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COMPARATIVE ANALYSIS OF EMBROIDERY AND SCREEN-PRINTING TECHNIQUES FOR TEXTILE-BASED FREQUENCY SELECTIVE SURFACES

TEKSTİL TEMELLİ FREKANS SEÇİCİ YÜZEYLER İÇİN NAKIŞ VE SERİGRAFİ TEKNİKLERİNİN KARŞILAŞTIRMALI ANALİZİ

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***ABSTRACT*:** Frequency Selective Surface (FSS) is a specialized structure used in the field of electromagnetic waves and radio frequency (RF) engineering. It is designed to exhibit selective transmission or reflection properties based on the frequency of the incident electromagnetic waves. This article describes the design, construction, and analysis of a textile-based band-stop frequency selective surface for use in the highly EM-polluted GSM, Wi-Fi, LTE, and WiMAX bands. A full-wave EM solver called CST Microwave Studio was used to develop and simulate the unit cell of the proposed FSS at the relevant frequency. In this study, embroidered and screen-printed textile based FSSs were designed. According to the results of this study, it was demonstrated that both embroidery and screen printing FSSs exhibit resonance at a frequency of 3.5 GHz. The screen printing method yielded the best results in terms of resonance frequency sensitivity, while the embroidery method showed a resonance frequency shift. It was observed that the stitch directions and density are important parameters in the embroidery method. Gaps between the embroidery paths in the production of embroidered FSSs resulted in differences from simulations due to the disruption of the structural integrity of the unit cell. Consequently, textile-based FSSs offer advantages over traditional FSSs. This study highlights the potential of textile FSSs as an effective means of reducing electromagnetic pollution, and suggests that further improvements in the design and production processes of textile FSSs can be made.

Keyword: *EM filter, FSS, Embroidery, screen printing*

TEKSTİL TEMELLİ FREKANS SEÇİCİ YÜZEYLER İÇİN NAKIŞ VE SERİGRAFİ TEKNİKLERİNİN KARŞILAŞTIRMALI ANALİZİ

***ÖZ*:** Frekans Seçici Yüzey (FSY), elektromanyetik dalgalar ve radyo frekansı (RF) mühendisliği alanında kullanılan özel bir yapıdır. FSY, gelen elektromanyetik dalgaların frekansına bağlı olarak seçici iletim veya yansıma özellikleri sergilemek üzere tasarlanmıştır. Bu makale, yüksek elektromanyetik kirlilik içeren GSM, Wi-Fi, LTE ve WiMAX bantlarında kullanılmak üzere tekstil tabanlı bir bant-durdurma frekans seçici yüzeyin tasarımını, yapımını ve analizini açıklar. Önerilen FSY'nin birim hücresini geliştirmek ve simüle etmek için CST Microwave Studio adlı tam dalga EM çözücü kullanılmıştır. Bu çalışmada, nakış ve serigrafi baskıya dayalı tekstil tabanlı FSY'ler tasarlanmıştır. Bu çalışmanın sonuçlarına göre, nakış ve serigrafi baskı FSY'lerinin 3.5 GHz frekansında rezonansa sahip olduğunu gösterdi. Serigrafi baskı yöntemi, rezonans frekansı duyarlılığı açısından en iyi sonucu verirken, nakış yönteminde rezonans frekansı kayması gözlendi. Nakış yöntemindeki dikiş yönleri ve yoğunluğunun önemli parametreler olduğu görüldü. Nakış FSY'lerinin üretiminde dikiş yolları arasındaki boşluklar, birim hücrenin yapısal bütünlüğünü bozduğu için simülasyonlarla farklılık gösterdi. Sonuç olarak, tekstil tabanlı FSY'lerin geleneksel FSY'lere göre avantajları bulunmaktadır. Bu çalışma, tekstil FSY'lerin tasarım ve üretim süreçlerinin daha da geliştirilerek, EM kirliliğini azaltmada etkili bir yol olabileceğini göstermektedir.

Anahtar Kelimeler: *EM Filtre, FSY, Nakış, Serigrafi Baskı*

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1. INTRODUCTION

In today's modern world, the increasing use of electronic devices and wireless technologies has led to a significant rise in electromagnetic pollution. The intensity of electromagnetic waves (EM waves) of various frequencies such as WiFi, Wimax, Bluetooth, 2G, 3G, and LTE is known as EM pollution. This pollution, caused by the electromagnetic radiation emitted by various sources, poses potential risks to human health and the environment. The impact of EM-wave interference on human health is the latest focal point for many scientific researches. As a result, researchers and engineers are continuously exploring innovative solutions to mitigate the harmful effects of electromagnetic pollution. One promising approach gaining attention is the utilization of Frequency Selective Surfaces (FSS) which are designed and used more than six decades for for the reduction of electromagnetic (EM) pollution.

Frequency Selective Surfaces are engineered materials or structures that possess the unique ability to selectively control the transmission and reflection of electromagnetic waves based on their frequency. These surfaces act as filters, allowing certain frequencies to pass through while blocking or attenuating others. By incorporating FSS into the design of devices and structures, it is possible to regulate and manipulate electromagnetic fields, reducing the overall electromagnetic pollution. [1].

Frequency Selective Surfaces (FSS) can be classified based on various geometries engineered to manipulate the propagation of electromagnetic waves according to their frequency characteristics. In terms of simple geometries, square and hexagonal grids are commonly used. Square grid FSS structures consist of a regular array of metallic patches or slots, offering bandpass or bandstop responses [2]. Hexagonal grid FSS structures employ a hexagonal lattice of metallic elements, providing similar frequency selective characteristics [3]. When it comes to loop shapes, circular loops and elliptical loops are widely utilized. Circular loops can be arranged in regular or irregular patterns and offer polarization-independent behavior. Elliptical loops, on the other hand, have elliptical shapes and are useful for achieving polarization-dependent characteristics [4]. In patch shapes, square and circular patches are frequently employed. FSS structures with square metallic patches exhibit simple and symmetric responses, while circular patch FSS structures offer similar characteristics with circular symmetry. Additionally, cross-shaped metallic patches arranged in a grid pattern, known as cross patches, can provide polarization-dependent responses.

Combined shapes are also utilized in FSS designs. The Jerusalem Cross, composed of four thin metallic lines forming a cross-like pattern, exhibits polarization-dependent behavior and is often used for dual-band or multi-band applications. Furthermore, FSS structures often combine different geometries such as squares, circles, or loops to achieve more complex and versatile responses, resulting in enhanced frequency selectivity and polarization properties [5].

The choice of FSS geometry depends on the desired frequency response, polarization characteristics, and specific application requirements. By leveraging simulation techniques and optimization algorithms, engineers and researchers can design and fine-tune FSS structures to meet the desired performance parameters.

Recent research efforts have focused on integrating FSSs into textiles to create wearable electromagnetic shielding solutions. Textile-based FSSs offer several advantages, such as flexibility, lightweight, comfort, and the ability to conform to various shapes and sizes. These FSSs can be woven, printed, or embroidered onto fabrics, enabling the development of electromagnetic shielding garments, curtains, and flexible enclosures. Furthermore, textile-based FSSs can be designed to be highly selective in specific frequency bands while allowing other frequencies to pass through, ensuring effective electromagnetic pollution mitigation. Textile based FSSs can be classified into the partially-textile employed the metallic conductive patches over textile substrates and fully-textile FSS where both the patch and substrate were employed as a textiles. For example, Guan et. al. studied embroidered cross shaped textile based FSS at X band freaquency. In their study, it was observed that there was small resonance differences between experimental and simulation [6].

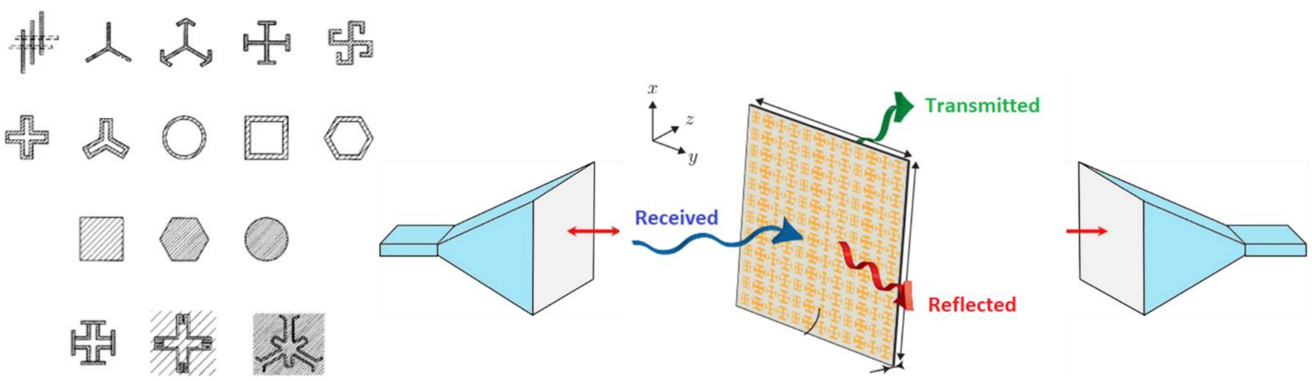

Figure 1. Shapes and princibles of FSS

Also, Uner et. al. studied embroidered FSS for GSM, Wifi and WIMAX [7]. Square loop designs in woven FSSs are frequently employed to construct high-pass filters in textile FSS research [8–10].]. Since silk screen printing delivers the right form with a small margin of error, the printing process is also promising for FSSs [11–13]. Massive pattern surfaces for embroidery may be created using CAD modeling and patterning technologies [6, 14–16].

In this study, band-stop FSS design at 3.5 GHz was made with CST microwave studio software. Embroidery and silkscreen printing methods were used for the production of optimized textile based FSS. In the study, embroidery and screenprintig FSSs were compared in terms of transmission coefficient.

2. EXPERIMENTAL STUDY

2.1. Materials

Embroidery and silk screen printing method was employed in this study. The plain weave cotton fabric was selected as the substrate for all samples: the fabric counts for warp and weft directions were 170 and 170 per 10 cm, respectively; the areal density of the fabric was 300 g/m^2; the equivalent thickness was 0.56 mm. The dielectric coefficient of fabric was determined as 1.83 in the aforementioned study [7]. The embroidery density applied in the study included 90 punch/cm^2 in complex fill and vertical onto horizontal embroidery direction was applied. Also, 80T mesh polyester silk was used for printing and silver conductive inks was carried out.

The band-stop characteristic FSS was modelled and simulated using computer simulation technology (CST) at a 3.5 GHz frequency. Also, copper tape FSS was designed to verify the simulation data.

2.2. FSS design and simulations

The unit-cell was developed in accordance with the waveguide boundary condition since the waveguide technique was employed in the study. The numerical analysis and optimization procedure for the band-stop characteristic at 3.5 GHz was carried out by CST Microwave Studio using the Jerusalem cross unit-cell, and the geometric dimensions of the unit-cell are shown in figure 2.

The scattering parameters were calculated by considering the dielectric coefficients of the fabric used in the study.

According to figure 2, it is seen that the Jerusalem cross unit-cell was fitted at a frequency of 3.5 GHz and a band-stopping characteristic was observed. In the design, the dimensions of the substrate were determined according to the WR 229 waveguide which have a frequency range of 3.3 GHz to 4.9 GHz and 58.17x29.08 mm dimension.

3. TEXTILE BASED FSS FABRICATION

Band-stop filters at the relevant frequencies are produced by textile production methods. In this process, Pfaff Creative 1.5 computerized embroidery machine was employed for embroidery process (Figure 3). While shieldex statex 117 / f 17-2 layers of silver coated nylon thread was used as upper yarn, conventional polyester yarn was prefered as a bottom yarn. In the study, two-stage embroidery design was applied in the fabrication of the embroidered FSSs. The sticth direction was utilized in the vertical direction in the 1st stage and in the horizontal direction in the 2nd stage to allow the surface current generated in the patch to move in both directions.

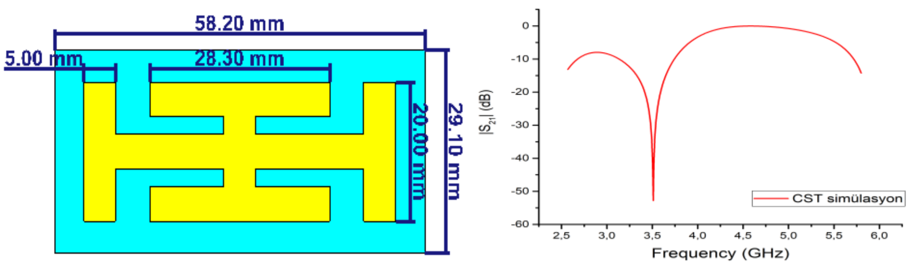

Figure 2. Jarusalem cross unitcell and transmission coefficient

Figure 3. Embroidered and Screen printed textile FSS

Embroidered FSS samples were analyzed using an image processing software (ImageJ) in terms of embroidery regularity, structural integrity of the embroidery, and the form of conductive thread. ImageJ is a popular open-source image processing and analysis software developed by the National Institutes of Health (NIH) in Java programming language. It is widely used in scientific research and provides a variety of tools for image analysis, including measurement, enhancement, filtering, and annotation. Image analysis software plays a crucial role in extracting meaningful insights from images by enabling both qualitative and quantitative analysis of their characteristics. This analytical approach offers valuable information about the examined material. By employing image analysis software, researchers can swiftly and consistently assess image quality, eliminating subjective biases. Consequently, the utilization of such software in scientific studies is on the rise due to its ability to provide efficient and reliable results [17].

Novacentrix silver conductive ink is preferred for screen printing. Screen printing process including lacquer drawing, exposure and printing steps is performed, and then pre-drying at 120 ^oC for 20 minutes and sintering at 200 ^oC for 1 minute.

4. TESTING METHOD

Waveguides were used in both simulation and measurement setups to analyze unit cell responses. For this purpose, the Pasternack WR-229 waveguide (2.29 Inch [58,166 mm] x 1.145 Inch [29,083 mm]) with a frequency range of 3.3 GHz to 4.9 GHz was employed. Since the unit cell was designed according to the waveguide boundary conditions, the side lengths of the unit cell were defined as having the length value and the width value of waveguide. The textile substrate with thickness value 0,56 mm was considered as substrate with permeability value 1.83 and the resonator model was proposed.

Pasternack WR-229 waveguide was connected to Rohde & Schwarz ZVL13 Vector Network Analyzer, which is capable of measuring a frequency interval of 9 kHz - 13.6 GHz, and the cross-section of the waveguide was shown in Figure 4.

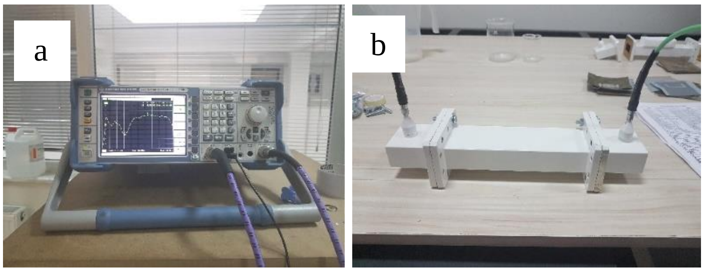

Figure 4. Measurement setup, Network analyzer (a), WR 229 waveguide (b)

5. RESULT AND DISCUSSION

Studies in the literature show inconsistencies between the experimental measurements of textile-based FSSs and the simulations. In particular, the conductivity and geometry differences between the copper tape model and the textile experiments are decisive in this regard.

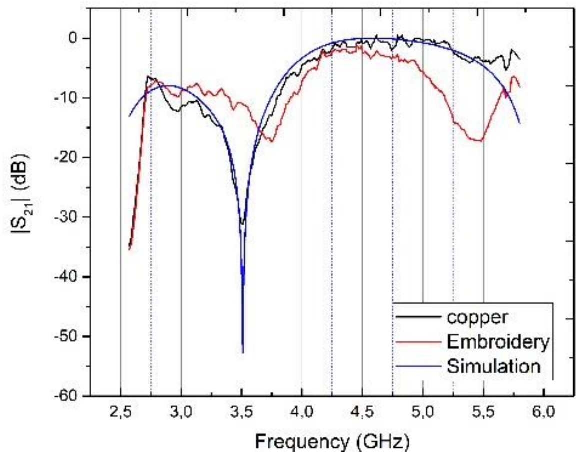

Figure 5. S-parametres of embroidered FSS

According to figure 5, as expected from the literature, there is resonance in embroidery and copper tape FSS at 3.5 GHz. The resonance is observed at around -30dB at 3.5GHz at copper tape and -18 dB at embridered FSS. Also, resonance shifting occurs as expected from study [6]. When the embroidered FSS patch surface is examined in detail, it is seen that the stitch directions and density are important parameters. The gaps between the embroidery paths in both directions are analyzed with the help of ImageJ (Figure 6) and measurement data is given in the table 1.

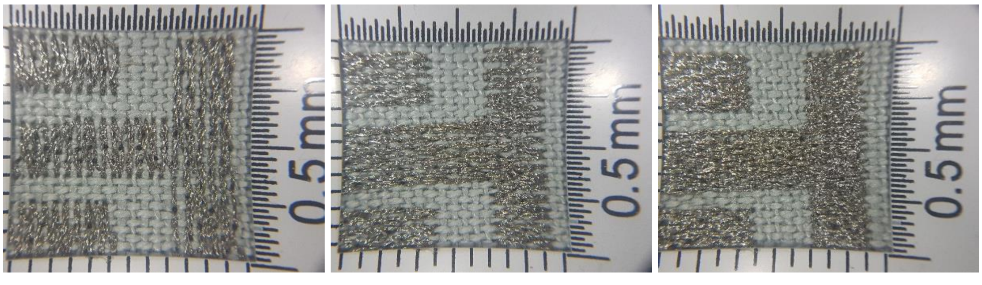

Figure 6. Details of embroidery directions

Table 1. Measurements of stitch gaps

Count No	Vertical Stitch Gap (mm)	Horizontal Stitch Gap (mm)
1	1.161	0.388
2	0.581	0.504
3	0.677	0.659
4	0.645	0.233
5	0.645	0.349
6	0.516	0.426
7	0.613	0.426
8	0.419	0.233
9	0.452	0.388
10	0.613	0.388
11	0.871	0.388
12	0.516	0.388
13	0.452	0.388
14	0.677	0.504
15	0.742	0.426
16	0.581	0.31
17	0.581	0.31
18	0.548	0.426
19	0.387	0.388
20	0.935	0.504
Mean	**0.631**	**0.401**
SD	0.186	0.097
Min	0.387	0.233
Max	1.161	0.659

According to table 1, both vertical and horizontal directions have approximately 0.5 mm stitch gaps. It is possible to say that the gaps between the stitch paths disrupt the structural integrity of the unit cell. These design and manufacturing limitations cause differences between simulation and embroidered FSS resonance frequencies.

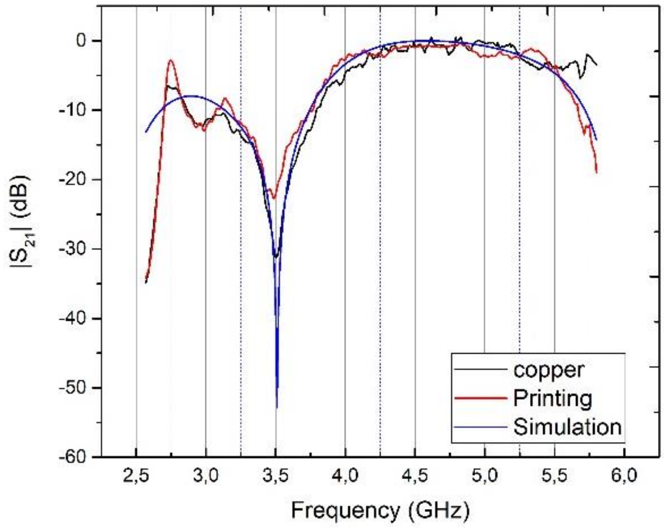

Figure 7. S- parametres of screen printing FSS

As can be seen in figure 7, there is resonance in screen printing and copper tape FSS at 3.5 GHz. The resonance is observed at around -30dB at 3.5GHz at copper tape and -23 dB at screen printed FSS. There is no resonance shifting between simulation, copper tape, and screen printing FSS. The unit cell pattern fabricated by the screen printing method structurally has the same structural integrity as the copper tape. therefore, it performs a filtering characteristic quite compatible with the copper tape and simulation.

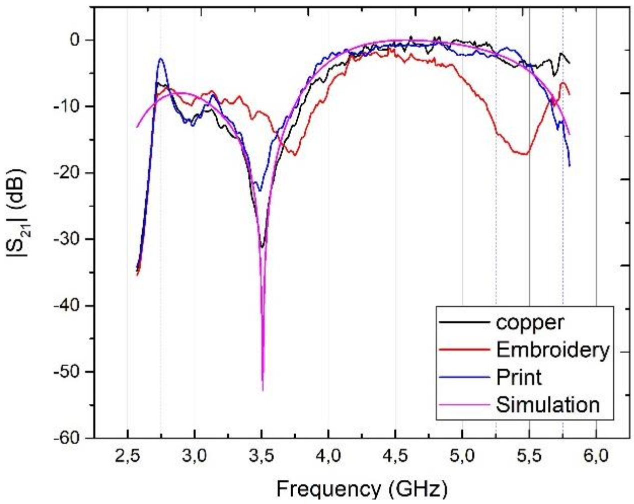

Figure 8. Transmission coefficient of textile based FSSs

Among all the methods, the screen printing exhibits the best result in terms of resonance frequency sensitivity. In contrast to screen printing, resonance frequency shift occurred in embroidered FSS (Figure 8). It can be said that the parameters of the embroidery process such as direction, stitch density have an effect on the scattering parameters.

5. CONCLUSION

Embroidery and screen-printing techniques have been used to fabricate the conductive patches in textile-based FSSs. While silver-coated conductive thread is used in the embroidery technique, conductive ink with silver nanoparticles is used in screen printing. In this study, horizontal onto vertical stitch direction and 90 punch/cm^2 stitch density are applied in embroidery process. The transmission coefficient of embroidered FSS is around 3.75 GHz and approximately 0.25 GHz resonance shifting is occurred. In embroidered FSS, the attachment of the conductive yarn to the fabric by needle prick movements and the presence of small gaps between the parallel penetrating paths can be considered as structural defects on the patch surface. As a matter of fact, in 3D CST modelling, the patch surface is modelled with perfect roughness. therefore, resonance frequencies in copper tape and silkscreen printed FSSs are identical to simulation. As a result of the study, the usability of the textile mass production method in the design of textile-based FSSs has been proven. Also, 3D modelling and simulations of embroidery parameters are appropriate for a better understanding of stitch direction and density.

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