Research Article

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Complementary frequency selective surface pair-based intelligent spatial filters for 5G wireless systems

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Abstract: Frequency selective surface (FSS)-based intelligent spatial filters are capturing the eyes of the researchers by offering a dynamic behavior when exposed to the electromagnetic radiations. In this manuscript, a concept of creating complementary structures which stems from Babinet's principle is illustrated. A hybrid complementary pair of FSS (CPFSS) comprising double square loop FSS (DSLFFSS) and double square slot FSS (DSSFSS) on either side of the dielectric substrate is proposed. DSLFFSS offers band-pass behavior and can be placed as a superstrate, whereas DSSFSS behaves as a band-stop intelligent spatial filter that blocks the radiations falling on it, thus making them applicable for use as a substrate. The technique utilized for analyzing DSLFFSS and DSSFSS structures is based on the equivalent circuit modeling and transmission line methodology. The CPFSS structure offers the design simplicity, hence, suitable for placing them with the printed patch antenna radiators in wireless networking devices operating in sub-6 GHz 5G spectrum. DSLFFSS offers band-pass behavior ranging from 2.99 to 5.56 GHz, whereas DSSFSS offers band-stop behavior ranging from 2.85 to 5.42 GHz covering all n77 (3.3–4.2 GHz), n78 (3.3–3.8 GHz), and n79 (4.4–5 GHz) bands of FR1 spectrum of sub-6 GHz 5G range. The passband and the stopband offered by the two structures of CPFSS geometry are stable to oblique angles of incidence and the proposed design also offers polarization-independent behavior. The thickness of the dielectric region existing within the pair of designed structures is critical for the location of the passbands and the stopbands. The impact of the overall thickness of the dielectric substrate on the passbands and stopbands is also reported in this article.

Keywords: Babinet's principle, frequency selective surface, double square loop FSS, double square slot FSS, complementary pair FSS, equivalent circuit model, sub-6 GHz FR1 5G spectrum

1 Introduction

Intelligent spatial filters protect a wireless system from the interference of the unwanted signals sent by other electronic devices. These filters have a built-in frequency selector that improves transmitter output when used. Frequency selective surfaces (FSSs) have attracted a lot of attention in recent years as a means of being incorporated as intelligent spatial filters because they can impart diagnostic properties in the intelligent spatial domain [1]. Figure 1 shows the filtering function of FSS, which allows required radiations

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Figure 1: Illustration of the working of FSS layers based on different element designs.

to go through it while suppressing all unwanted signals. These layers consist of regular structures ordered in a periodic pattern and show the filtering features of either a band-pass or a band-stop filter. The use of wireless technologies has grown dramatically for telecommunication systems because of providing an additional benefit of allowing us to be physically free from cabling. The problems encountered in wireless networking devices are to ensure the information flow without any loss and interference. Intruders can hack information from wireless networking devices at radio frequencies of operation. Microwaves, infrared, and other visible frequencies are processed or blocked by these surfaces [2]. An important application of FSS as intelligent spatial filters is in the form of a band-stop FSS which can be posted on walls of buildings for providing structural health monitoring and safety of sensitive devices. Also, FSSs are employed in wireless local area networking for allowing useful radio frequency signals to pass through while blocking all other signal frequencies due to FSS's selective nature. The most basic feature is on microwave oven doors, which allows us to see the food being cooked without transferring any heat through the transparent plate. At the harmonic resonance for which they are designed, these surfaces show filtering properties by reflection or propagation. These surfaces are usually created by assembling structures with random geometries in a regular pattern [3,4]. In the recent times, more innovative FSS screens are developed based on the thermoelectric materials which are targeted for usage in terahertz frequency range [5]. As shown in recent years, research has attempted to assemble and suggest various geometric structures that can be used in the wavelengths, such as a square-shaped triangle, concentric ring, ellipsoid, hexagonal geometry, and a cross dipole [6–8]. These intelligent spatial filters play a variety of roles in the control of electromagnetic flow in telecommunications. FSS has been used for electromagnetic shielding such that it allows for the passage of specific frequencies while maintaining angular stability. Other uses include radomes, which protect antennas from high temperatures and electromagnetic interference. These structures also serve as a sub-reflector above high gain radiators which usually require different transmissive and reflective bands [9].

FSSs have been increasingly important in the filtering of electromagnetic radiations and are employed in wireless communication in the present era. The spectral responses are determined by the element geometry, gaps between individual elements, and the choice of the dielectric substrate. The study of the characteristics of FSS constitutes an analysis of a unit cell (i.e., the shape of the element implemented on a substrate with a particular periodicity) arranged in a periodic fashion and illuminated uniformly. The arrangement resembles such that an infinite number of elements are arranged in a periodic geometric fashion. The synthesis of the periodic FSS gratings may be done using the concept of Floquet theory [1–3]. The Floquet theory proposes a strategy for investigating structure behaviors with a periodic configuration [10].

In this article, a comparative analysis for complementary FSS-based intelligent spatial filters, which is based on the numerical synthesis technique and the output characteristics, is presented. Using Babinet's principle, a complementary pair of double square loop FSS (DSLFFS) and double square slotted FSS

(DSSFSS) geometries are developed which exhibit a band-pass and a band-stop behavior in the lower bands of the microwave spectrum. The synthesis technique illustrated in this article is based on the equivalent circuit (EC) model analysis, which offers simplicity along with the larger computations in a short span. The comparison is done based on the output characteristics of the intelligent spatial filters created using DSLFSS and DSSFSS structures. Also, the detailed descriptive analysis about the parameters affecting the performance of both structures is given. Parametric optimization is carried out using ANSYS high frequency structure simulator (HFSS). The designed prototype is fabricated and measurements are performed for validating the results. Henceforth, the orientation of the rest of the manuscript comprises geometric design of the complementary FSS with mathematical formulations in Section 2. The parametric optimizations with the effect of variation of the parameters on the output performance characteristics are presented in Section 3, and the concluding statement is given in Section 4.

2 Design of complementary FSS

CPFSS can be made using DSLFSS and DSSFSS geometries of the intelligent spatial filters such that when they are stacked on top of each other, they form a complete perfectly conducting plane. The construction of complementary pair of intelligent spatial filters using FSS is based on Babinet's principle which states that complementary pair depicts opposite filtering behavior [11]. According to this principle, the propagation coefficient for one array of FSSs is equal to the reflection coefficient for the other complementary array of intelligent spatial filters. It is important to mention that the thickness of the metal sheet must be taken into consideration for the accurate construction of intelligent spatial filters. Depending upon the thickness of the metal sheet, we can vary the bandwidth of the designed geometry. In this article, CPFSS has been designed by making use of the traditional DSLFSS and the DSSFSS geometries which are printed on a thin dielectric spacer as shown in Figure 2. The transmission line model has been utilized for formulating the overall impedance offered by the dielectric substrate and evaluating its coupling effect on the FSS elements. Resonance matching is attained when both the complementary structures are excited by an incident plane wave under normal conditions and the structures are excited by the induced currents.

The reflections from the FSS-based intelligent spatial filters are measured in terms of reflection coefficients which attain different values based on the type of polarization of the incident electromagnetic wave and are defined as follows [12]:

$$\Gamma_{\text{TEco}}(f) = \frac{\frac{1}{X_{\text{rad,TE}}} - \frac{1}{X_{\text{rad,TM}}} - \frac{1}{X_0} - \frac{2j(f-f_r)}{f_r}}{\frac{1}{X_{\text{rad,TE}}} + \frac{1}{X_{\text{rad,TM}}} + \frac{1}{X_0} + \frac{2j(f-f_r)}{f_r}}, \quad (1)$$

$$\Gamma_{\text{TMco}}(f) = \frac{\frac{1}{X_{\text{rad,TM}}} - \frac{1}{X_{\text{rad,TE}}} - \frac{1}{X_0} - \frac{2j(f-f_r)}{f_r}}{\frac{1}{X_{\text{rad,TM}}} + \frac{1}{X_{\text{rad,TE}}} + \frac{1}{X_0} + \frac{2j(f-f_r)}{f_r}}, \quad (2)$$

$$\Gamma_{\text{Cross}}(f) = \frac{\frac{2}{\sqrt{X_{\text{rad,TE}}X_{\text{rad,TM}}}}}{\frac{1}{X_{\text{rad,TM}}} + \frac{1}{X_{\text{rad,TE}}} + \frac{1}{X_0} + \frac{2j(f-f_r)}{f_r}}, \quad (3)$$

where Γ_{TEco} is the co-polar reflection coefficient of transverse electric mode, Γ_{TMco} is the co-polar reflection coefficient of transverse magnetic mode, Γ_{Cross} represents reflection coefficient due to cross polarization, $X_{\text{rad,TE}}$ and $X_{\text{rad,TM}}$ are defined as the radiation factors for transverse electric (TE) and transverse magnetic (TM) modes, respectively. The notation f denotes the operating frequency, f_r denotes the resonant frequency, and X_0 is given by the parallel combination of conductor loss and dielectric loss which is defined by equation (4) as follows:

Figure 2: Configuration of FSS, (a) unit cell of CPFSS comprising DSLFSS and DSSFSS, (b) top layer consisting of DSLFSS, (c) bottom layer consisting of DSSFSS, (d) 2×2 DSLFSS fabricated array, and (e) 2×2 DSSFSS fabricated array.

$$X_0 = \frac{X_c X_d}{X_c + X_d}, \quad (4)$$

where the conductor loss (X_c) is defined as:

$$X_c = h\sqrt{\pi f \mu \sigma}, \quad (5)$$

and the dielectric loss (X_d) as:

$$X_d = \frac{1}{\tan \delta}. \quad (6)$$

In equation (5), h denotes the overall thickness of the substrate, μ denotes the permeability, σ denotes the conductivity of the conductor, and δ is the phase difference, respectively. Furthermore, general equation for X_{rad} can be formulated as:

$$X_{\text{rad}} = 2\pi f_r \frac{W_s}{P_{\text{rad}}}, \quad (7)$$

where W_s and P_{rad} denote the energy stored in the radiator and the power radiated from the radiator at an excited mode, respectively. EC analysis is utilized for analyzing the performance of the designed CPFSS pair of the DSLFSS and DSSFSS geometries. Mathematical formulations are made for predicting the performance of the complementary pair of FSS structures. The EC model of CPFSS geometry is described in Figure 3. The DSLFSS is formulated as a serial combination of inductance (L) and capacitance (C), while its complementary structure is modeled as a parallel combination of L and C . The mutual coupling between two layers is modeled by the use of mutual conductance (M). The substrate layer between the two layers of CPFSS acts as a short transmission line. The EC model is often used for calculating the true and imaginary components of the structure's surface impedance.

Figure 3: EC model of the CPFSS comprising DSLFSS and DSSFSS structures.

The values of lumped circuit elements are derived from the EC model analysis which further depends upon the values of periodicity (p), the width of the square loop (s), incidence angle (θ , ϕ) and on the mode of incidence, i.e., either TE or TM. So, when the TE plane-polarized wave is incident on the surface then the EC elements for each square loop structure can be extracted as [13]:

$$X_{L_{\text{Loop}}} = \frac{\omega_r L_{\text{Loop}}}{Z_0} = \frac{d}{p} \cos(\theta) F(p, 2s, \lambda, \theta), \quad (8)$$

where

$$F(p, 2s, \lambda, \theta) = \frac{p}{\lambda} \left[\ln \left(\csc \left(\frac{\pi s}{p} \right) \right) + G(p, s, \lambda, \theta) \right]. \quad (9)$$

Also,

$$X_{C_{\text{Loop}}} = \frac{\omega_r C_{\text{Loop}}}{Y_0} = \frac{4d}{p} \sec(\theta) F(p, g, \lambda, \theta) \varepsilon_{\text{eff}}, \quad (10)$$

where ε_{eff} , Z , and Y are the effective permittivity of the surface, the impedance, and the admittance, respectively. The parameter $F(p, g, \lambda, \theta)$ is given by:

$$F(p, g, \lambda, \theta) = \frac{p}{\lambda} \left[\ln \left(\csc \left(\frac{\pi g}{2p} \right) \right) + G(p, g, \lambda, \theta) \right]. \quad (11)$$

In the above-mentioned equations, the terms ε_{eff} , Z_0 , Y_0 , $G(p, g, \lambda, \theta)$, and $G(p, s, \lambda, \theta)$ denote the effective dielectric permittivity of the designed FSS, characteristic impedance of the engineered FSS structure, the characteristic admittance of the structure, and the correction terms for the values of the inductance and capacitance associated with the designed FSS surface, respectively. In ref. [14], Archer has evaluated the value of normalized wave reactance and has given some generalized expressions for the correction terms mentioned in equations (8)–(11). The first-order correction term $G()$ was identified to be evaluated as:

$$G(p, g, \lambda, \theta) \quad \text{or} \quad G(p, s, \lambda, \theta) = \frac{A}{B}, \quad (12)$$

where

$$A = 0.5(1 - \beta^2)^2 \left[\left(1 - \frac{\beta^2}{4} \right) (C_{+1} + C_{-1}) + 4\beta^2 C_{+1} C_{-1} \right], \quad (13)$$

$$B = \left(1 - \frac{\beta^2}{4} \right) \beta^2 \left(1 + \frac{\beta^2}{2} - \frac{\beta^2}{8} \right) (C_{+1} + C_{-1}) + 2\beta^6 C_{+1} C_{-1}, \quad (14)$$

where $\beta = \frac{\sin \theta}{\sin \theta_0}$. Also, the terms related to first-order coefficients are calculated as:

$$C_n = \frac{1}{tS_n} - \frac{1}{\text{mod}(n)}; \quad n = \pm 1, \pm 2, \dots \quad (15)$$

For TE incident ray:

$$S_n t = \sqrt{\left(\frac{p \sin \theta}{\lambda} \pm n \right)^2 - \frac{p^2}{\lambda^2}}. \quad (16)$$

For TM incident ray:

$$S_n t = \sqrt{\left(\frac{p \sin \theta}{\lambda} \right)^2 + n^2 - \frac{p^2}{\lambda^2}}. \quad (17)$$

So, to make our computations easier, we ignore correction factor terms at the stake of minor deviations in our end results which are depicted in equations (9) and (11), respectively.

$$\frac{\omega_r L}{Z_0} = \frac{d}{p} \cos(\theta) \frac{p}{\lambda} \ln \left[\csc \left(\frac{\pi s}{2p} \right) \right], \quad (18)$$

$$\frac{\omega_r C}{Z_0} = \frac{4d}{p} \sec(\theta) \frac{p}{\lambda} \ln \left[\csc \left(\frac{\pi g}{2p} \right) \right] \epsilon_{\text{eff}}. \quad (19)$$

Equations (18) and (19) are only valid if we have $s \ll p$, $d \ll p$, and $p \ll \lambda$. Considering air as a substrate and after multiplying equations (18) and (19), we get:

$$\omega_r^2 LC = 4 \left(\frac{d}{p} \right)^2 \left(\frac{p}{\lambda} \right)^2 \ln \left[\csc \left(\frac{\pi s}{2p} \right) + \csc \left(\frac{\pi g}{2p} \right) \right]. \quad (20)$$

In equation (20), the left-hand side depicts the resonance phenomenon and is termed as a measure of quality factor for square loop geometry. Also, the total impedance of the double square loop structure is given by:

$$Z_{\text{Loop}} = (X_{L1\text{Loop}} + X_{C1\text{Loop}}) || (X_{L2\text{Loop}} + X_{C2\text{Loop}}). \quad (21)$$

Furthermore, for its complementary pair which is composed of the DSSFSS geometry, the EC analysis is given by [15]:

$$X_{L1} = \frac{\omega_r L_1}{Z_0} = F(p, g, \lambda, \theta), \quad (22)$$

$$X_{L1\text{slot}} = X_{L2\text{slot}} = \frac{\omega_r L_{\text{slot}}}{Z_0} = X_{Ls1} + \left(\frac{s}{d - 2s + g} \right) X_{L1}, \quad (23)$$

where

$$X_{Ls1} = \frac{p - 2s}{p} F(p, d - 2s, \lambda, \theta). \quad (24)$$

Also, the equivalent capacitance values from the slotted structure can be evaluated as:

$$B_{c1} = \omega_r C_1 = 4F(p, d, \lambda, \theta), \quad (25)$$

$$B_{c2} = \omega_r C_2 = 4F(p, d - s, \lambda, \theta), \quad (26)$$

$$B_{c1\text{slot}} = B_{c2\text{slot}} = \frac{\omega_r C_{\text{slot}}}{Y_0} = (1.75B_{c1} + 0.6B_{c2})\epsilon_{\text{eff}}. \quad (27)$$

Also, ϵ_{eff} denotes the effective dielectric constant of the substrate and can be evaluated as:

$$\epsilon_{\text{eff}} = \begin{cases} \frac{\epsilon_{\text{eff}} + 1}{2} - \left(\frac{\epsilon_{\text{eff}} - 1}{2} \right) e^{-\frac{13H}{p}} - \left(\frac{100s^2}{d} - 2g + 10H \right); & \text{for loop structure} \\ \frac{\epsilon_{\text{eff}} + 1}{2} - \left(\frac{\epsilon_{\text{eff}} - 1}{2} \right) e^{-995H} - \left(\frac{155s^2}{d} \right); & \text{for slot structure,} \end{cases} \quad (28)$$

where the terminologies X_{g1} and X_{g2} are given as:

$$Z_{\text{slot}} = X_{g1} || X_{g2}, \quad (29)$$

$$X_{g1} = j\omega_r L_1, \quad (30)$$

and

$$X_{g2} = j \left(\omega_r L_2 - \frac{1}{\omega_r C_{\text{slot}}} \right). \quad (31)$$

Thus, the overall input intrinsic impedance of the CPFSS structure is given by:

$$Z_{\text{in}} = Z_{\text{loop}} || Z_{\text{d}}, \quad (32)$$

where the terms Z_{loop} denotes the overall impedance of the square loop and Z_d denotes the intermediate impedance offered by the dielectric substrate which is given by:

$$Z_d = Z_{01} \frac{Z_{\text{slot}} + jZ_{01} \tan(\beta H)}{Z_{01} + jZ_{\text{slot}} \tan(\beta H)}. \quad (33)$$

The term Z_{slot} in the above equation represents the impedance offered by the square slots, Z_{01} is the intrinsic impedance, and β denotes the phase constant of the transmission line engraved in dielectric substrate with height H , respectively. Finally, the transmission coefficient (T) of the CPFSS geometry is given by:

$$T = 1 - |\Gamma|. \quad (34)$$

The term Γ denotes the reflection coefficient and is given by:

$$\Gamma = \frac{Z_{\text{in}} - Z_0}{Z_{\text{in}} + Z_0}. \quad (35)$$

In the above equation, the term Z_0 corresponds to free space impedance. The above equations are used to characterize the performance of the proposed CPFSS design to behave as a perfect conducting plane by making combination of band-pass and band-stop filters in intelligent spatial domain. The resonant frequencies of the designed structure can be determined by applying the concept of LC circuits as shown below:

$$\omega_{r1} = \frac{1}{\sqrt{L_1 C_1}}; \quad \omega_{r2} = \frac{1}{\sqrt{L_2 C_2}}, \quad (36)$$

where ω_{r1} and ω_{r2} are the resonant frequencies achieved due to each loop and slot independently and L_1 , C_1 , L_2 , and C_2 are the inductance and capacitance associated with each concentric loop and slot. Maximum induced current distribution is achieved in the DSLFSS and DSSFSS at the resonant frequencies of operation resulting in a transmission null as at this point all the incident power is radiated back. The parametric details are illustrated in Figure 4, and the detailed dimensions of the DSLFSS and DSSFSS are mentioned in Table 1.

Figure 4: Unit cell configurations of (a) DSLFSS and (b) DSSFSS.

The terms mentioned in Table 1 are briefed as: f_{r1} and f'_{r1} : lower resonant frequency of operation of DSLFSS and DSSFSS structures; f_{r2} and f'_{r2} : higher resonant frequency of operation of DSLFSS and DSSFSS structures; λ_{mid} : the wavelength at a center frequency of operation, i.e., 4.15 GHz; p : the value of periodicity fixed for DSLFSS and DSSFSS structures; d_1 : length of the outer loop of DSLFSS; d_2 : length of the inner loop

Table 1: Unit cell dimensions of DSLFSS and DSSFSS geometries for CPFSS structure

S. no.	Structure (filter characteristics)	Parameter	Value
1	DSLFSS (band-pass filter)	f_{r1} (GHz)	2.99
2	DSLFSS (band-pass filter)	f_{r2} (GHz)	5.56
3	DSLFSS (band-pass filter)	p	$0.41\lambda_{\text{mid}}$
4	DSLFSS (band-pass filter)	s_1	$0.041\lambda_{\text{mid}}$
5	DSLFSS (band-pass filter)	s_2	$0.027\lambda_{\text{mid}}$
6	DSLFSS (band-pass filter)	d_1	$0.38\lambda_{\text{mid}}$
7	DSLFSS (band-pass filter)	d_2	$0.14\lambda_{\text{mid}}$
8	DSSFSS (band-stop filter)	f'_{r1} (GHz)	2.85
9	DSSFSS (band-stop filter)	f'_{r2} (GHz)	5.41
10	DSSFSS (band-stop filter)	p'	$0.41\lambda_{\text{mid}}$
11	DSSFSS (band-stop filter)	s'_1	$0.02\lambda_{\text{mid}}$
12	DSSFSS (band-stop filter)	s'_2	$0.19\lambda_{\text{mid}}$
13	DSSFSS (band-stop filter)	d'_1	$0.38\lambda_{\text{mid}}$
14	DSSFSS (band-stop filter)	d'_2	$0.34\lambda_{\text{mid}}$
15	DSSFSS (band-stop filter)	d'_3	$0.11\lambda_{\text{mid}}$

of DSLFSS; s_1 : the thickness of the outer loop of DSLFSS; s_2 : the thickness of the inner loop of DSLFSS, d'_1 : length of an outer slot of DSSFSS; d'_2 : length of the inner part of an outer slot of DSSFSS; d'_3 : length of the innermost metallic part of DSSFSS; s'_1 : thickness of the outer slot of DSSFSS; and s'_2 : thickness of the inner slot of DSSFSS. Figure 5 depicts scattering parameters for a two-port network. A scattering parameter relationship is defined as $|S_{11}|^2 + |S_{21}|^2 = 1$ and is valid for lossless conditions, where $|S_{11}|$ and $|S_{21}|$ are the reflection coefficient and transmission coefficient, respectively. It specifically shows that the responses of $|S_{11}|$ and $|S_{21}|$ are reciprocal within operating spectrum.

Figure 5: Two-port network.

$$b_1 = a_1 S_{11} + a_2 S_{12}; \quad b_2 = a_1 S_{21} + a_2 S_{22}, \quad (37)$$

where b_1, b_2 are output coefficients and a_1, a_2 are the input coefficients. S_{11} is the input reflection coefficient, S_{12} is the reverse transmission gain, S_{21} is the forward transmission gain, and S_{22} is the output reflection coefficient.

$$S_{11} = \left| \frac{b_1}{a_1} \right|, \quad a_2 = 0 \text{ (port-1)}; \quad S_{12} = \left| \frac{b_1}{a_2} \right|, \quad a_1 = 0 \text{ (port-1)} \quad (38)$$

$$S_{22} = \left| \frac{b_2}{a_2} \right|, \quad a_1 = 0 \text{ (port-2)}; \quad S_{21} = \left| \frac{b_2}{a_1} \right|, \quad a_2 = 0 \text{ (port-2)}. \quad (39)$$

The analyses of DSLFSS and DSSFSS are completed by using equivalent circuit modeling (ECM). Also, the scattering parameters are related to impedance offered by the designed structure by following relation [16]:

$$Z_{11} = \left[\frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}} \right] Z_0, \quad (40)$$

$$Z_{11} = \left[\frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}} \right] Z_0, \quad (41)$$

$$Z_{11} = \left[\frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}} \right] Z_0, \quad (42)$$

$$Z_{11} = \left[\frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}} \right] Z_0, \quad (43)$$

where Z_0 denotes the characteristic impedance of the designed geometry.

Resonance phenomenon in CPFSS is studied by performing simulations of the proposed design of DSLFSS and DSSFSS geometries and comparing the reported results for transmission coefficients using scattering matrix as shown in Figure 6. It is clearly indicated that the DSLFSS acts as a band-pass intelligent spatial filter and is best suited for applying in the superstrate of the antenna. Also, the transmission coefficients of the DSSFSS geometry indicate its intelligent spatial band-stop characteristics making it best suitable to be added as a substrate in the patch antenna design. The complementary pair of DSLFSS and DSSFSS termed as CPFSS helps to increase the performance of the printed patch antennas by mitigating the interferences and preventing radiation losses.

Figure 6: Transmission coefficient of the DSLFSS and DSSFSS geometries of the CPFSS.

The efficiency of the modeling equations extracted from ECM as illustrated in Section 2 has been verified with full-wave simulation using ANSYS HFSS software based on FEM technique, and the comparison is shown in Figure 7. However, it is worth mentioning here that analysis through ECM technique needs initial knowledge of design parameters and the electromagnetic behavior which has a great impact on the transmission coefficients. Whereas, by using full-wave simulation technique, an additional degree of freedom is there with researchers for optimizing the design of intelligent spatial filters.

Figure 7: Comparison of the scattering parameters of the CPFSS structures using ECM and FEM (HFSS).

3 Parametric analysis

When FSSs are used as intelligent spatial filters with the printed patch antenna radiators, then it is important to have prior knowledge of the variation in the output characteristics with respect to the angle of incidence and at different polarization angles. The effectiveness of the CPFSS structure is validated by varying angles of incidence (θ) and polarization (ϕ), for which response is recorded. As per the simulations reported in Figure 8, it is seen that the proposed CPFSS design is exhibiting stable resonance characteristics for the wide range of variation of incidence angles ranging from 0 to 60°. So, the proposed CPFSS design made up of complementary pair of DSLFSS and DSSFSS offers an added advantage of stability to wide oblique incidence angles.

Figure 8: Transmission coefficient of the CPFSS structure at different incidence angles (DSLFSS shows transmission while DSSFSS shows reflection).

Furthermore, the angle of polarization plays a vital role in determining the characteristics of the FSS-based intelligent spatial filters. The effect of variation of the angle of polarization is studied for the designed geometry and is shown in Figure 9. It is clearly indicated that within the range of 0–60°, the designed CPFSS geometry shows a stable response which makes our design polarization insensitive.

Figure 9: Transmission coefficient of the CPFSS structure at different polarization angles.

The performance analysis of the CPFSS structure comprising square-shaped loop and slot structures has been completed in previous research studies [17]. The effect of height of the substrate plays a vital role in managing the bandwidth of the printed patch radiator but at the cost of losses. In this work, the variations of the transmission coefficients are studied by varying the overall thickness of the substrate. As the dielectric substrate on which the complementary pair of FSS has engraved acts as a buried capacitor, whose overall capacitance is inversely proportional to the thickness of the substrate. The effect of substrate height on the transmission coefficient is computed. It is found that the resonance characteristics are slightly shifting to lower frequencies as the overall thickness is increased. So, the effect of the thickness of the substrate (H) on the output transmission coefficient of the designed CPFSS structure must be reported. Hence, variation of the thickness of the substrate is done and the results retrieved are compared in Figure 10.

According to the Floquet theory, the characteristics of the FSSs are identical when extended to an array, which is the combination of the unit cells [18]. Hence, the dimensions of the unit cell of both DSLFSS and

Figure 10: Variation in the transmission coefficient characteristics of the CPFSS structure at different thicknesses (H) of the dielectric substrate.

DSSFSS structures are replicated for all elements of an array. Using this theory, the analysis has been extended for developing a 2×2 CPFSS array which may be generalized into an $N \times N$ array. A novel schematic of CPFSS is used to make a prototype with desired characteristics. This CPFSS structure is built by using a simple configuration of single surface layers. The structure built is meant to be utilized for printed patch antenna radiators operating in sub-6 GHz 5G frequency bands of operation. The frequency response of the prototype was tested for both the normal angle of incidence and the oblique angle of incidence. The measurement results were in good agreement with simulation results. Minor fluctuations and discrepancies which have occurred between the simulation and measurement results may be because of the tolerances involved in the fabrication process and also due to numerical errors in simulations. The experimental setup was arranged as visualized in Figure 11. The transmission coefficient parameter is measured for the complementary pair of FSS-based intelligent spatial filter made by the combination of DSLFSS and DSSFSS and is placed in between two horn antennas. Vector network analyzer helps us in providing an input excitation and its one port is connected with horn antennas at the transmitter end by using a coaxial cable, whereas the second port is connected to the receiver horn antenna, which is meant for capturing received radiations through a coaxial cable.

Figure 11: Experimental set up for measuring the transmission coefficient of the CPFSS.

An angle of incidence independent and polarization-tolerant CPFSS structure with a broad operating bandwidth in the sub-6 GHz FR1 5G frequency spectrum is defined in this article. The design is realized on a single layer by arranging a combination of metallic DSLFSS/DSSFSS structures on a 1.6 mm thick FR4 dielectric substrate with a loss tangent of 0.02 and a relative permittivity of 4.4. The dimension of DSLFSS for operation as band-pass filter is optimized using parametric sweep in such a way that -3 dB transmission bandwidth comes out to be 2,570 MHz from 2.99 to 5.56 GHz and for DSSFSS the stop-band attains a bandwidth of 2,560 MHz ranging from 2.85 to 5.42 GHz covering all n77 (3.3–4.2 GHz), n78 (3.3–3.8 GHz), and n79 (4.4–5 GHz) bands of FR1 spectrum of sub-6 GHz 5G range. The measurement results extracted in the free space environment conditions are in accordance with the simulated ones, as shown in Figure 12. The minor variations, as shown in Figure 12, between the measured and simulated transmission coefficients are due to fabrication losses and errors in measurements, which might have occurred in orienting the CPFSS sample.

The advantages of the proposed CPFSS design to be used as superstrate and substrate with printed patch antenna design are compared with the state-of-art literature as described in Table 2. The comparison is done on the basis of design parameters such as thickness, size, and dielectric constant of the substrate along with the bandwidth performance. In the state-of-art literature as stated, the limitations were reported in the form of limited bandwidth, high structural complexity, etc. Also, the angular stability was not fully investigated. All these issues were addressed in the proposed design as illustrated. The proposed design finds its best usage in the following applications: spatial filters: The CPFSS design is used as a spatial filter

Figure 12: Simulated versus measured transmission coefficients of the CPFSS structure.

Table 2: Comparison of the proposed CPFSS design with the existing designs available in the literature

Ref.	H	Unit cell size	ϵ_r	FBW (%)	Geometries utilized	Remarks
[19]	—	$0.175 \times 0.175 \lambda_{\text{mid}}^2$	2.1	37	Double square double cross loops	Limited BW
[20]	$0.046 \lambda_{\text{mid}}$	$0.18 \times 0.18 \lambda_{\text{mid}}^2$	2.2	34	DSL with gridded square loops	Complex structure
[21]	$0.003 \lambda_{\text{mid}}$	$0.26 \times 0.26 \lambda_{\text{mid}}^2$	3.5	46	Modified double square loop	Low power handling, limited BW
[22]	$0.13 \lambda_{\text{mid}}$	$1.67 \times 1.67 \lambda_{\text{mid}}^2$	4.4	32.5	Gridded square loop	Thick substrate, limited BW
[23]	$0.018 \lambda_{\text{mid}}$	$0.175 \times 0.175 \lambda_{\text{mid}}^2$	4.4	50	Reconfigurable square loops	Angular stability not investigated
[24]	$0.06 \lambda_{\text{mid}}$	$0.2 \times 0.2 \lambda_{\text{mid}}^2$	2.2	24	Jerusalem cross Metasurfaces	Limited BW
This work	$0.02 \lambda_{\text{mid}}$	$0.2 \times 0.2 \lambda_{\text{mid}}^2$	4.4	60	CPFSS	Angular stability, large BW, design flexibility

and requires no external stimulus to operate. It is a passive device which exhibits the filtering properties on the basis of the structure used to design these surfaces. The design describes the range of the frequencies which may either pass through or may get blocked through these surfaces. On-chip shielding: These structures are a possible contender for a variety of 5G applications such as on-chip shielding. The dimensions of the CPFSS design depend on the frequency range for which these are designed. As the potential applications of the 5G lie in the range of mm-wave at which the dimensions reduce to micrometers, hence CPFSS may be beneficial to provide on-chip shielding to the 5G circuits. Isolation devices: CPFSS structures may be utilized to block the undesired and hazardous microwave L- and S-band radiations to enter in hospitals, schools, and homes. Secure communication devices: These surfaces help to prevent a potential threat of leaking of voice call information by providing a high end secure communication. This may be helpful in the communication devices being used by the armed forces where the frequency selective shielding is used. Enhancement of the output characteristics of a patch antenna: These structures help to mitigate the unwanted radiations from reaching the patch antenna surface which reduces the interference and helps to increase the gain, directivity, and radiation efficiency of a patch antenna.

4 Conclusion

A complementary frequency selective surface formed by the combination of dDSLFSS and DSSFSS has been discussed in this article. DSLFSS designed is exhibiting a band-pass frequency response which can be incorporated as a superstrate to allow a selective desired portion of frequency bands, whereas its complementary geometry formed using Babinet's principle is depicting opposite behavior. The complementary structure formed in the form of DSSFSS exhibits band-stop frequency response and can be incorporated as a substrate for increasing performance characteristics. The complementary pair of the proposed FSS geometry helps in providing design flexibility and offers polarization stability. Also, a constant behavior of the proposed design is reported for oblique angles of incidence which offers additional stability. Moreover, the proposed designed structure is having very less thickness, making it easy for getting incorporated within the wireless networking devices. The prototype is formulated, which has shown adequate performance characteristics which are in very good agreement with the simulation results. The proposed intelligent spatial filters tend to be a good candidate for the printed patch antenna design in sub-6 GHz 5G applications.

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