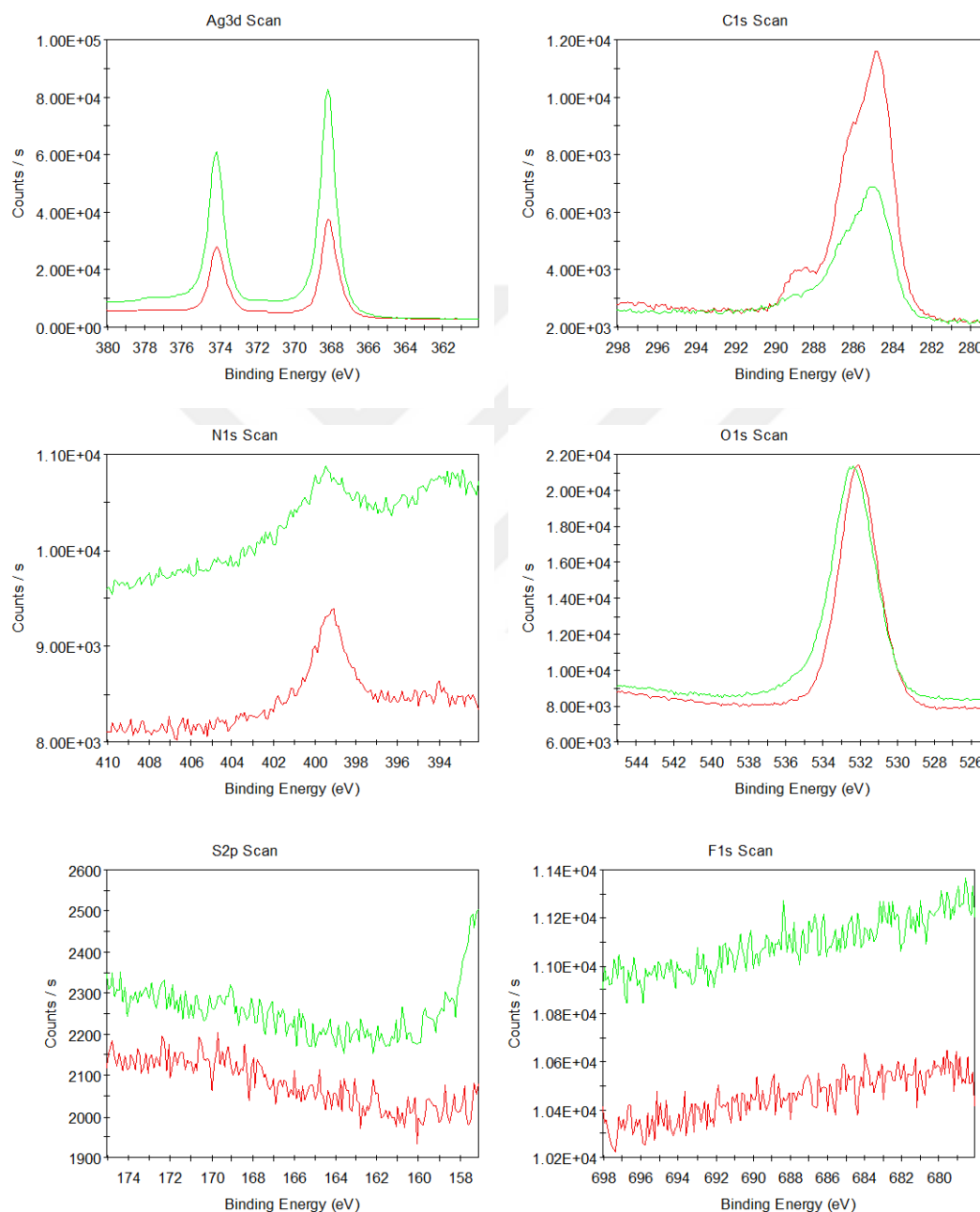


Figure 4.10. Ag3d, C1s, N1s, O1s, S2p and F1s regions of the XPS spectra of plasma treated FSS pattern.

After plasma applied surface characterization was completed, modified surfaces were analyzed through XPS.

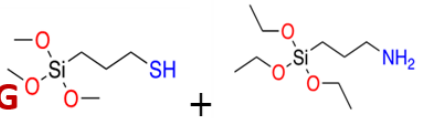
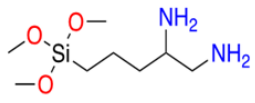
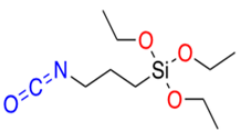
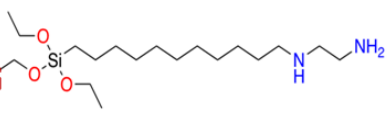
1	(3-Mercaptopropyl)trimethoxysilane + (3-Aminopropyl)triethoxysilane	1ST SIZING 
2	(3-Trimethoxysilylpropyl)ethylenediamine	2ND SIZING 
3	(3-Isocyanatopropyl)triethoxysilane	3RD SIZING 
4	(2-Aminoethyl)-11-Aminoundecyltriethoxysilane	4TH SIZING 
5	Tridecafluoro-1-octanethiol	5TH SIZING 

Figure 4.11. Chemical formula of coupling agents used as sizing.

Tridecafluoro-1-octanethiol coupling agent (5th sizing) was used as a marker since thiol functional group reacts with silver in FSS print and there is no other F source that can be observed in the printed FSS pattern. Therefore, it was easy to detect F in XPS analysis since thiol functional group reacts with silver.

XPS analysis was used to control if the 1st and 5th coupling agent applications on the surface were successful. The other coupling agents have similar elements to the as-received surface. Therefore, an XPS analysis of these coupling agent applications

were not performed. It is seen from the XPS results that the surface modification of printed FSS pattern with 5th sizing was done and the presence of the marker F on surface was observed after applying coupling agent (Figure 4.12).

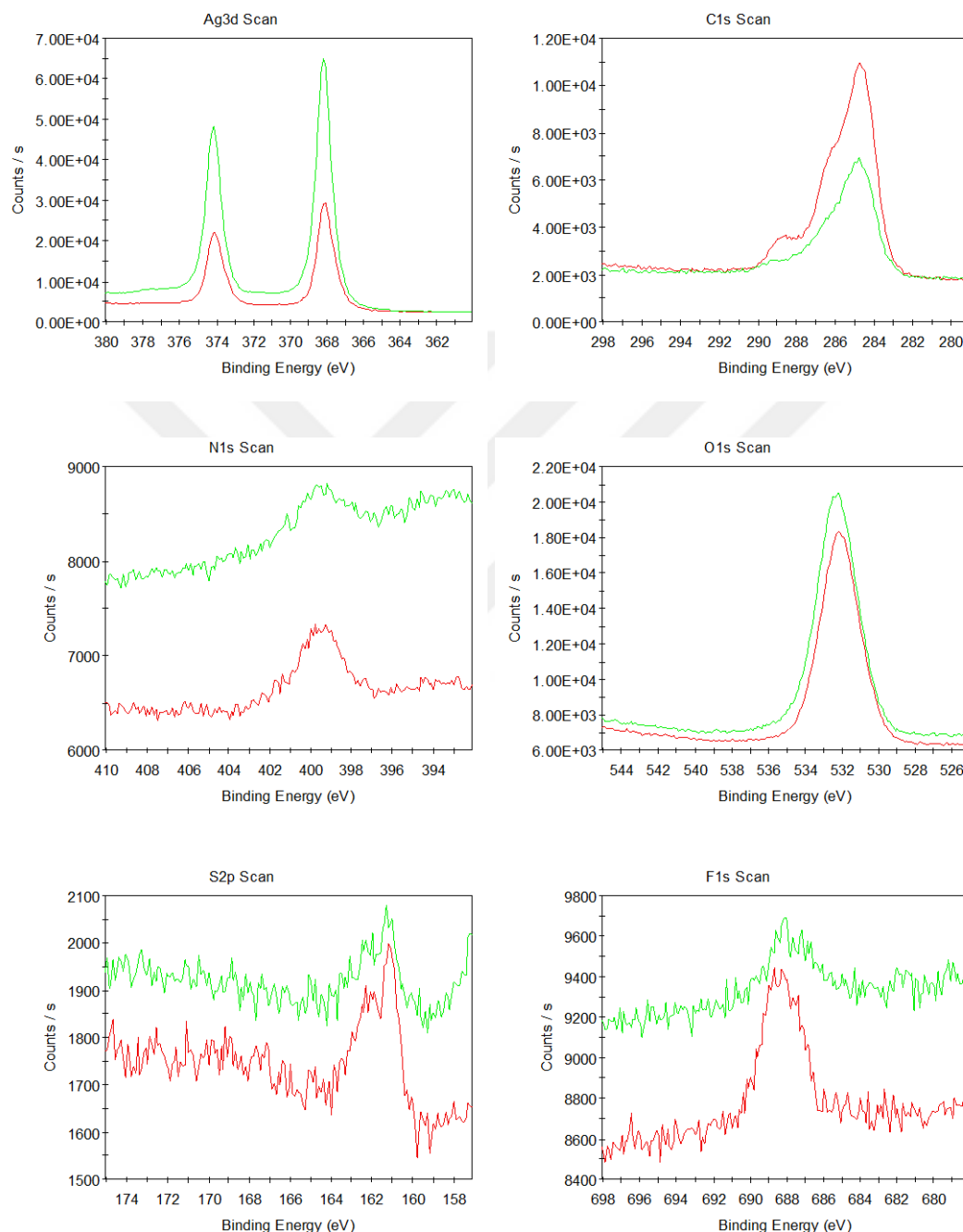


Figure 4.12 Ag3d, C1s, N1s, O1s, S2p and F1s regions of the XPS spectra of surface modified FSS pattern with 5th sizing.

When it comes to 1st sizing, (3-Mercaptopropyl)trimethoxysilane + (3-Aminopropyl)triethoxysilane solution (1:1 vol. ratio) was used to provide bonding between silver ink and epoxy resin. XPS analysis results of this application are given in Figure 4.13.

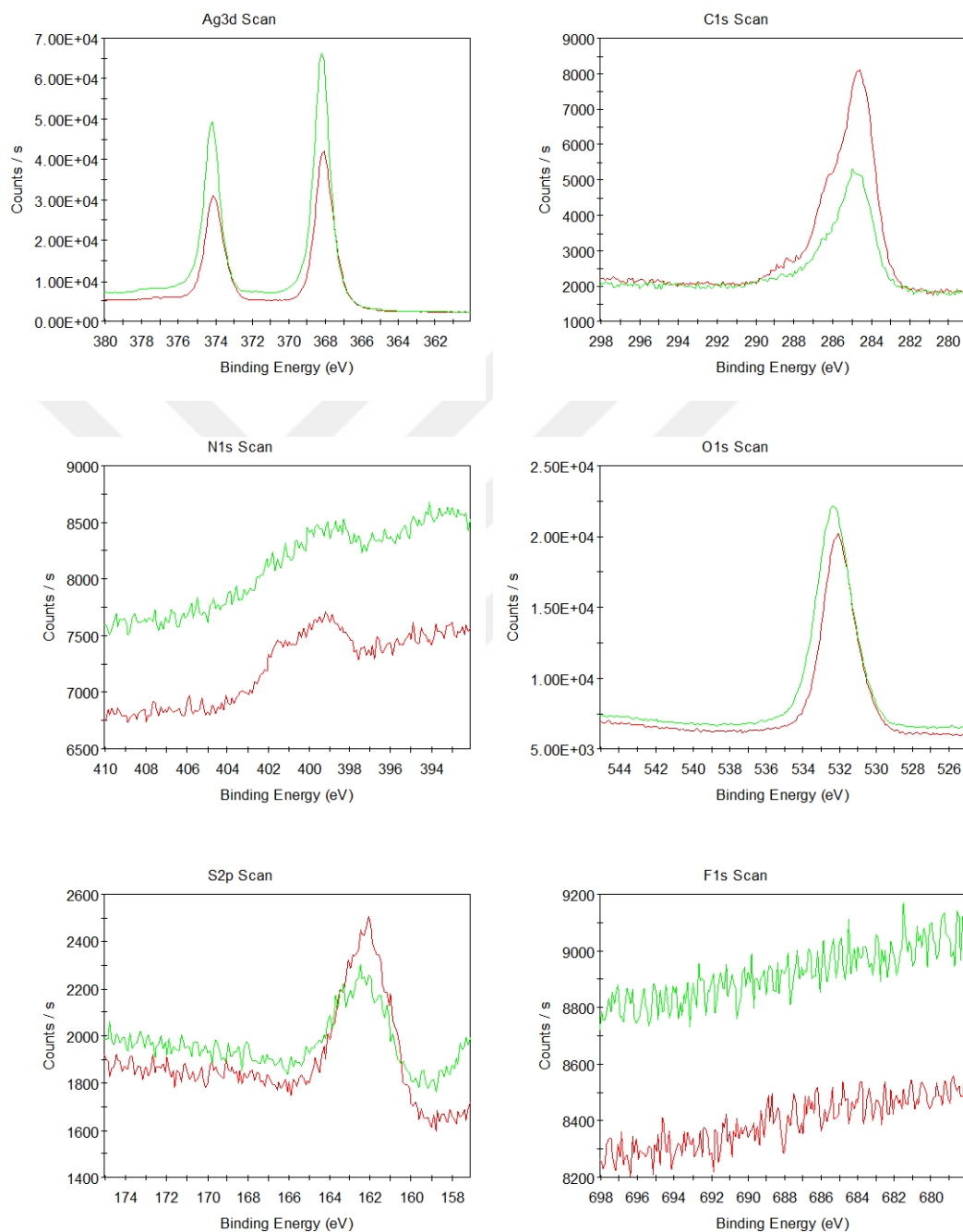


Figure 4.13. Ag3d, C1s, N1s, O1s, S2p and F1s regions of the XPS spectra of surface modified FSS pattern with 1st sizing.

As it can easily be seen from the results, thiol functional group was attached to the silver in FSS print and according to the presence of S, it can be said that the coupling agent was applied on the surface.

Effect of these coupling agents on interlaminar properties of final composite panel was analyzed through three-point bending test in following chapters.

4.4 FSS Pattern Resolution and Thickness

In this study, it is aimed to obtain high resolution conductive patterns on glass fabric showing required electromagnetic performances without damaging mechanical properties of final composite structure. Hence, as thickness of the pattern decreases, effect of this pattern on mechanical properties (especially interfacial properties) will be lowered.

According to skin depth theory, pure silver FSS pattern thickness in the X-band should be at least around 1 micrometer thick [63]. In typical applications, FSS pattern thickness values are at least three times of this value. In the current study, the thickness of the printed FSS pattern was determined according to screen printing process limitations (mesh thickness, opening ratio, etc.). Printed paste thickness after curing was measured differentially by a micrometer and determined to be around 20 μm throughout the coated area for both pastes. Normally, similar volumes of uncured pastes were transferred through the stencil during printing for both paste types. When cured, due to difference in their densities and solid contents, final weights of cured conductive pastes and related thicknesses of FSS patterns were expected to be different. However, their final thickness was found accidentally similar, since Type-2 paste penetrated through the glass fabric, and some part of the transferred paste was left on the printing table due to its smaller particles and lower viscosity.

Table 4.2 Weight ratio calculation of Type-1/Type-2 inks.

	TYPE-1 PASTE	TYPE-2 PASTE
Uncured Conductive Paste Density (g/cm ³)	2.14	3.0
Conductive Paste Solid Content (%) (from TDS)	60	75.6
Estimated Conductive Paste Density After Curing Related to Solid Content (g/cm ³)	1.284	2.268
Expected Weights of Conductive Pastes in case of Same Volume Transfer (g)	1.284x	2.268x
Type-2/Type-1 Weight Ratio	$(2.268x) / (1.284x) = 1.770$	

Since the same volume of uncured conductive paste is transferred through the stencil during printing, it is expected to have heavier Type-2 paste coating after curing due to its higher density and solid content.

However, as explained in detail in the manuscript, due to its low viscosity and smaller conductive particles, during printing, some part of the transferred ink is penetrated through the fabric and lost on the application table. This loss is also validated through weight measurement of bare and coated fabrics. It was seen that the weight ratio of two different inks is lower than the expectation which validates the loss of Type-2 paste. Due to this loss, even though their solid contents are different, final cured coating thicknesses converge and measured to be like each other which is around 20 μm . Micrometer measurements are also provided below.

Table 4.3. Weight ratio validation of Type-1/Type-2 inks.

	EMPTY GLASS FABRIC	TYPE-1 COATED GLASS FABRIC	TYPE-2 COATED GLASS FABRIC
Total Weight (g)	0.1699	0.1935	0.2049
Conductive Coating Weight (g)	0	0.0236	0.0350
Type-2/Type-1 Weight Ratio	-	$(0.0350) / (0.0236) = 1.483$	

Table 4.4. Coating thicknesses of Type-1 and Type-2 inks together with glass fabric.

	EMPTY GLASS FABRIC	TYPE-1 COATED GLASS FABRIC	TYPE-2 COATED GLASS FABRIC
Total Thickness (mm)	0.10	0.12	0.12
Coating Thickness (mm)	-	0.02	0.02
Micrometer Measurement			

Coating thickness on glass fabric was also controlled by weighing bare and printed glass fabrics having the same area. Indeed, the areal weight increase ratios are measured to be 1.483 instead of theoretical 1.77 which indicates a slight loss of the Type-2 (less viscous) paste during the printing process. It was validated that amount of accumulated pastes were different from each other after accounting for cured densities. As it will be discussed in the following sections, accumulation behavior of pastes is different namely either remaining on the surface of the fabric or penetrating the fabric.

For resolution, SEM images are used, and it is seen that if the fiber bundle is parallel to printing direction, almost no scattering is observed. In case of fiber bundles perpendicular to printing direction, minor scattering occurs at the edges on pattern. This effect can be seen easily at the images given in Figure 4.14 and Figure 4.15. Blue lines show the printing direction.

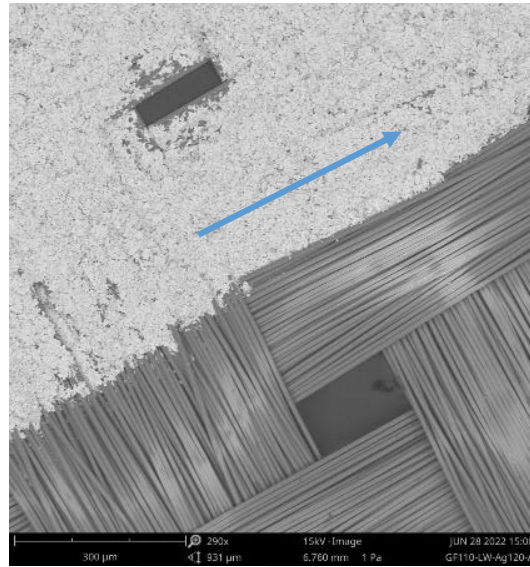


Figure 4.14. SEM image of Type-1 paste pattern edge.

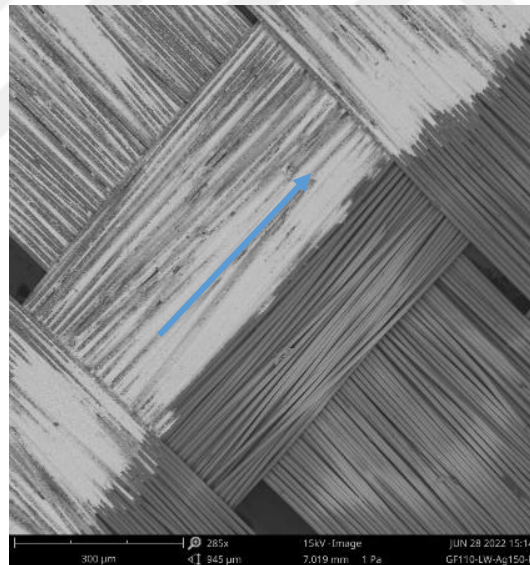


Figure 4.15. SEM image of Type-2 paste pattern edge.

4.5 Adhesion of Printed FSS Patterns

The adhesion behavior of the conductive pastes on the glass fiber woven fabric surface has been tested by the simple band tape test (Figure 4.16). The adhesion behavior of Type-2 paste was determined to be better than that of Type-1 paste, as demonstrated by the lower amount of residue of Type-2 paste on the band tape compared to Type-1 paste according to the test (Figure 4.16 (d) vs. (b)). This can be attributed to the fact that Type-2 paste penetrates the glass fabric substrate leading to less particle accumulation on the surface compared to Type-1 paste and better interlocking with the glass fiber bundles in the fabric. Since there is less accumulation, less material would adhere to the adhesive band tape. In addition, as it is seen in the SEM images given in Figure 4.16, Type-2 particles are well sintered and connected to each other better than the silver particles in Type-1 paste rendering them more resistant to mechanical forcing.

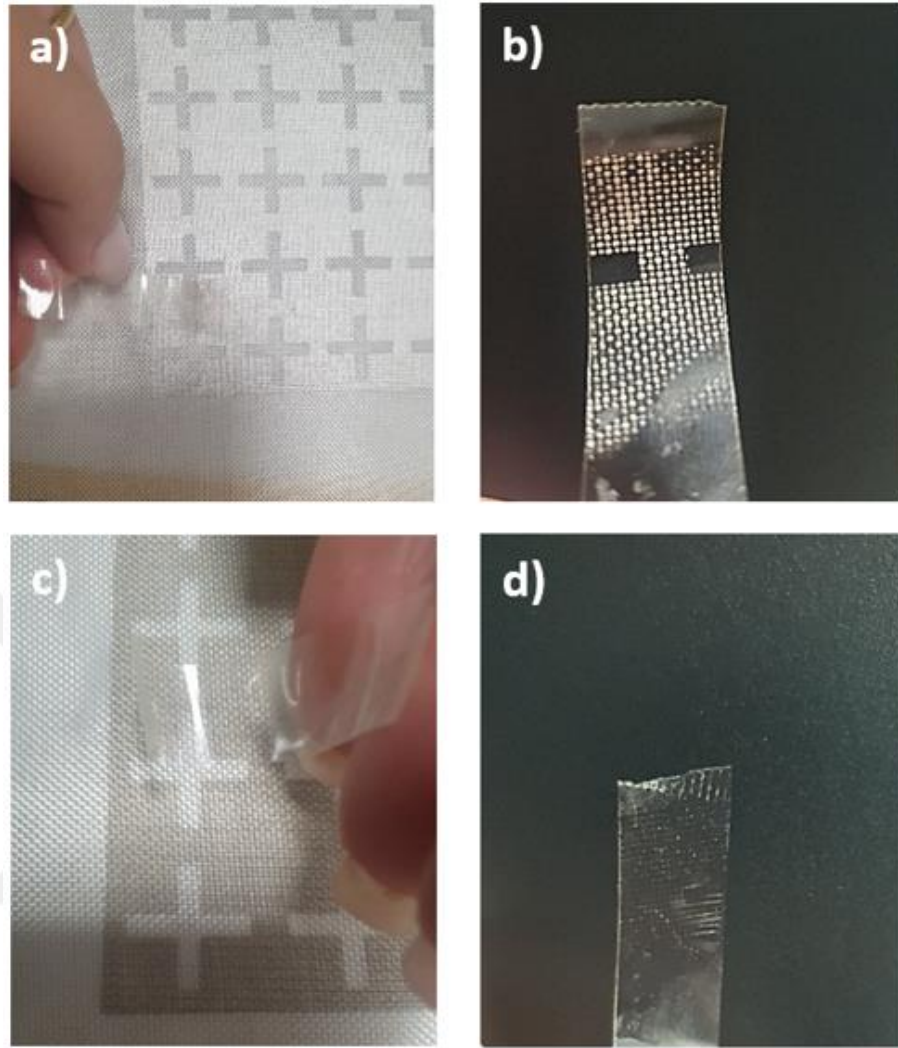


Figure 4.16. Band tape test of Type-1 paste, b) Type-1 paste residue on the band tape; c) Band tape test of Type-2 paste, d) Type-2 paste residue on band tape.

4.6 Conductivity of Printed FSS Patterns

Electrical resistance of each pattern has been measured at different regions on the surface. It is a well-known fact that having more the conductive particle content in conductive paste provides higher conductivity printed pattern due to increasing number of conducting pathways formed per unit length [60]. In this case, even though Type-2 paste has higher metallic filler content, due to the lower aspect ratio

and penetration of the silver particles into the substrate, contrary to expectations, DC resistance values of the patterns with Type-2 paste were higher (Table 4.5). In literature, increasing resistivity due to lack of electrical connection in the case of porous substrates was also observed and discussed in detail [8].

Table 4.5. Resistance of cured Type-1 and Type-2 pastes.

	Measured Resistance (Ω)
Type-1 Paste	0.15 – 0.17
Type-2 Paste	0.20 – 0.23

Resistivity when cured on a flat glass surface has been measured by using the same equipment and the results are given in Table 4.6.

Table 4.6 Resistance of Type-1 and Type-2 pastes printed and cured on flat substrate.

	Type-1 Paste	Type-2 Paste
Resistivity on Flat Surface (Polyimide Tape) (Ω)	0.053 – 0.065	0.037 – 0.050

4.7 RF Measurement of Frequency Selective Surfaces

EM characterization of FSS design had three main steps where each step should be optimized to continue the following part. The first step was to characterize the FSS pattern printed on dry glass fabric and to optimize the parameters of screen printing process. This step has a crucial role in comparing the performance of the FSS simulation with the printed FSS pattern on glass fabric and validating the printing method for this application. After FSS patterns on dry glass fabric were validated, fabrics were impregnated with epoxy resin to obtain FSS prepregs. Then, the second

step of EM characterization where these prepregs' EM performances were measured and compared with FSS fabrics to understand the effect of resin was performed. As the third and final step, EM performances of multilayer FSS composites including already characterized FSS prepregs were measured and the results were compared with initial multilayer FSS simulations (Figure 4.17).

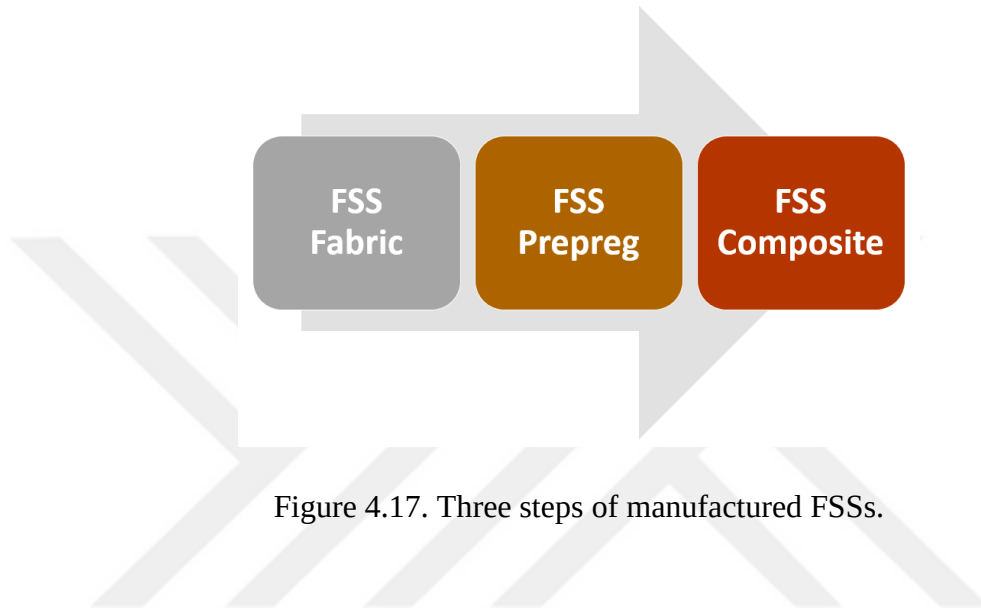


Figure 4.17. Three steps of manufactured FSSs.

These three steps were applied individually for both sandwich and monolithic configurations since their initial FSS unit cell designs, consequently their FSS patterns and final composite stack-up sequences are different from each other.

4.7.1 RF Characterization of FSS Pattern for Sandwich Configuration

FSS unit cell was designed for the required EM performance of sandwich composite and the FSS pattern was established based on this unit cell. After FSS pattern, which was aperture type in this case, was established, negative of this pattern, patch type, was also studied and the expected EM performances were simulated for both patterns. Schematic representation of FSS approach for sandwich configuration is given in Figure 4.18.

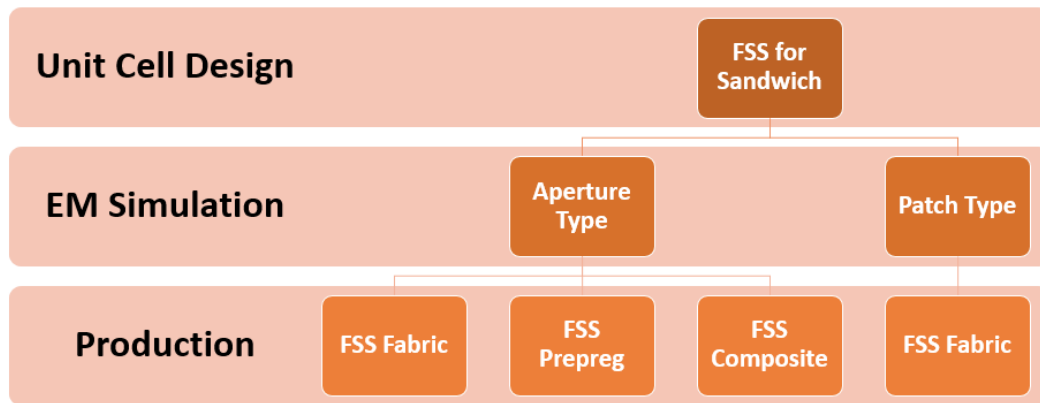


Figure 4.18. Schematic representation of FSS approach for sandwich configuration.

First of all, both aperture and patch type, which should show opposite EM performances as they are negative of each other, were produced in FSS fabric step and the results were compared. After the applicability of this method for both FSS types was understood, FSS prepregs were manufactured by using aperture type FSS fabrics since the final composite stack-up includes only aperture type FSS layers. Figure 4.19 was prepared to summarize all production steps starting from the unit cell design to final multilayer composite for sandwich configuration.

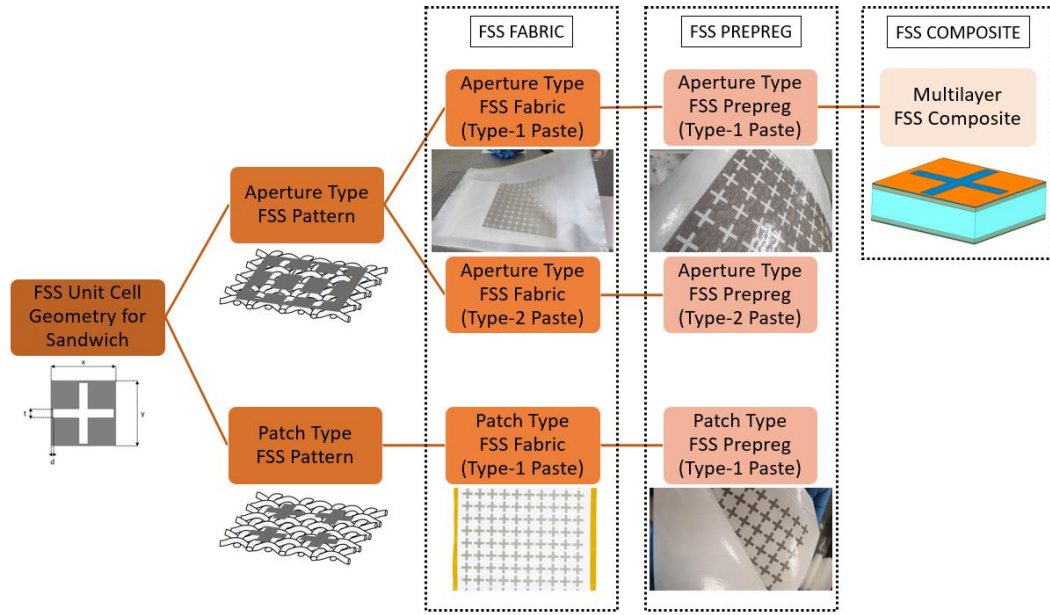


Figure 4.19. Production steps of FSS for sandwich configuration.

4.7.1.1 FSS Fabric for Sandwich Configuration

Two different types of conductive pastes were used to produce FSS fabric for sandwich configuration. Type-1 and Type-2 pastes were printed by using the same screen without changing the process parameters. Measured reflection and transmission losses of the FSS printed layers are given in Figure 4.20 and Figure 4.21, respectively, together with the corresponding losses obtained by the simulation. Measured and simulated reflection and transmission losses of the FSS pattern screen-printed with Type-1 paste match with each other remarkably, while those of the FSS pattern with Type-2 paste deviate from each other significantly.

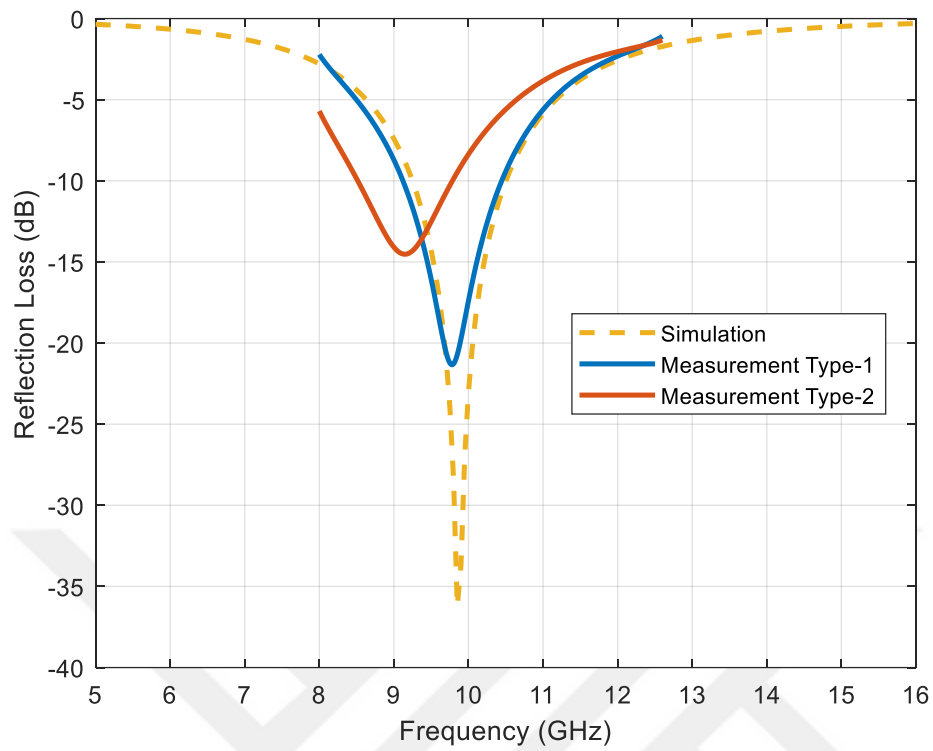


Figure 4.20. Measured reflection losses of the FSS pattern screen-printed with Type-1 and Type-2 pastes along with the simulated reflection loss of the pattern.

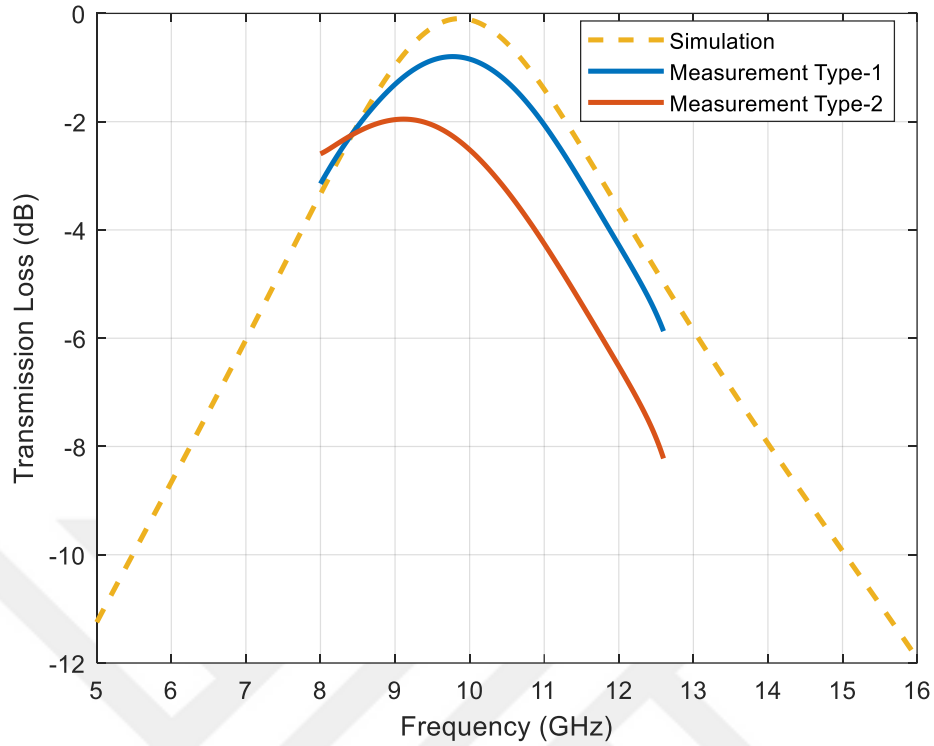


Figure 4.21. Measured transmission losses of the FSS pattern screen-printed with Type-1 and Type-2 pastes along with the simulated transmission loss of the pattern.

At first glance, the observed difference in the EM behavior of patterns made of these two pastes seems to have arisen mainly from the difference in the coverage of the silver particles on the glass fabric surface. In other words, Type-1 paste does not penetrate into the fabric and stays on the top of the surface as a continuous sheet leading to higher surface conductivity, as demonstrated by its lower resistance (Table 4.5), being closer to the bulk conductivity of silver used in simulations. Even though Type-1 paste accumulates on the glass fabric surface and acts closer to pure bulk silver, its reflection and transmission losses still deviate from the simulated ones, as its resistivity is still higher than that of the bulk silver, since Type-1 paste includes not only silver particles but also dielectric polymeric ingredients. Therefore, it is understood that even though the conductive paste forms a well covering FSS

medium, due to its higher resistivity compared to bulk silver, its EM responses will slightly deviate from the simulation.

In the case of Type-2 paste, it is considered that not only the conductivity decreasing effect of the dielectric constituents in the conductive paste formulation but also the penetration of the paste into the fabric substrate and lack of electrical connection between conductive particles result in a combined effect as evidenced by the observed major deviation between the measured and the simulated EM responses.

EM performance is highly dependent on the first interaction between the incoming wave and the surface. In case of accumulation of conductive particles on fabric surface, the wave fully interacts with the conductive surface and reflection and transmission responses occur similar to the prediction of the simulation. On the other hand, in case of the penetration of the conductive particles into the fabric substrate, incoming wave dominantly interacts with the dielectric glass fabric instead of the patterned conductive surface. Therefore, the interaction behavior between the FSS pattern and the incoming wave alters from the simulation considerably. To observe this effect, HFSS analysis was conducted on the FSS pattern covered with a continuous layer of glass with varying thickness representing the penetration of the conductive paste into the substrate where the incoming wave interacts first with the glass layer on the surface rather than the conductive pattern. Figure 4.22 (a) shows the original simulation where conductive particles (dark grey parts) were assumed to accumulate on the glass fabric surface (light grey parts). Figure 4.22 (b)-(e) shows design assumptions of partial and full penetrating alternatives to understand the effect of penetration. Incoming wave direction was indicated with black arrow and four different surface dielectric (glass) layer thicknesses from 10 μm to 100 μm were used in the simulation.

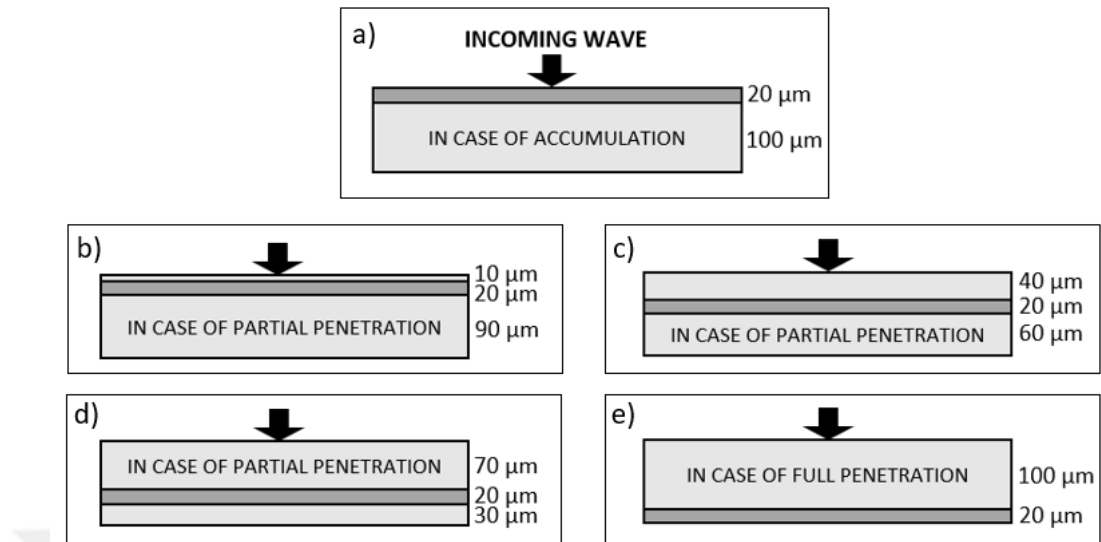


Figure 4.22. Schematic of design assumptions to understand the effect of the penetration of the conductive paste.

Reflection and transmission loss results of these simulations are given in Figure 4.23 and Figure 4.24, respectively. Simulation results exhibit that as the penetration of conductive particles into the glass fabric and resultingly thickness of the dielectric medium on the conductive pattern increases, reflection and transmission notches shift to lower frequencies from the targeted value of 9.8 GHz. As evidenced by this model, for Type-2 paste, penetration of conductive particles into the glass fabric causes deviation of the EM responses from the simulations.

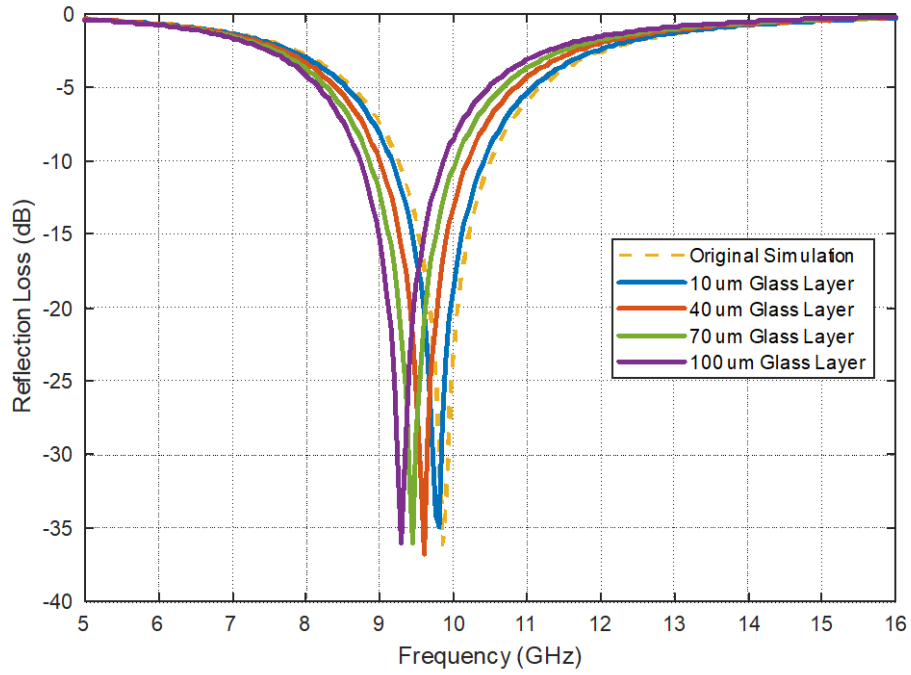


Figure 4.23. Simulated reflection losses of different surface glass layer coverings on the FSS pattern.

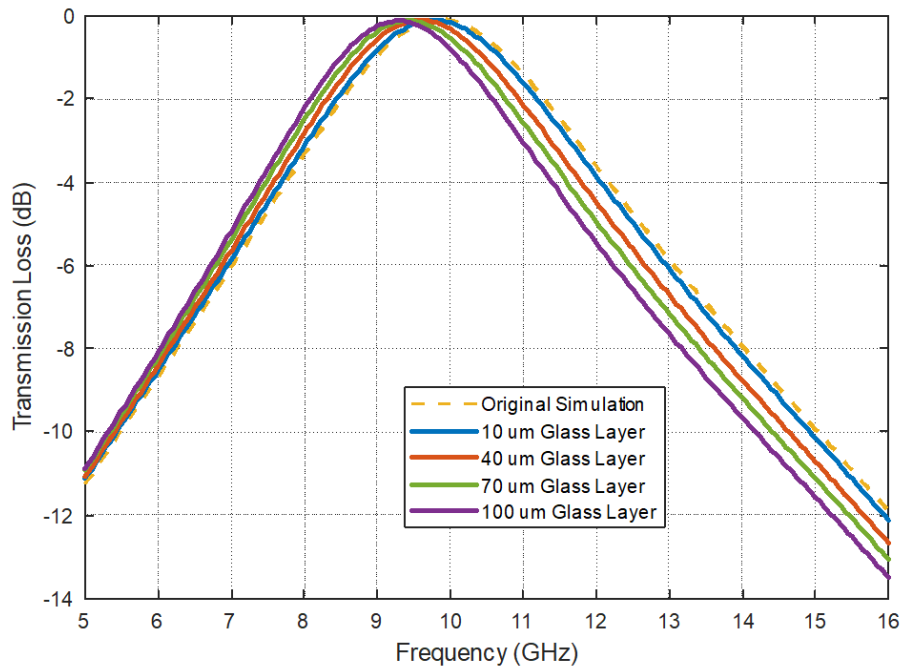


Figure 4.24. Simulated transmission losses of different surface glass layer coverings on the FSS pattern.

Reproducibility is an important factor in printing FSS patterns, especially for high volume productions. To observe the reproducibility of FSS patterns, several FSS printed glass fabrics were manufactured, and their EM performances were compared with each other. It was seen from the reflection and transmission losses of these aperture type FSS fabrics (Figure 4.25) that Type-1 paste assures reproducible printing for each application.

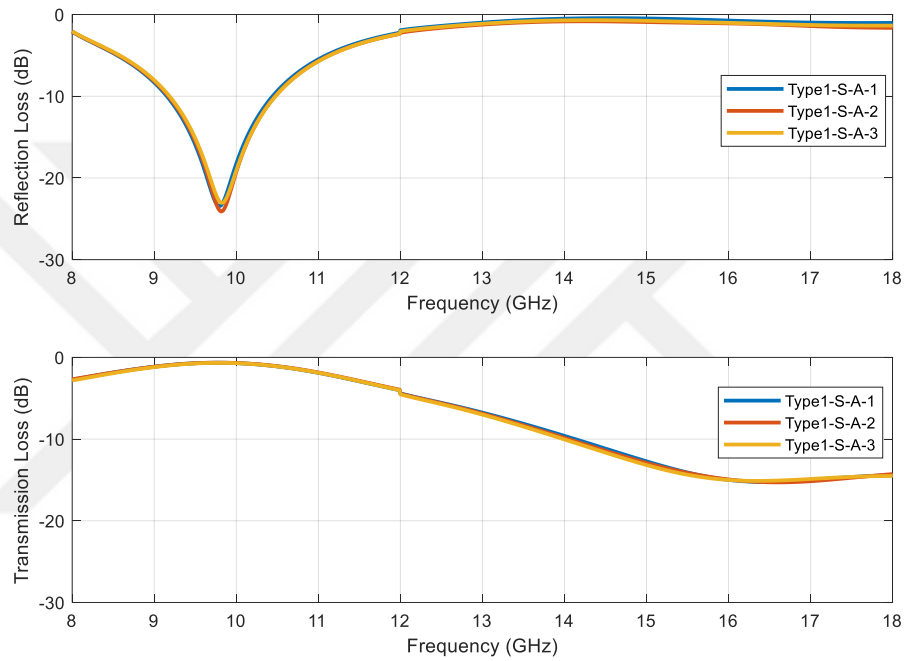


Figure 4.25. Measured reflection and transmission losses of the three different layers of aperture type FSS pattern of sandwich configuration screen-printed with Type-1 paste.

The same result was obtained for patch type FSS fabric produced by using Type-1 paste (Figure 4.26). This way, it was clear that Type-1 paste is suitable for both aperture and patch type FSS applications on glass fabric.

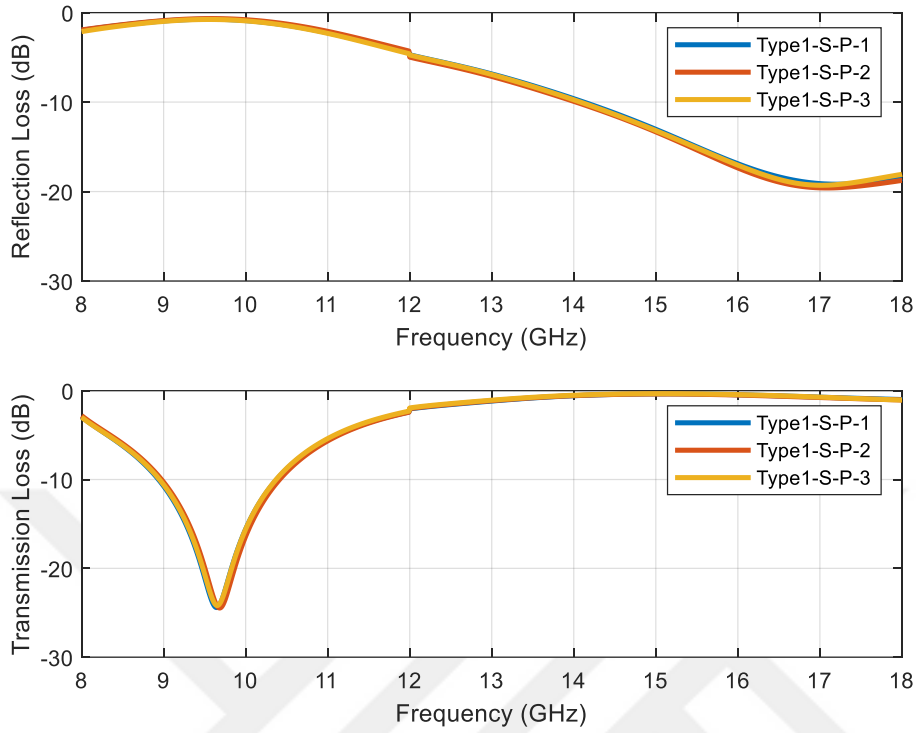


Figure 4.26. Measured reflection and transmission losses of the three different layers of patch type FSS pattern of sandwich configuration screen-printed with Type-1 paste.

After completing the reproducibility control of Type-1 paste for both aperture and patch type FSS, reflection and transmission loss results of these productions were compared with each other to observe if the transmission loss of the aperture type matches the reflection loss of the patch type FSS and vice versa. Comparison graph is given in Figure 4.27. Blue lines show the transmission loss behavior of FSS fabric where orange lines are for the reflection loss. Dashed lines belong to the patch type FSS pattern where flatlines are for the aperture type. From Figure 4.27, it is seen that the reflection loss lines and the transmission loss lines confront each other with the opposite designs. According to the results, it is understood that FSS patterns manufactured by Type-1 paste are consistent in both aperture and patch type designs.

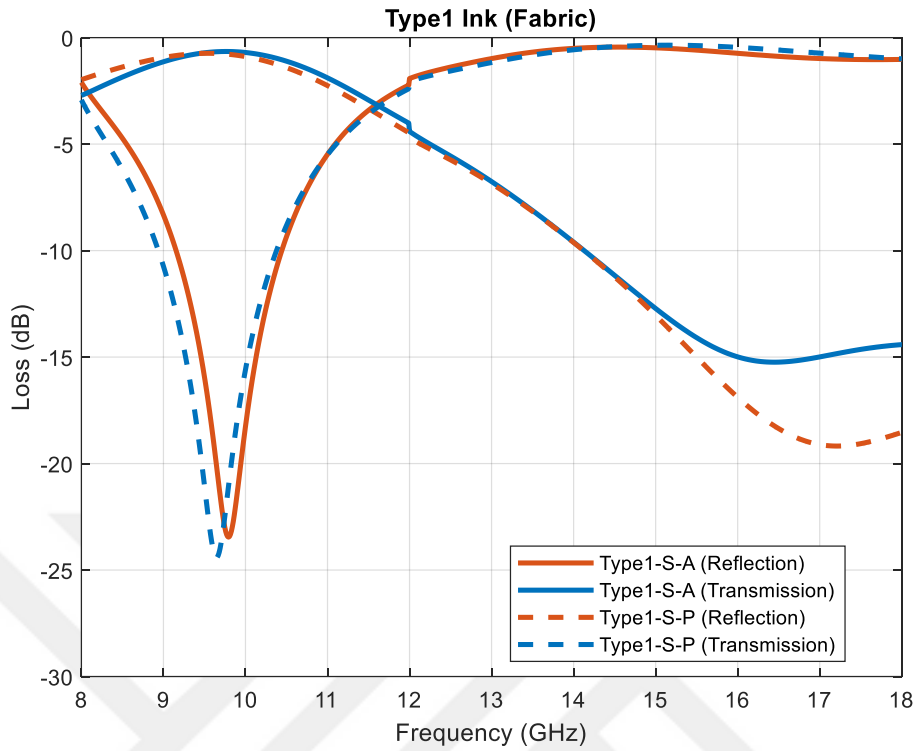


Figure 4.27. Comparison of measured reflection and transmission losses of aperture and patch type FSS patterns of sandwich configuration screen-printed with Type-1 paste.

Same steps were applied for Type-2 paste to examine its consistency and reproducibility. Three aperture type FSS fabrics were produced by using Type-2 paste and their reflection and transmission loss results were compared with each other. According to EM measurement results of these FSS fabrics (Figure 4.28) Type-2 paste shows unrepeatable printing performance. The possible reason for this difference was already explained in the beginning of this section. Conductive particles in Type-2 paste penetrates the glass fabric bundles which causes the reflection and the transmission loss behaviors of FSS fabric to deviate from the initial EM simulation. Since the penetration of the particles cannot be controlled, these three FSS fabrics show their resonance notches at different frequencies. Similar effect was also observed in patch type FSS fabric (Figure 4.29).

Consequently, the overall performance of Type-1 paste was found more consistent and more accurate than Type-2 paste as referenced to the initial EM simulation.

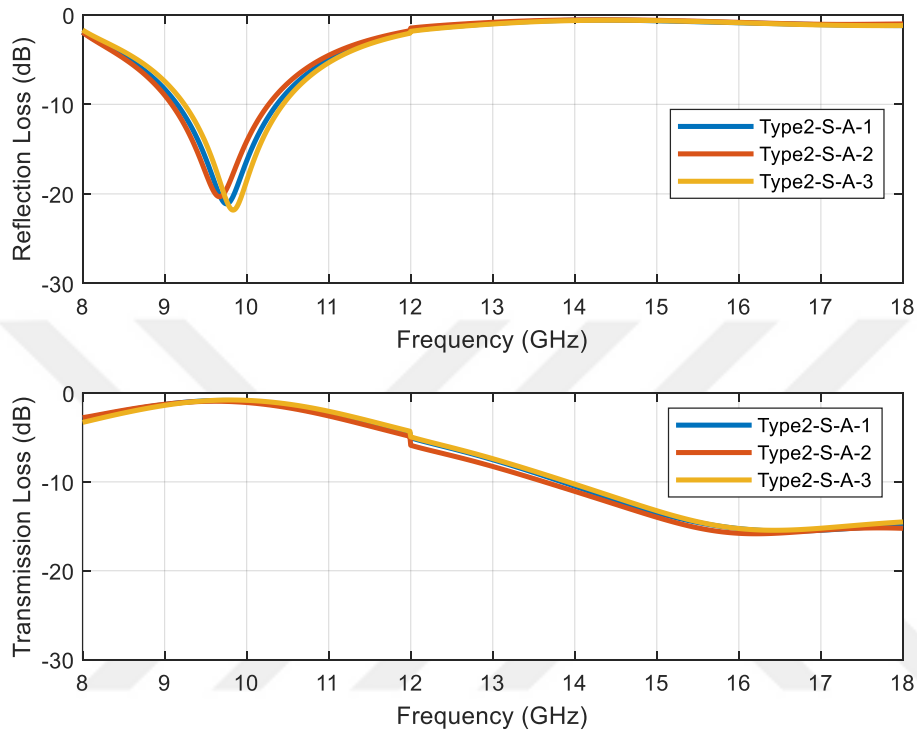


Figure 4.28. Measured reflection and transmission losses of the three different layers of aperture type FSS fabric screen-printed with Type-2 paste.

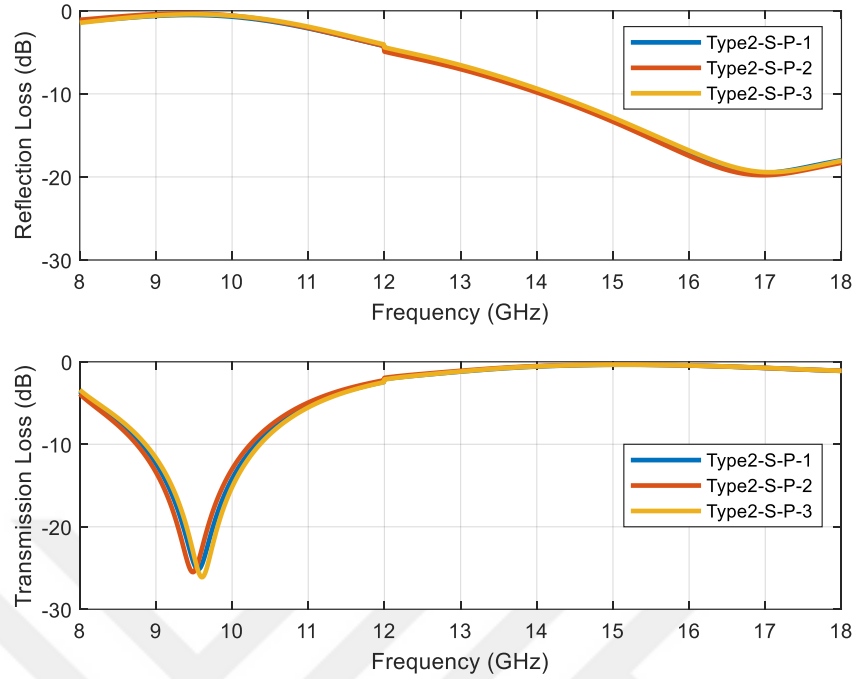


Figure 4.29. Measured reflection and transmission losses of the three different layers of patch type FSS fabric screen-printed with Type-2 paste.

As expected from Type-2 paste, the reflection and transmission loss results of aperture and patch type FSS fabrics were not similar (Figure 4.30). Consistency and repeatability of Type-2 paste was a major disadvantage since the reproducibility of FSS fabrics plays a crucial role in final multilayer composite performance. Achieving the same performance in each application was one of the most important criteria in this thesis. To conclude, Type-2 paste could not meet this criterion and failed in the repeatability evaluation.

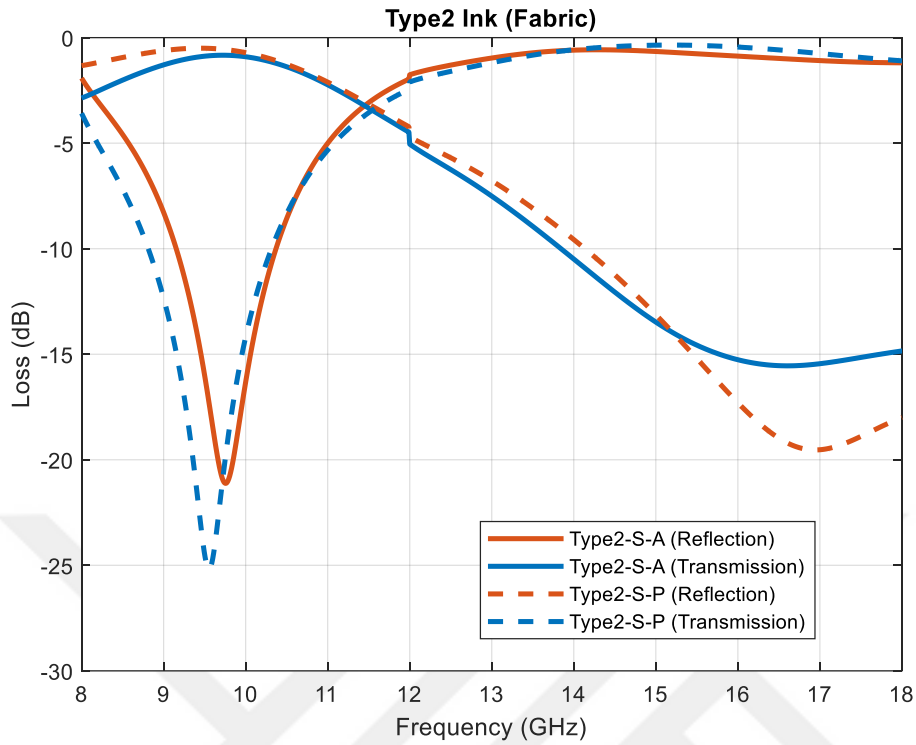


Figure 4.30. Comparison of measured reflection and transmission losses of aperture and patch type FSS fabrics screen-printed with Type-2 paste.

EM simulation result of the aperture type FSS pattern, which was designed to be used as an FSS layer in multilayer composite, was simulated in Figure 4.31 together with printed FSS fabric with Type-1 paste. It is clear from the comparison in Figure 4.31 that Type-1 paste is suitable for screen printing applications on glass fabric and the required EM performance can be achieved by using Type-1 paste with proper FSS design selection.

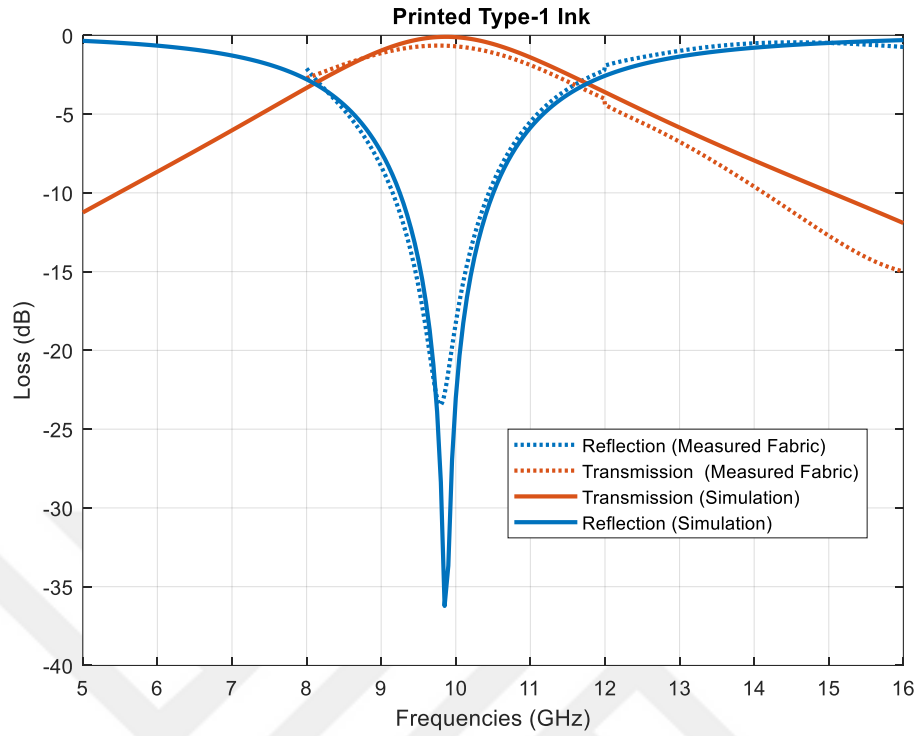


Figure 4.31. Selection of Type-1 paste for screen printing of FSS pattern on glass fabric substrate.

4.7.1.2 FSS Prepreg for Sandwich Configuration

Printed FSS fabric was impregnated with epoxy resin in the second step to obtain FSS prepreg. Therefore, the EM performance after resin impregnation plays an important role and should be characterized. Resin impregnation effect was distracted from the comparison between FSS fabric and FSS prepreg for the same pattern. As can be seen in Figure 4.32, resin impregnation causes resonance notch to shift lower frequencies. This phenomenon is observed due to the change in dielectric constant of substrate material when changing from fabric to prepreg. Since the dielectric constant of prepreg is higher than the glass fabric, the speed of the wave in the material behaves slower in prepreg than in the fabric according to the equation given below where V_p is the speed of wave in the material, ϵ_r is the relative dielectric

constant of the material and c is the speed of light. As the dielectric constant increases, the speed of the wave in this media decreases relatively.

$$V_p = c / \sqrt{\epsilon_r} \quad (12)$$

As V_p decreases, dielectric media acts thicker in electrical approach which causes resonance notch to shift lower frequency. Therefore, the resin impregnation effect, independent from the FSS pattern, can be summarized as a decrease in resonance frequency.

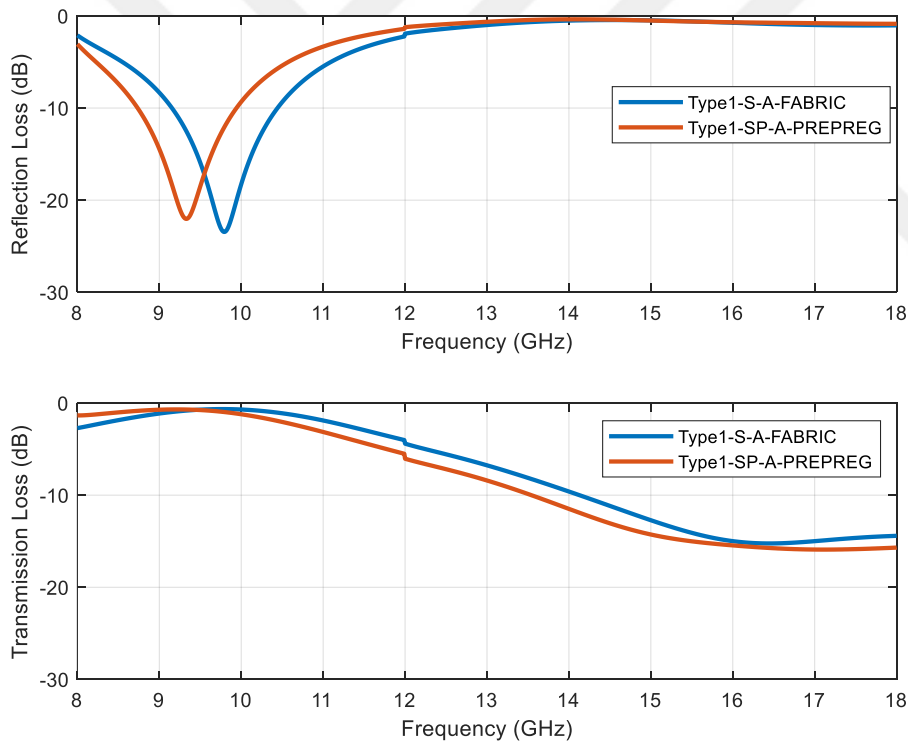


Figure 4.32. Comparison of measured reflection and transmission losses of aperture type FSS fabric and FSS prepreg screen-printed with Type-1 paste.

The amount of decrease is directly related with the resin content of the prepreg since the increase in dielectric constant is caused by the epoxy resin and the ratio of the resin to overall material affects the dielectric properties. As the resin content of the prepreg increases, it is more likely to obtain larger shifts compared to lower resin content. Also, if a higher dielectric constant resin is used in impregnation step, for the same resin content, delta between fabric and prepreg notches would be higher than lower dielectric constant resin case.

Similar behavior was observed in comparison of patch type FSS fabric and patch type FSS prepreg and the EM comparison results are given in Figure 4.33. Consequently, apart from their initial FSS designs, the resonance notch of both patch and aperture type FSS fabrics shift to lower frequencies as a result of resin impregnation.

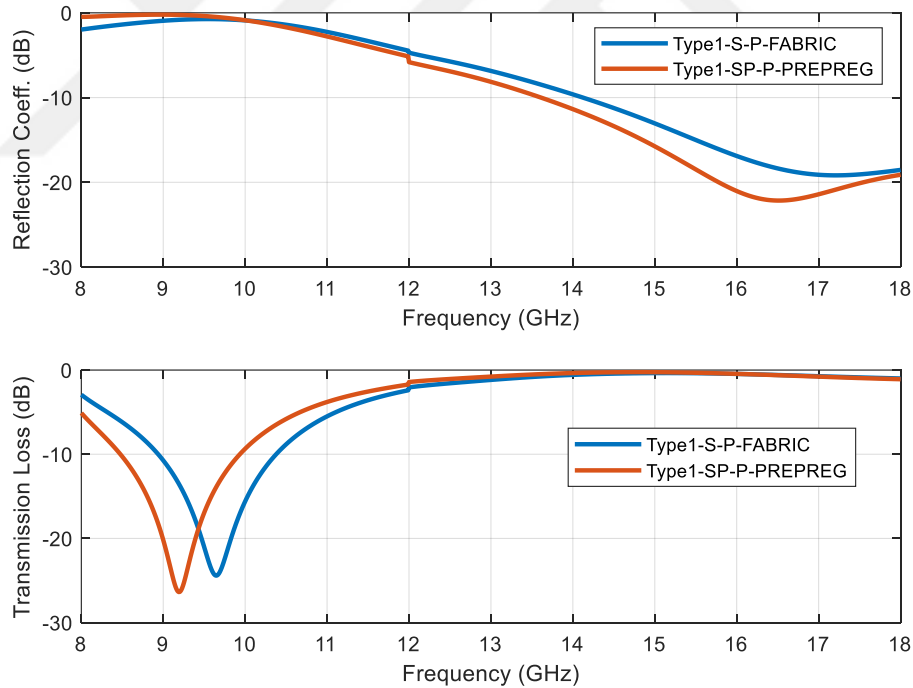


Figure 4.33 Comparison of measured reflection and transmission losses of patch type FSS fabric and FSS prepreg of sandwich configuration screen-printed with Type-1 paste.

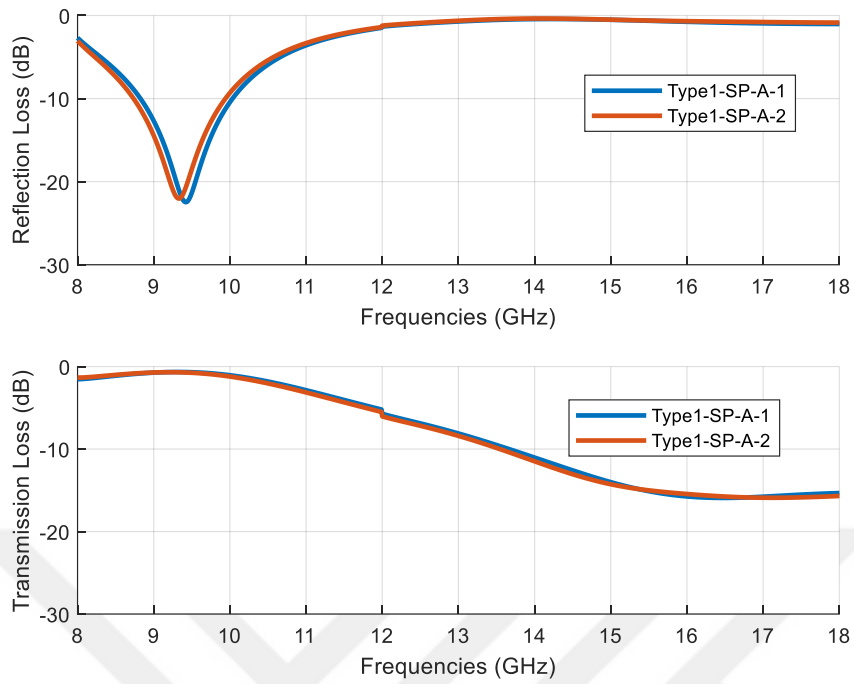


Figure 4.34. Measured reflection and transmission losses of two different layers of aperture type FSS prepreg screen-printed with Type-1 paste.

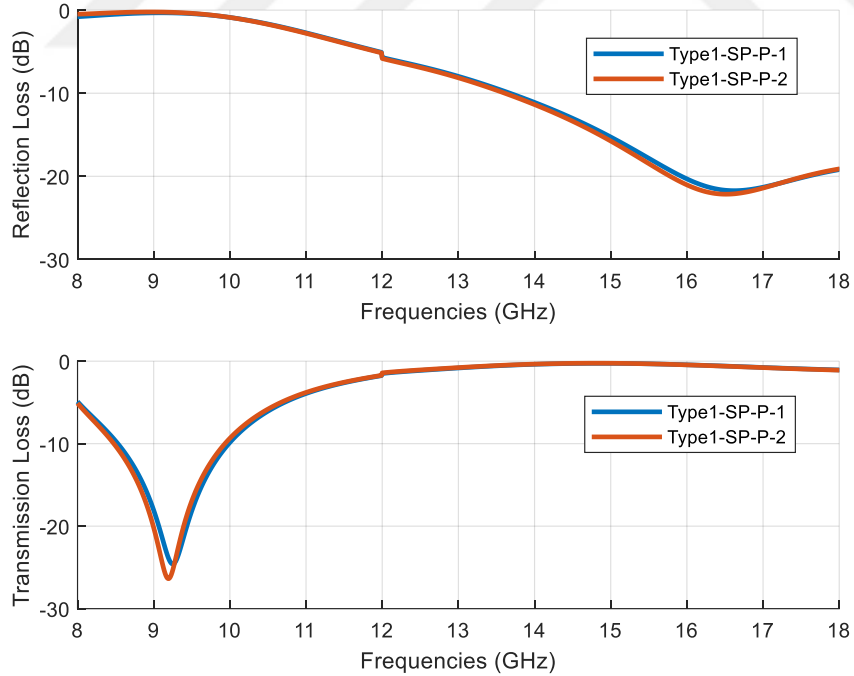


Figure 4.35. Measured reflection and transmission losses of two different layers of patch type FSS prepreg screen-printed with Type-1 paste.

Repeatability of FSS prepreg manufacturing was another important parameter for FSS composite production as in fabric step. Hence, obtaining similar EM results in each production was the most important criterion. Two different FSS prepreps produced from different FSS fabrics, both in aperture and patch types, were characterized and the results are given in Figure 4.34 and Figure 4.35, respectively. It is obvious from the EM measurement results that even though resin impregnation has an impact on final reflection and transmission losses, this effect is similar for each application. Therefore, repeatable results could be achieved by using Type-1 paste.

8-12 GHz frequency range focused EM measurement results for reflection and transmission losses of FSS fabric and FSS prepreg printed with Type-1 paste are given in Figure 4.36.

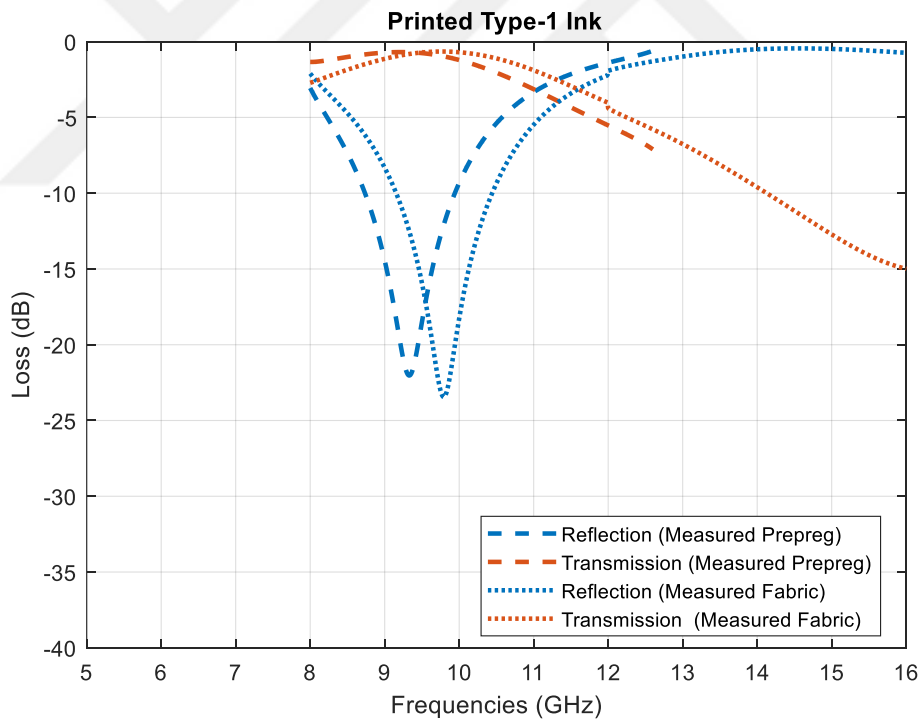


Figure 4.36. Effect of resin impregnation on reflection and transmission losses of aperture type FSS of sandwich configuration screen-printed with Type-1 paste.

8-12 GHz frequency range focused EM measurement results for reflection and transmission losses of initial EM simulation, FSS fabric and FSS prepreg printed with Type-1 paste are given in Figure 4.37.

Consequently, Type-1 paste is suitable for screen printing of FSS pattern on glass fabric and the initial EM simulation expectations can be achieved. After prepreg manufacturing, resin impregnation had an impact on resonance frequency, but this difference is predicted be tolerated in multilayer FSS composite production step. Since Type-2 paste could not meet the initial EM simulation expectations and has disadvantages as in repeatability of FSS pattern performances, it was eliminated from further applications and multilayer FSS composite structure was manufactured by using only Type-1 paste FSS layers.

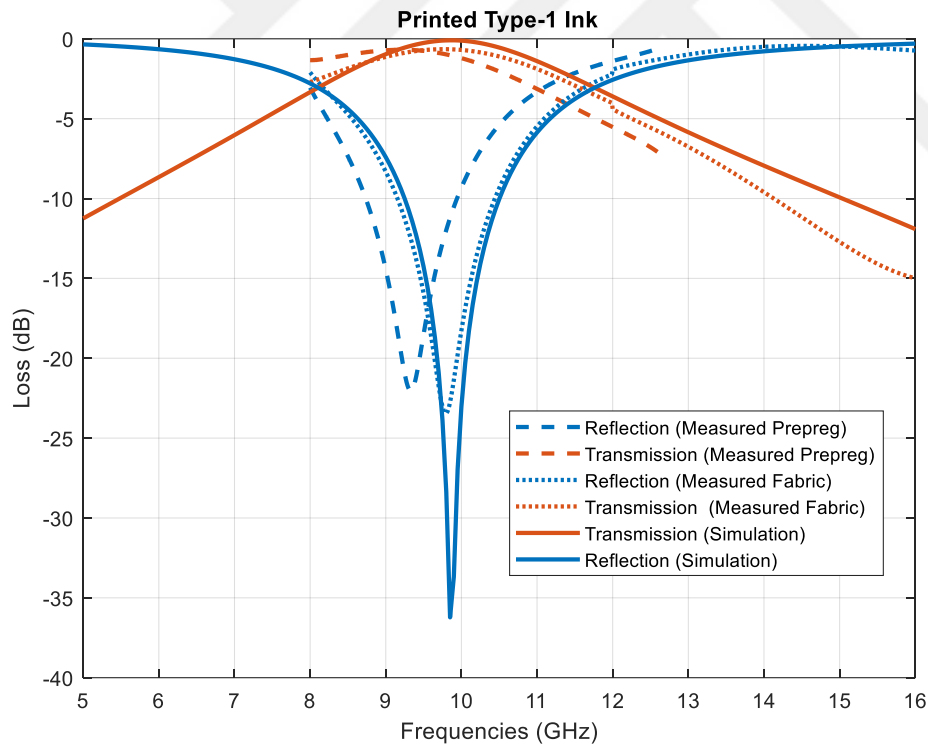


Figure 4.37. Comparison of measured reflection and transmission losses of aperture type simulation, FSS fabric and FSS prepreg screen-printed with Type-1 paste.

4.7.1.3 FSS Composite for Sandwich Configuration

Multilayer FSS sandwich composite was produced by using FSS prepregs printed with Type-1 paste. The comparison of initial EM simulation and final FSS composite structure measurement is given in Figure 4.38. According to Figure 4.38, it is seen that this structural FSS composite transmits in 8-9 GHz range as intended in initial FSS composite design with an insertion loss of -2 dB. Out of the pass band (8-9 GHz), this FSS composite structure provides a good reflection behavior.

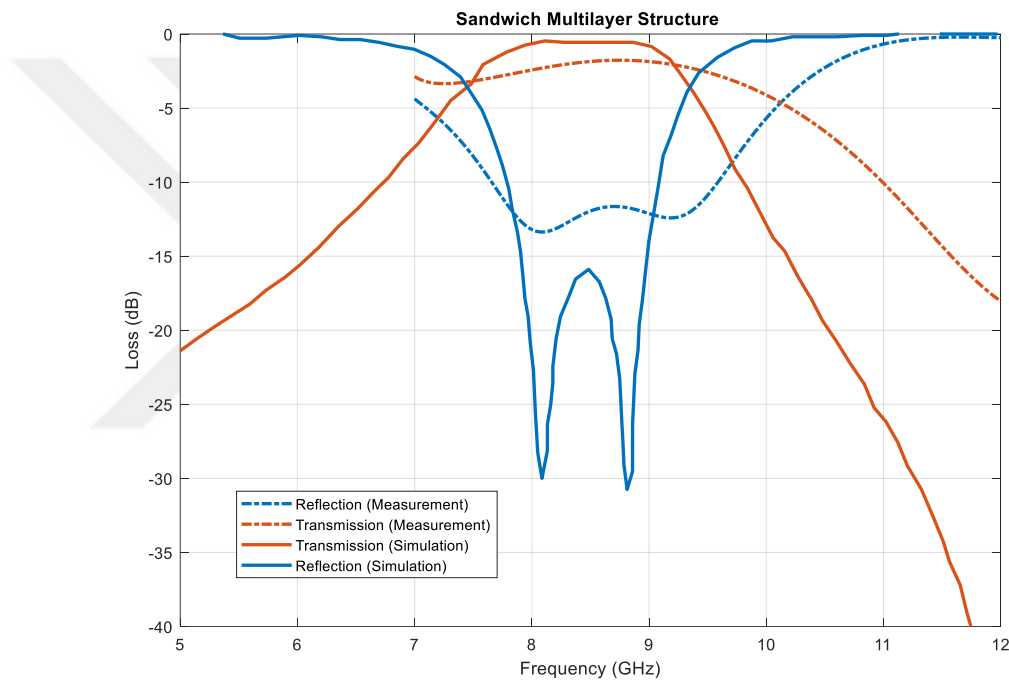


Figure 4.38. Comparison of measured reflection and transmission losses of aperture type simulation and sandwich FSS composite screen-printed with Type-1 paste.

This result shows that screen printing of FSS pattern on glass fabric substrate, which later used as a prepreg layer in polymer composite structure, is an alternative method for producing multilayer FSS composite in sandwich configuration.

4.7.2 RF Characterization of FSS Pattern for Monolithic Configuration

For monolithic composite configuration, FSS unitcell was designed and the expected results were obtained through simulations. For this FSS design, only the aperture type FSS was produced with using Type-1 paste since the accuracy of FSS patterns was already discussed in sandwich configuration section and Type-1 paste was selected as a conductive paste based on its EM performance. Schematic representation FSS approach for monolithic configuration is given in Figure 4.39.

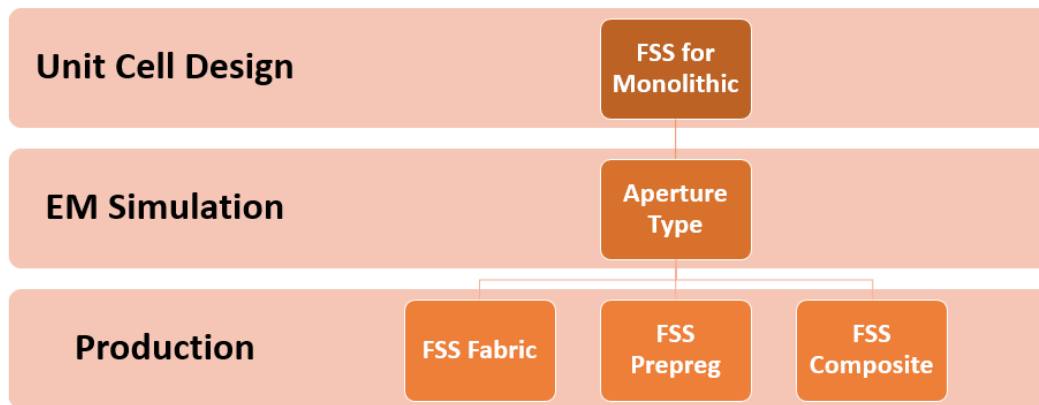


Figure 4.39. Schematic representation of FSS approach for monolithic configuration.

First of all, aperture type FSS were produced in FSS fabric step, and the results were compared with the initial EM simulation. After the applicability of this method was understood, FSS prepregs were manufactured by using FSS fabrics. Figure 4.40 was prepared to summarize all production steps starting from the unit cell design to final multilayer composite for sandwich configuration.

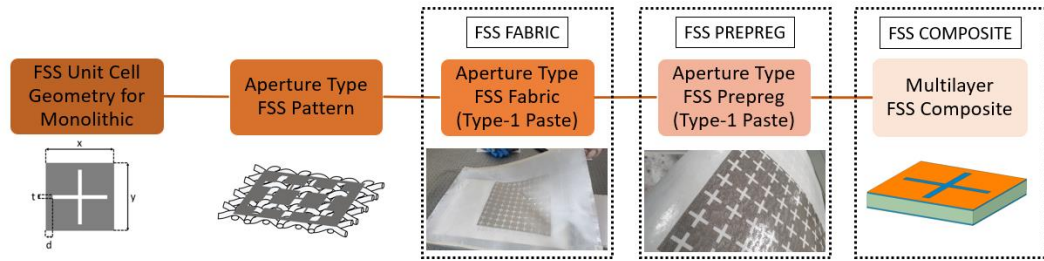


Figure 4.40. Production steps of FSS for sandwich configuration.

4.7.2.1 FSS Fabric for Monolithic Configuration

Aperture type FSS fabrics were printed by using Type-1 paste and the EM characterization results are given in Figure 4.41. According to the measurement results, repeatability of printing is provided also in monolithic configuration, as in sandwich configuration, with Type-1 paste.

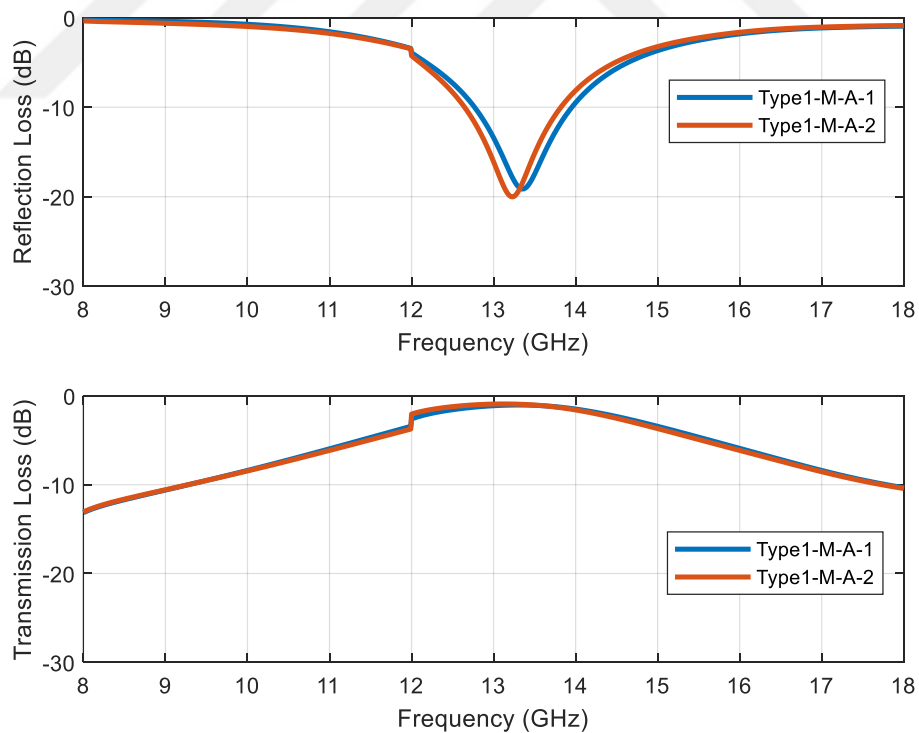


Figure 4.41. Measured reflection and transmission losses of the two different layers of aperture type FSS pattern screen-printed with Type-1 paste.

4.7.2.2 FSS Prepreg for Monolithic Configuration

The effect of resin impregnation on EM behavior is an inevitable fact and should be controlled by comparing FSS fabric and FSS prepreg for the same pattern. The comparison of reflection and transmission loss results of FSS fabric and FSS prepreg is given in Figure 4.42. As expected, the resonance notch shifts to the lower frequencies with resin impregnation.

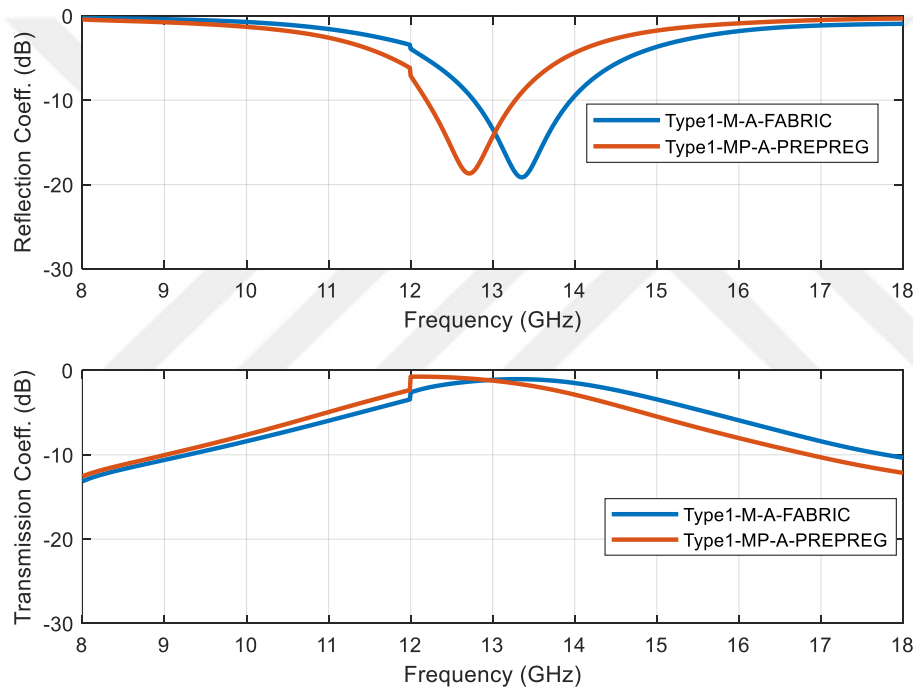


Figure 4.42. Comparison of measured reflection and transmission losses of aperture type FSS fabric and FSS prepreg screen-printed with Type-1 paste.

The difference between the resonance frequencies of FSS fabric and FSS prepreg was found to be larger than the difference in sandwich configuration. Possible reasons behind this variance are assumed to be the frequency range of the FSS pattern and the dimensions of the FSS unit cell. Since the FSS unit cell of monolithic

configuration is smaller than that of sandwich configuration, FSS pattern resolution is more vulnerable through the impregnation process. Moreover, higher frequency ranges of monolithic FSS pattern results in smaller wavelength which causes the reflection and transmission loss of the FSS layer to be easily affected by environmental factors. Therefore, for monolithic configuration, impregnation step could have a negative effect on EM performance of final multilayer composite.

Overall EM measurement results for reflection and transmission losses of initial EM simulation, FSS fabric and FSS prepreg printed with Type-1 paste are given in Figure 4.43.

To conclude, even though Type-1 paste is suitable for screen printing of FSS pattern on glass fabric and the initial EM simulation expectations can be achieved in FSS fabric step, after prepreg manufacturing, resin impregnation had a negative impact on resonance frequency which resulted in deviation from the initial simulation.

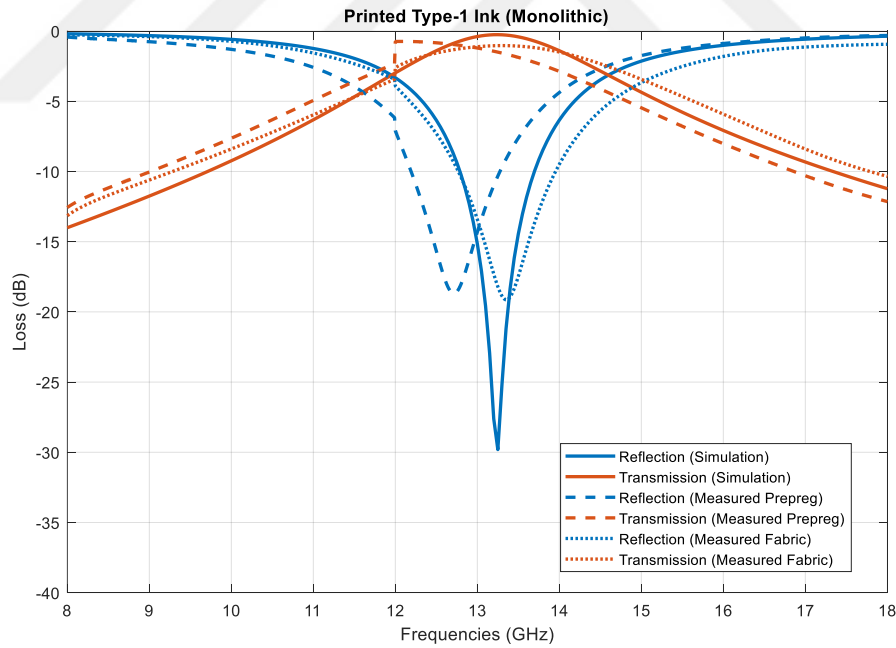


Figure 4.43. Comparison of measured reflection and transmission losses of aperture type simulation, FSS fabric and FSS prepreg screen-printed with Type-1 paste.

4.7.2.3 FSS Composite for Monolithic Configuration

Multilayer FSS monolithic composite was produced by using FSS prepregs printed with Type-1 paste. The comparison of initial EM simulation and final FSS composite structure measurement is given in Figure 4.44. Initially simulated multilayer FSS composite was aimed to transmit the incoming wave at around 9.5-10 GHz. However, according to Figure 4.44, it is seen that the manufactured structural FSS composite transmits in 11-11.5 GHz range as different from the initial FSS composite design.

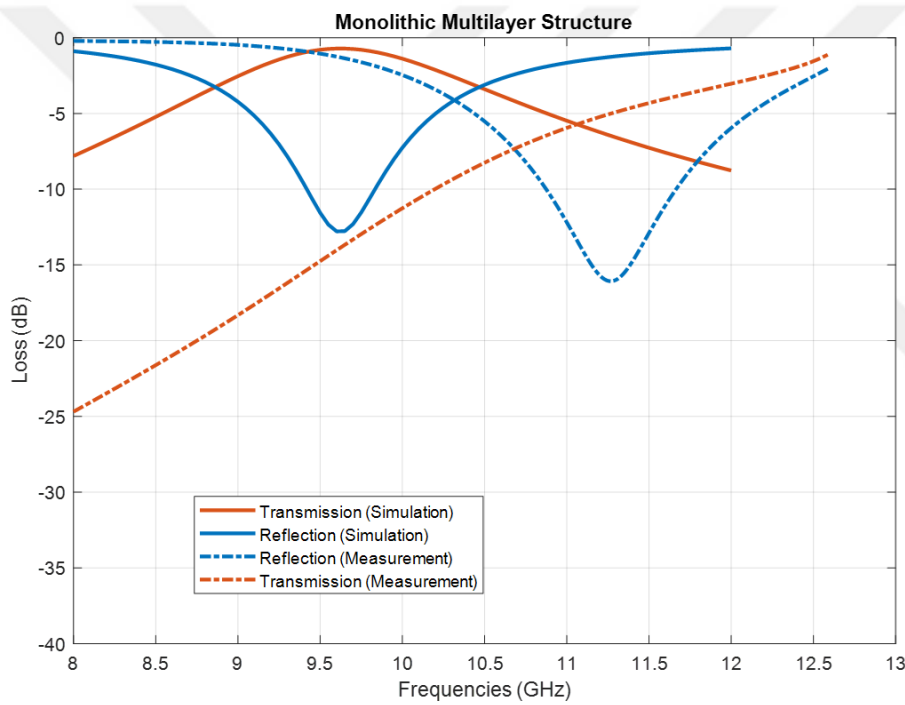


Figure 4.44. Comparison of measured reflection and transmission losses of aperture type simulation and monolithic FSS composite screen-printed with Type-1 paste.

The major reason for this difference is the resonance frequency of the single layer FSS pattern which is around 9.8 GHz for sandwich configuration and 13.2 GHz for monolithic configuration. Since their resonance frequencies are different, FSS unit cell geometries are also different where the lower frequency pattern has larger unit

cell dimensions and vice versa. Therefore, FSS pattern for monolithic configuration has smaller FSS unit cell which makes it more sensitive to process related defects and other application parameters. Also, the FSS prepregs of monolithic configuration showed more shift in resonance frequency than the FSS prepregs of sandwich configuration. Therefore, the resulting reflection and transmission losses of final multilayer monolithic FSS composite deviate from the initial EM simulation expectation.

4.8 Mechanical Analysis of FSS Composite

The mechanical strength of the composite structures was determined in terms of the interlaminar shear strength (ILSS) by conducting the three-point bending test according to EN2377 standard. ILSS can be described as the value of the shear strength producing a delamination between two composite layers along the plane of their interface. FSS patterns were printed on the fiber woven fabric surface, which directly affects the fiber/resin interaction of the resulting polymer composite. Normally, fiber surfaces are already modified, generally with silane-based coupling agents, to react with the epoxy resin of the matrix. However, in the current case, the silane-based coupling agent on the fiber surface was covered with silver paste, and hence it was expected to have negative effect on ILSS properties of the composite material. In order to observe the effect of FSS patterns on the mechanical behavior, ILSS has been the most relevant mechanical property determined by the three-point bending test.

Three-point bending test results of FSS layer embedded composites were compared with as-is composite panel which have the same lay-up configuration without any FSS patterns inside. Three important parameters were analyzed through this test. One of them was to understand the effect of the covered area on the interlaminar behavior. For this purpose, aperture type and patch type FSS layers having the same conductive paste (Type-1) were tested and compared with each other. The second parameter was to observe the effect of conductive paste type on interlaminar behavior. Patch type

FSS layers printed using Type-1 and Type-2 pastes were analyzed. Finally, the effect of surface modification on the mechanical properties was examined by comparing different surface modified FSS patterns. Three samples were tested for each combination and for 16 different combinations 48 samples were tested in total.

Overall mechanical test results of these samples are summarized in Figure 4.45.

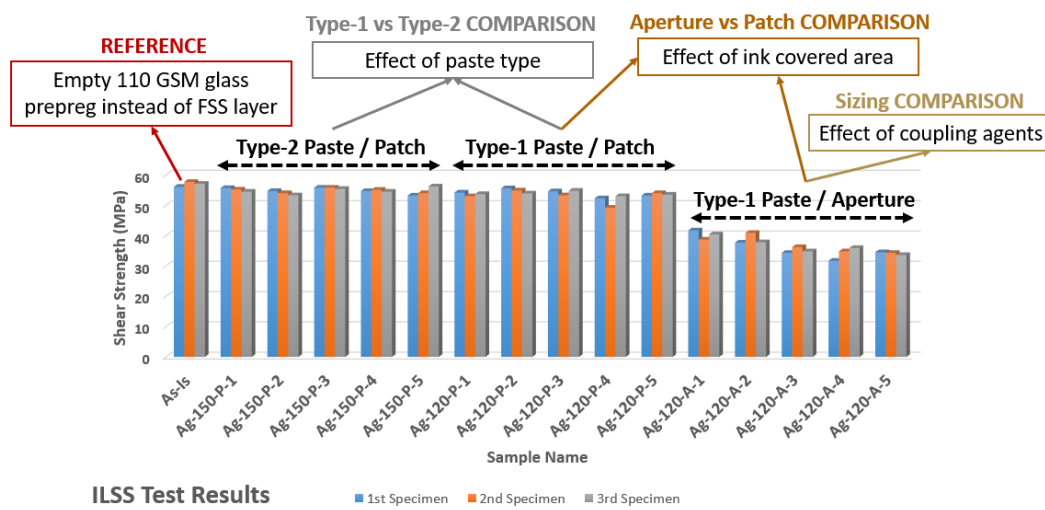


Figure 4.45 Summary of the mechanical test results for different combinations.

Shear failure takes place at the midplane of the sample in the form of delamination. Failure mode of each sample was controlled after the test. All samples failed in horizontal shear at the neutral fibre axis of the composite specimen according to standard's description (Figure 4.46).

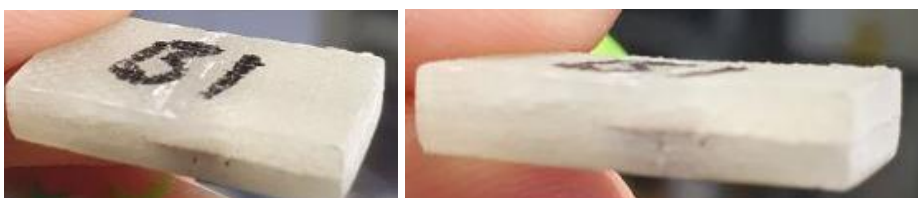


Figure 4.46 Single shear failure mode of the ILSS sample.

4.8.1 Effect of Patterned Area on The Interlaminar Behavior

Aperture type FSS patterns cover the interfacial areas more than patch type FSS patterns. Therefore, it was expected to see lower interlaminar shear strength value for aperture type than that of patch type FSS composite. Type-1 paste coated interfacial area of aperture and patch type FSS layers are given in Figure 4.47.

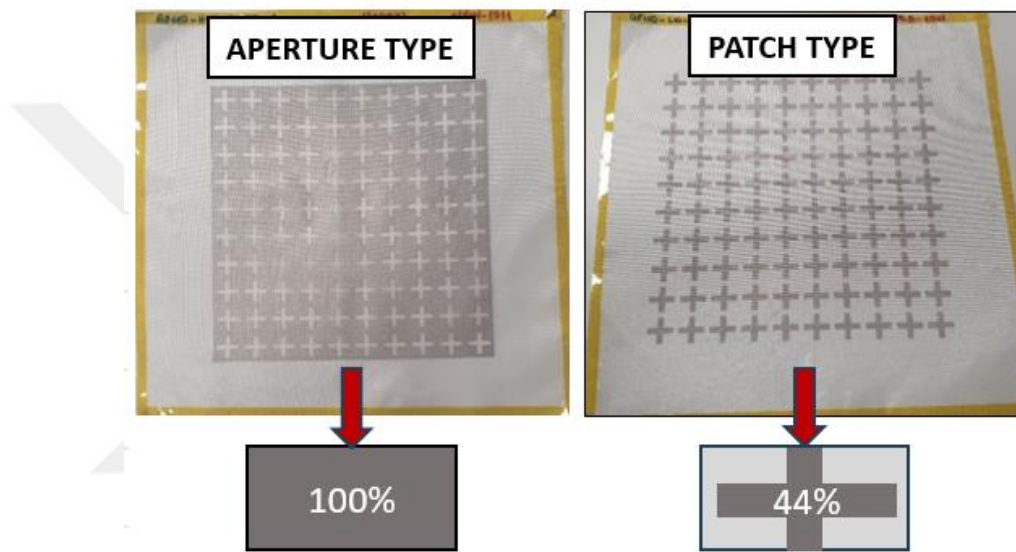


Figure 4.47 Conductive paste coated area of FSS layer in ILSS sample.

In patch type pattern, 44% of the FSS prepreg is covered with conductive Type-1 paste. On the other hand, in aperture type pattern, almost 100% of FSS prepreg is covered with conductive Type-1 paste. As can be seen from Figure 4.48, full coverage of the paste on the FSS layer causes around 30% decrease in the interlaminar shear strength of the composite material.

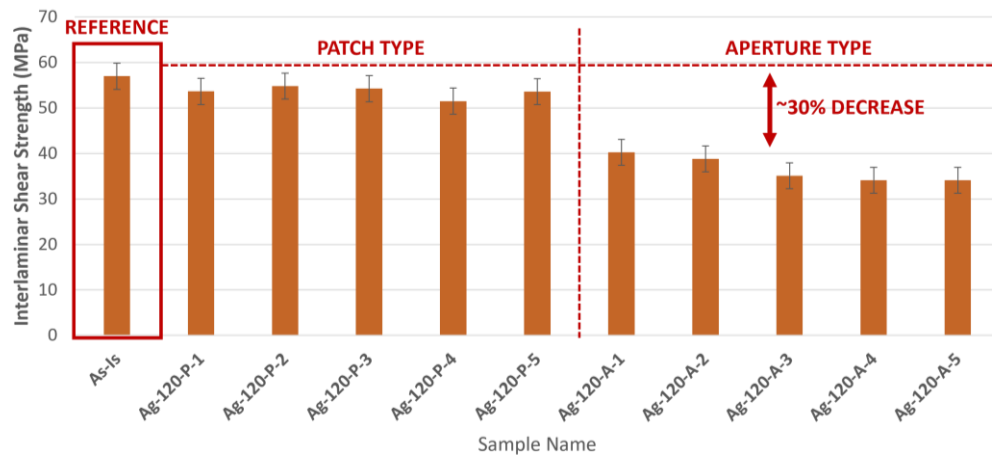


Figure 4.48 ILSS test results of aperture and patch type FSS patterns.

4.8.2 Effect of Conductive Paste Type on The Interlaminar Behavior

The effect of conductive paste type on the interlaminar behavior was observed via testing the same FSS pattern with different conductive pastes. Patch type FSS patterns were used in this comparison (Figure 4.49).

Type-1 and Type-2 pastes differentiate from each other in terms of the size of their conductive particles. The variance in conductive particle size results in a difference between their accumulation behavior on perforated surfaces, such as glass fabric substrate. Type-1 paste accumulates on top of the fabric where Type-2 paste penetrates the fabric. Moreover, the adhesion property of Type-2 paste was superior to Type-1 paste according to band tape test. Consequently, Type-1 paste was expected to show inferior mechanical properties when compared with Type-2 paste.

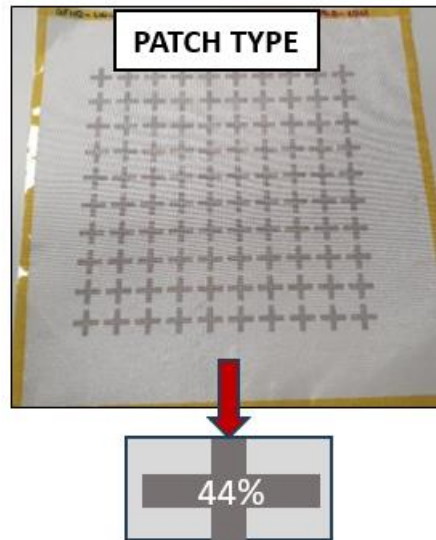


Figure 4.49 Patch type FSS and the schematic representation of its conductive paste covered interlaminar area.

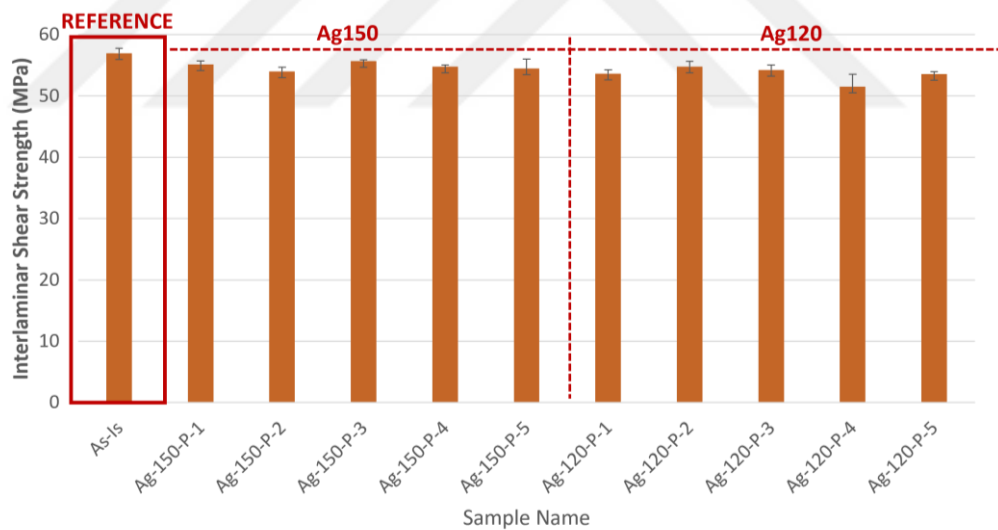


Figure 4.50 ILSS Test results of Type-1 and Type-2 pastes.

Even though it was expected for Type-1 paste to deteriorate interlaminar strength due to the reasons given above, it is seen from Figure 4.50 that ILSS properties of Type-1 paste are almost similar with Type-2 paste in all sizing forms. In addition,

these ILSS results are almost similar with the reference result given in Figure 4.50. In conclusion, the difference in morphologies of conductive pastes in this study does not play a crucial role on interlaminar shear strength of patch type FSS composite.

4.8.3 Effect of Surface Modification on The Interlaminar Behavior

The effect of surface modification on the interlaminar behavior was observed through the aperture type FSS composite, since the effective area of the surface modification is larger in aperture type (Figure 4.51).

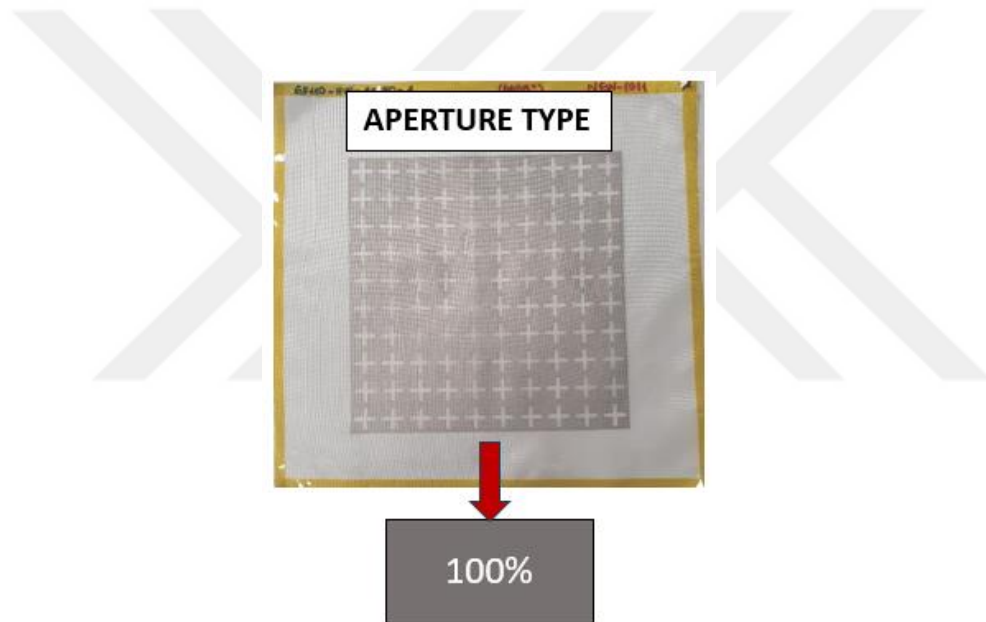


Figure 4.51 Aperture type FSS and the schematic representation of its conductive paste covered interlaminar area.

ILSS test results of the surface modified FSS composites are given in Figure 4.52. 1st and 2nd coupling agents were specifically chosen to enhance the chemical interaction between the conductive paste and the epoxy resin.

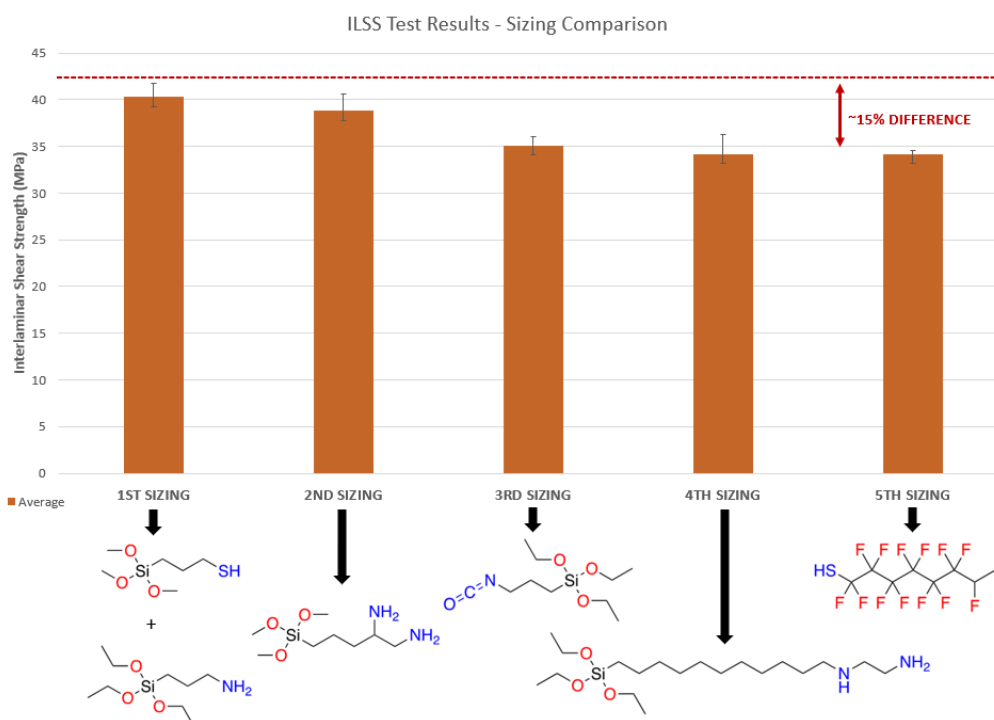


Figure 4.52 ILSS test results of the surface modified FSS composites.

As intended initially, they show superior interlaminar shear strength values. However, the difference between the 5th sizing and the rest of the coupling agents was expected to be higher since the 5th sizing contains F, which was used as a marker in XPS. Therefore, it was understood that the surface modification was not effective enough as only the surface of the FSS pattern was modified. The FSS pattern has two surfaces, one side interacts with the glass fabric and the other side with the epoxy resin. Surface modification in this study aimed to improve only the interaction at the FSS pattern and epoxy interface, hence the shear failure might have initiated from the other side of the FSS pattern. As the interlaminar shear strength values were adequate for this application, no further modification was applied on the FSS pattern surfaces.



CHAPTER 5

CONCLUSION

The main objective of this study was to develop a novel method for fabricating frequency selective surfaces to be utilized as a reinforcement in polymer matrix composite structures by using commercially available conductive pastes. Conventional screen printing method was used, and the printing process was optimized based on the properties of the glass fiber woven fabric substrate and the conductive paste. In conclusion, FSS composite material showing the target performance, which is minimum -10 dB reflection loss and -2 dB insertion loss in 8-9 GHz frequency range, was demonstrated. Therefore, minimum 90% shielding efficiency was achieved in aimed frequency range. The key outcomes of the investigation can be summarized as follows:

1. It was demonstrated that screen printing can be used with ease to pattern the glass fiber woven fabric surface with high topography using commercially available products without further surface modifications.
2. Two different types of silver-based pastes having different conductive particle size and geometries were used to print an X-band FSS pattern on the glass fabric substrate by screen printing method. The differences in the observed EM responses between the measurements and the simulations were attributed to the particle size and morphology effect which leads to variation in the accumulation behavior of the conductive pastes, especially in the case of a porous/perforated substrate as used in this study.

3. It was observed that conductive paste containing larger metallic particles accumulate on top of the glass fabric whereas the one containing smaller metallic particles penetrate the fabric which is affecting the surface conductivity, and hence, electromagnetic reflection and transmission behaviors of the printed pattern.
4. It was revealed that to achieve matching between the physically measured and simulated EM responses, electrically conductive network between the particles in the paste should be well established such that resulting printed pattern could have higher surface conductivity closer to that used in the simulation.
5. EM simulations showed that the reflection loss and the transmission loss behaviors deviate from the original simulation as conducting particles penetrate the substrate, and to overcome this deviation, properties of the conductive pastes should be selected regarding the textile substrate.
6. In light of these studies, it was revealed that in case of porous/perforated substrates, conductive pastes having larger size and flake-like geometry should be preferred for screen printing to lead accumulation behavior on the substrate surface and to obtain continuous conductive FSS layer to be utilized in FSS thermoset radome.
7. The resin impregnation step of FSS fabric caused the resonance notch to shift to lower frequencies, hence the reflection loss and transmission loss behavior of FSS prepreg deviated from those of the FSS fabric. This difference was tolerated in the final multilayer FSS composite, however, in case of larger deviations, the initial simulation must be updated according to the EM performance of FSS prepreg.

8. The required EM performance of the multilayer FSS composite was achieved in sandwich configuration, however, in monolithic composite configuration, the deviation from the desired EM performance was intolerable.
9. FSS unit cell dimensions were found to have a significant effect on the producibility of the FSS by screen printing. As the unit cell dimensions decrease, the sensitivity of the FSS pattern increases, causing the reflection loss and transmission loss behavior of the FSS to be affected from process steps and parameters.
10. The interlaminar shear strength of the FSS layer inserted polymer composite was measured by three-point bending test. Mechanical performance of the resulting FSS composite was found to be inferior compared to the reference composite material, containing bare glass fabric instead of FSS patterned one.
11. The effect of the FSS pattern on the interfacial properties of the FSS composite was related with the coverage of the patterned area, hence, the patch type FSS pattern, having larger patterned area than the aperture type, further deteriorated the mechanical properties.
12. Surface modification on the FSS pattern was conducted to enhance the chemical interaction between the conductive paste and the epoxy resin. Although the effect of surface modification on the interlaminar shear strength was unignorable, in scope of this study, surface modification was found not to be crucial.

The following future studies are recommended to further optimize the screen printing method for FSS applications in polymer composite structures.

1. The alignment of the FSS patterns, especially for multilayer designs including more than one FSS layer, plays a crucial role in the final EM performance. Therefore, composite lay-up steps are strongly advised to be optimized to align FSS layers on top of each other with high sensitivity.
2. More research is needed to understand the effect of conductive paste type on the EM performance, since there were several factors affecting the final EM behavior. However, some parameters, such as the rheologic properties of the conductive paste, were considered to be insignificant to facilitate the scope of this study. Hence, increasing the number of conductive paste types, showing different properties, would be beneficial in order to understand the effect of conductive paste parameters in detail.
3. Surface modification appears to be a promising approach to improve the mechanical properties of the FSS composite structure. Instead of applying the surface modification to one of the surfaces of the FSS pattern, treating both surfaces (fabric/FSS and FSS/epoxy) with proper coupling agents would promote the interlaminar shear strength. Therefore, it is recommended to consider modifying both surfaces of the FSS pattern with proper coupling agents when mechanical property improvement is necessary.

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PUBLICATIONS

1. Ersan, T. A., Birer, O., Dalkilic, A., Inal, M. E., & Dericioglu, A. F. (2024). Fabricating X-band frequency selective surface on glass fabric by screen printing method. *IEEE Journal on Flexible Electronics*, 1–1.
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FOREIGN LANGUAGES

Advanced English, Intermediate French, Intermediate Korean.