Design of a wideband square slot bandpass frequency-selective surface using phase range analysis

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This article presents the design of a wideband bandpass frequency-selective surface (FSS). The structure is designed using the analysis of the generalized scattering matrix (GSM)-based transmission phase range. A relationship between the transmission phase range and the bandpass fractional bandwidth (FBW) is developed. The analysis reveals that the FBW of the FSS unit-cell is proportional to the phase range. Based on the interpretation of results, a design curve has been drawn, and using this curve, a simple square slot FSS on a low-cost FR-4 substrate has been fabricated and measured. Using the design curve, a 53% FBW has been predicted. The simulated results show a 52% FBW with the 3.52-GHz center frequency ($f_o$). The response for the transverse electric (TE) and transverse magnetic (TM) modes has been measured. The structure has a bandpass FBW equal to 50% and 53.3% in TE and TM modes, respectively. The method presented in this article may be used to increase the bandpass response of different FSS topologies.

KEYWORDS
bandwidth, frequency-selective surface, generalized scattering matrix, passband, phase range

1 | INTRODUCTION

In general, frequency-selective surfaces (FSSs) consist of a two- or three-dimensional periodic array of slots or patches designed on a dielectric substrate.1 Due to the expansion of wireless system operating frequency bands, these structures find a wide range of applications.2-4 However, the narrow operating bandwidth (BW) is the fundamental limitation of a bandpass FSS.5-7

In the past decade, researchers have experienced the need for the wide BW bandpass FSS in the radomes, electromagnetic shelters, and in the frequency reuse systems; however, in spite of the great demands, few wideband bandpass FSS structures have been reported.8

To increase the operating BW of the bandpass FSS, a number of 2-dimensional (D), 2.5-D, and 3-D topologies have been developed. In the past few years, 2.5-D and 3-D FSS structures have been investigated in References 9-14. These structures have an extra degree of freedom in design but at the cost of compactness and fabrication difficulties. On the other hand, due to their design simplicity, 2-D planar structures are quite popular and a number of 2-D structures using...
planar circuit board printing technology have been reported in References 15-25. A planar FSS designed using three metallic and two dielectric layers is reported in Reference 15, but due to the high-quality factor (Q-factor), only a 20.5% −3-dB fractional BW (FBW) has been achieved. Using a stable Q-factor, a multilayered angular stable FSS using metal patch and wire-frame layer is reported in Reference 16. It also has a narrow passband. The BW of FSS can be enhanced by increasing the number of conducting layers. Using the nonresonant constituent elements, a multilayered bandpass FSS with a 20% FBW in the X-band is reported in Reference 17. In the multilayered FSSs, the BW is increased by placing the attenuation poles close to each other, which is governed by the number of the substrate and metallic layers. The passband may also be controlled by introducing the transmission zero frequencies, and using this technique, a dual-band narrow bandpass FSS has been developed in Reference 19. It consists of two substrate and three metallic layers. In Reference 20, a narrow-band FSS with quasielliptic bandpass response using two metallic layers is reported where the positions of pole and zero frequencies control the filtering action. To enhance the −3-dB transmission BW, a mushroom-type structure is proposed and a 15% FBW has been achieved in Reference 21. The FSS BW may be increased by merging the multiple resonance frequencies of the structure, and thus, an FBW of about 11.35% using a hybrid boundary cavity is reported in Reference 22. A multilayered FSS using wire grid and square loop has been developed to operate over two widely separated frequency bands with a 35% FBW in the X-band. Another double-layered antenna-filter-antenna FSS to operate in the C-band with 14.2% FBW is reported in Reference 24.

Due to the tight packaging, self-convoluting structures are also used to enhance the FBW of the bandpass FSS, and a 55% FBW is reported in Reference 25. Similarly, a narrow band C-type convoluting structure with a relatively narrow band has been reported in Reference 26. However, these structures suffer from the asymmetric response in different modes of operations. Recently, in another approach, a capped dielectric with perforated metallic plates has been used in the FSS design, where in spite of the design complexity, it has only a 20% FBW. In References 15-27, efforts have been made to increase the operating BW of a bandpass FSS. However, there is a scope to improve the transmission BW.

In this article, we present a low-cost double metallic with single dielectric-layered simple bandpass FSS with a 53% FBW in the S-C band (2.72-4.69 GHz) of the electromagnetic spectrum. The FSS has been analyzed using the generalized scattering matrix (GSM) approach. With the use of GSM approach, we developed an equation for the phase range of the bandpass FSS. Based on the analysis, a design curve is proposed to find the approximate FBW corresponding to the phase range. It is observed that the FBW is proportional to the transmission phase range. The MatLab and CST Microwave Studio Software have been used to obtain the analytically and simulated phase ranges, respectively. Finally, the structure has been fabricated and the transmission BW has been measured and it is in good agreement to the analytical value.

## 2 THEORETICAL ANALYSIS

The FSSs consist of a single or the multiple conducting layers supported by the dielectric slabs. The behavior of this multilayered structure may be analyzed using a GSM analysis technique. The multilayered scattering structure is considered as the cascaded arrangement of dielectric and conducting layers. For a two-layered scattering (S) structure, the S-matrix is written as Equations (1) to (3).  

\[
S_{11}^M = \frac{S_{11}^1S_{12}^1S_{21}^1}{1 - S_{11}^1S_{22}^1} + S_{11}^1, \quad (1)
\]

\[
S_{12}^M = S_{21}^M = \frac{S_{11}^1S_{21}^2}{1 - S_{11}^1S_{22}^2}, \quad (2)
\]

\[
S_{22}^M = \frac{S_{12}^1S_{21}^2S_{12}^2}{1 - S_{11}^1S_{22}^2} + S_{22}^2. \quad (3)
\]

where \(S_{11}^M, S_{12}^M, S_{21}^M, \) and \(S_{22}^M \) are the S-parameters of the cascaded layers and \(S_{11}^1, S_{12}^1, S_{21}^1, \) and \(S_{22}^1 \) are the S-parameters of first layer. Similarly, \(S_{11}^2, S_{12}^2, S_{21}^2, \) and \(S_{22}^2 \) are the S-parameters of the second layer. When a dielectric substrate is placed between them, the S-matrix of the second layer in Equations (1) to (3) is replaced by the S-matrix of the substrate given in Equations (4) to (7) and the S-matrix of this combination is cascaded to the third layer, and the total S-parameters of
the multilayered scattering FSS are obtained. Since the FSS unit-cell is a passive structure, for the multilayered FSS, the total scattering behavior is obtained by Equations (1) to (3).

\[ S_{11} = S_{22} = \frac{\Gamma (1 - e^{-j2\beta L_d})}{1 - \Gamma^2 e^{-j2\beta L_d}}, \]  
\[ S_{12} = S_{21} = \frac{(1 - \Gamma^2)e^{-j\beta d}}{1 - \Gamma^2 e^{-j2\beta L_d}}, \]  
\[ \Gamma = \frac{1 - \sqrt{\epsilon_r}}{1 + \sqrt{\epsilon_r}}, \]  
\[ \beta = \frac{2\pi \sqrt{\epsilon_r}}{\lambda_0}, \]  

where \( \epsilon_r, L_d, \Gamma, \lambda_0, \) and \( \beta \) are the dielectric relative permittivity, substrate thickness, reflection coefficient, free-space wavelength at center frequency, and the phase constant, respectively.

With the assumptions that FSS screen is reciprocal, lossless, and satisfies Fresnel conditions, we may write the S-matrix of the conducting layers of a two-metallic layered FSS as Equation (8), in which superscripts 1 and 3 represent the first and third (metallic) layers supported by a sandwiched dielectric layer, acting as the second layer.31

\[
\begin{bmatrix}
S_{11}^{13} & S_{12}^{13} \\
S_{12}^{13} & S_{22}^{13}
\end{bmatrix} =
\begin{bmatrix}
\sin(\angle S_{21})e^{j0.5\pi + \angle S_{21}} & \cos(\angle S_{21})e^{j\angle S_{21}} \\
\cos(\angle S_{21})e^{j\angle S_{21}} & \sin(\angle S_{21})e^{j0.5\pi + \angle S_{21}}
\end{bmatrix}.
\]  

Since Equation (8) is a generalized S-matrix, irrespective of the shape of the conducting layer, the transmission parameter \( |S_{21}^{13}| \) is given by \( \cos(\angle S_{21}) \), and thus, the phase angle \( \angle S_{21} \) corresponding to a given magnitude may be calculated. Now, this phase angle in conjunction with the S-matrix of dielectric slab given in Equations (4) to (7) may be suitably placed in Equations (1) to (3) to calculate S-parameters of the structure at any frequency. For example, at a \(-3\)-dB lower cut-off frequency of transmission BW of an FSS, \( \angle S_{21} \) is calculated by equating \( \cos(\angle S_{21}) = -3 \) dB and substituting this value in the exponential term of \( |S_{21}^{13}| \) and it gives the phase angle. For the given dielectric substrate material, using Equations (4) to (7), the S-parameters of the dielectric substrate are calculated and substituted in Equations (1) to (3) to obtain the S-matrix of the multilayered FSS. The transmission parameter of the combined FSS structure at a frequency \( f_L \) is given by \( S_{21}^{M} \) whose magnitude and angle are \( |S_{21}^{M}| \) and \( \angle S_{21}^{M} = \theta_1 \) respectively. For the \(-3\)-dB transmission BW, this \( f_L \) is the lower cut-off frequency whose magnitude is \(-3\) dB and \( \angle S_{21}^{M} = \theta_1 \). Thus, when \( |S_{21}^{M}| \) vs \( \angle S_{21}^{M} \) is plotted on a polar plot, the first intersection point of magnitude and phase occurs at angle \( \theta_1 \) and then \( \angle S_{21}^{M} \) intersects the magnitude curve \(-3\) dB at a number of points. For the two-metallic layered FSS, the angular distance between the two distant intersections of \( \angle S_{21}^{M} \) to \( |S_{21}^{M}| \) gives the phase range \( \phi_1 \), which is related to \( \theta_1 \) in Equation (9), where \( n \) is the positive integer.

\[ \phi_1 = (2n - 1)\pi + 2\theta_1. \]  

The value of \( \phi_1 \) is analytically calculated using the MatLab code for the scattering matrix. To obtain this, the magnitude of \( S_{21} \) parameter is equated to the required value, and in the present case, it is \(-3\) dB at the given frequency \( f_L \).

Any FSS unit-cell of a given topology when simulated using commercially available software gives the instantaneous phase range \( \phi_2 \) between two \(-3\)-dB frequency points. When the design parameters of the unit-cell are parametrically varied, \( \phi_2 \) also varies. Thus, \( \phi_2 \) may be parametrically optimized by changing the physical parameters of the unit-cell to obtain a condition where \( \phi_2 \cong \phi_1 \), which gives the optimum FBW of the FSS structure.

Furthermore, in this article, we show that the analytical and simulated phase ranges are proportional to the transmission BW of the FSS. The procedure of obtaining the phase range \( \phi_1 \) and \( \phi_2 \) is summarized in the flowchart given in Figure 1. The proposed method helps in maximizing the operating BW from the knowledge of the phase range of the transmission parameter of the unit-cell of FSS.
3 Phase Range and Its Relation to BW

3.1 Phase range and BW analysis

The analytical procedure outlined in the previous section has been applied on a simple square slot FSS unit-cell shown in Figure 2, and the investigated design parameters under different cases are shown in Table 1. Following the analytical procedure, the phase range $\phi_1$ corresponding to $-3$-dB cut-off frequencies has been calculated for all the cases, but polar plots depicting the intersection points of $\angle S_{21}^M$ to the $|S_{21}^M|$ have been drawn for two cases, namely, case #1 and case #12. The result plots are shown in Figures 3 and 4, respectively. The analytical results of $\phi_1$ for these cases calculated using MatLab Code are shown in Figures 3A and 4A, respectively. As stated in the previous section, the analysis is independent of the shape of the topology and it only depends on the scattering behavior. Thus, the proposed method may be applied to any shape of the FSS unit-cell. However, in this analysis, we have only used a simple square slot topology. Once $\phi_1$ is calculated, the FSS unit-cell is parametrically optimized to tune simulated phase range ($\phi_2$) equal to the analytical phase range ($\phi_1$). Table 1 shows the unit-cell dimensions with varying slot lengths ($L_1$) and the relative permittivity of the substrate ($\varepsilon_r$). In general, we use the commercially available substrate of a given relative permittivity and the substrate thickness. Thus, these parameters have been kept constant. The periodicity of the structure has also been kept constant. If we change the periodicity, the complete design and its response including the BW and the lower cutoff frequency would change. Similarly, there will be an effect of $W$ on the response, and thus, it would lead to multiple variable optimization problems. However, for $\lambda_0 \gg W$, the parametric variation of $W$ has less effect on the response. Thus, the effect of change in $L_1$ has only been studied in this article.

In this case, $L_1$ is the optimization parameter, which governs the variation in $\phi_2$. Thus, the slot length $L_1$ is tuned to make $\phi_2 \equiv \phi_1$. For the sake of brevity, the effect of variation in $L_1$ and other design parameters on $S_{21}$ is not shown here.

FIGURE 1 Flow chart for analysis of frequency-selective surface bandwidth

FIGURE 2 Two-conducting layered square slot frequency-selective surface.
A, Front, bottom. B, Side view
TABLE 1 Parameters of two-conducting layered unit-cell

| Cases | Design parameters (in mm) | Substrate/relative permittivity ($\varepsilon_r$) |
|-------|---------------------------|-----------------------------------------------|
|       | $L$ | $L_1$ | $W$ | $L_d$ |                                   |
| # 1   | 17.86 | 17.8 | 0.5 | 3.75 | 1.0                               |
| # 2   | 17.86 | 17.81 | 0.5 | 3.75 | 1.1                               |
| # 3   | 17.86 | 17.84 | 0.5 | 3.75 | 1.2                               |
| # 4   | 17.86 | 17.785 | 0.5 | 3.75 | 1.3                               |
| # 5   | 17.86 | 17.75 | 0.5 | 3.75 | 1.4                               |
| # 6   | 17.86 | 17.7 | 0.5 | 3.75 | 1.5                               |
| # 7   | 17.86 | 17.6 | 0.5 | 3.75 | 1.6                               |
| # 8   | 17.86 | 17.5 | 0.5 | 3.75 | 1.8                               |
| # 9   | 17.86 | 17.4 | 0.5 | 3.75 | 2                                 |
| # 10  | 17.86 | 17 | 0.5 | 3.75 | 2.2                               |
| # 11  | 17.86 | 15 | 0.5 | 3.75 | 2.4                               |
| # 12  | 17.86 | 16.66 | 0.5 | 3.75 | 1.0                               |

FIGURE 3 $S_{21}$ magnitude vs phase angle for case #1. A, Analytical with $f_L = 1.85$ GHz. B, Simulated at fixed geometrical length of Table 1

FIGURE 4 $S_{21}$ magnitude vs phase angle for case #12. A, Analytical with $f_L = 6.3$ GHz. B, Simulated at fixed geometrical length of Table 1
The polar plots of $\phi_2$ for these two cases are shown in Figures 3B and 4B, respectively. The similar procedure has been applied to all the cases of Table 1. The corresponding analytical and simulated values of $\phi_1$ and $\phi_2$ are shown in Table 2.

In the multilayered structure, there are multiple dielectric and conducting layers where the dielectric layer scattering behavior given by Equations (4) and (7) is complex in nature. When, along with the scattering parameters of a conducting layer given by Equation (8) is substituted in Equation (2), it gives multiple solutions. For example, for a fixed magnitude say $|SM_{21}| = -3$ dB, it may have multiple roots, and thus, there may be the multiple intersection points of the magnitude to the phase angle. In the analytical results shown in Figures 3A and 4A, out of the multiple intersections of magnitude to the phase angle of $S_{21}$, the distance between the farthest intersections calculates $\phi_1$, which is given by Equation (9). An angle $\theta_1$ that is the phase angle of $SM_{21}$ resides in the first quadrant and it corresponds to the lower cut-off frequency $f_L$ of the $-3$-dB passband. When $\phi_1$ is added to $\theta_1$, it again intersects the same magnitude curve at other points, and the angular difference between two intersections gives the phase range corresponding to the magnitude. The new point of the intersection corresponds to the higher frequency $f_{H}$ and $f_{H} - f_{L}$ is the BW. Thus, $FBW = (f_{H} - f_{L})/f_0$, with $f_0$ being the center frequency of the passband, is proportional to the phase range. The FBW corresponding to each case of Table 1 is shown in the last column of Table 2. When we compare these cases, we see that the FBW is proportional to the analytical transmission phase range obtained using Equation (9).

In a double-metallic layered structure, $f_L$ and $f_H$ reside in two opposite quadrants and $\phi_1$ is the angular distance between the farthest intersection points corresponding to $|SM_{21}| = -3$ dB, and thus, the variation in the magnitude along the path of $\phi_1$ is not taken into the account.

### 3.2 Application of technique to single-layer FSS

We have also used this technique to analyze the phase range of a single-metallic layered FSS operating at higher frequency reported in Reference 32. Design parameters and the response of the topology are shown in fig. 5 of Reference 32 where results show two transmission zeros at 15.1 and 30.8 GHz, approximately. Between these frequencies, the structure behaves as a bandpass FSS where we have applied the proposed technique. For the $-3$-dB passband, $f_L$ is at 18.7 GHz. The $f_{H}$, the transmission BW, and the FBW are 26.3 GHz, 7.6 GHz, and 33.7%, respectively. The $f_L$ and the substrate parameters have been substituted in the MatLab code to calculate $\phi_1$ and it is shown in Figure 5A. The $\phi_1$ for the single-layer FSS is 88.9° close to 90.0°. The simulated value of $\phi_2$ for the same set of design parameters is shown in Figure 5B and it is 89.8°. Due to the smaller phase range in this case, the FBW (33.7%) is proportionally reduced in comparison to Table 2.


RELATION BETWEEN FBW AND THE PHASE RANGE

In Reference 33, to increase the gain BW of the transmit array antenna, a square slot unit-cell structure is proposed and the formula to calculate the BW is given. The analysis reveals that the FBW is proportional to the phase error and inversely proportional to the slope of the phase vs frequency. The focal distance ($F$) and the aperture size ($D$) are the other parameters on which the BW depends. However, the careful study shows that in comparison to the phase slope and phase error, $F$ and $D$ have less effect on the BW. The slope of the curve depends on the higher and lower bandstop notches. The analysis gives insight into the BW corresponding to the phase error and the slope of the curve. However, it cannot be directly used to calculate the BW where in place of the phase error, the phase range ($\phi_1$) is given. Due to the exponential terms in Equations (4) and (5), $\phi_1$ changes nonlinearly. It is important to mention that in these equations, these exponential terms depend on $\epsilon_r$, and thus, the nonlinearity is governed by the relative permittivity of the substrate.

Nevertheless, from these facts, it is established that the FBW of the bandpass FSS is proportional to the phase range, and by increasing its value, the FBW can be increased.

The interpretation of Tables 1 and 2 shows that FBW changes with respect to $\phi_1$. Based on the interpretation, the phase ranges for a number of topologies have been calculated and a design curve has been drawn in Figure 6. This curve serves as the design guideline in optimizing the FBW of the FSS unit-cell with a maximum deviation of 10%. Since the analysis in Section 2 does not depend on the shape of the topology, we may predict the FBW for any topology using this curve provided $\phi_2 \cong \phi_1$.

Interestingly, from Tables 1 and 2, it is noted that when the substrate permittivity is low, the phase range is high. For these cases, the slope between FBW and the phase range is nonlinear, which may cause deviation in the result to some extent. With the increase in the substrate permittivity, the phase range reduces, and thus, the FBW is also reduced. To find the deviation in the result, the curve fitting method has been used and it has been noted that the design curve predicts the FBW with an accuracy of ±10%. It is also pertinent to mention that for the two-metallic layered FSS designed on the vacuum substrate ($\epsilon_r = 1$) with the increased substrate thickness ($L_d = 6.5$ mm) in Reference 33, the maximum phase range is 187°, which has been increased to 254.1°, in our design, and thus, it is expected to obtain the wider $-3$ dB BW.

Finally, we conclude that the FBW of the bandpass FSS may be increased by optimizing the physical parameters in such a way that $\phi_2 \cong \phi_1$.  

FIGURE 5 Phase range for fig. 5 of Reference 32. A, Analytical. B, Simulated

FIGURE 6 Phase range vs fractional bandwidth of frequency-selective surface
5 | DESIGN EXAMPLES USING PROPOSED METHOD

The design curve shown in Figure 6 has been used to realize a practical wideband FSS designed on the commercially available FR-4 substrate material. The structure is experimentally verified for the wide transmission BW.

With the available resources in the Antenna and Microwave Design Lab., SMVDU, India, the square slot FSS has been designed on a low-cost FR-4 substrate ($\varepsilon_r = 4.4$, $\tan \delta = 0.02$). The topology is similar to that shown in Figure 2 with the design parameters $L = 17.86$ mm, $L_1 = 16$ mm, $W = 0.8$ mm, and $L_d = 3.17$ mm. To calculate the phase range $\phi_1$, the substrate parameters ($\varepsilon_r = 4.4$, $L_d = 3.17$) and the $f_L = 2.72$ GHz are input to the MatLab code and the phase range $\phi_1$ is calculated, which is $240.8^\circ$. The analytical phase range vs. $-3$-dB magnitude curve is shown in Figure 7A.

For the fixed periodicity $L = 17.86$ mm, the design parameter $L_1$ is parametrically optimized in the CST Microwave Studio to tune the simulated phase range $\phi_2$ close to $\phi_1$. The final value of $\phi_2 = 239.35^\circ$ is shown in Figure 7B. The analytical and simulated phase ranges are in close agreement. Corresponding to these phase ranges, we predict the FBW using Figure 6 and it is close to 53% for $\phi_1 = 240.8^\circ$. Thus, the proposed method gives a benefit of predicting the FBW of an FSS from the analytical phase range $\phi_1$.

6 | EXPERIMENTAL VERIFICATION OF FBW

In this section, the experimental result of the square slot FSS topology is presented. The square slot FSS structure comprising $16 \times 16$ unit-cells with an overall dimension of 285.76 $\times$ 285.76 mm$^2$ is fabricated on a readily available low-cost FR-4 substrate with $\varepsilon_r = 4.4$, $\tan \delta = 0.02$, and $L_d = 3.17$ mm. The design parameters of the unit-cell are $L = 17.86$ mm, $L_1 = 16$ mm, and $W = 0.8$ mm. The operating BW has been measured in the Antenna and Microwave Design Lab., Shri Mata Vaishno Devi University (SMVDU), Jammu and Kashmir, India. The dimension of the structure is chosen to be more than $3.5 \times 3.5 \lambda_0^2$. The fabricated FSS and the measurement setup are shown in Figure 8A,B, respectively. To accomplish the measurement, two horn antennas of width 23.5 cm were placed at a distance of $2h = 1.5$ m in the anechoic chamber.

**FIGURE 7** $S_{21}$ magnitude vs phase angle for (A) analytically with $f_L = 2.72$ GHz (B) simulated phase range

**FIGURE 8** Square slot frequency-selective surface. A, Fabricated topology. B, Measurement setup
In the first step, the $S_{21}$ (dB) parameter in the free space between the two antennas was measured, which acts as the reference for FSS measurement. Then, the FSS was placed midway and the $S_{21}$ (dB) parameter was remeasured. Finally, the reference value was subtracted from the second reading to obtain the measured result. For the normal incidence of the electromagnetic wave, the response has been measured for both (a) the transverse electric (TE) and (b) transverse magnetic (TM) modes. The simulated and measured responses of the structure are shown in Figure 9. The simulated response of the structure shows a 1.90-GHz $-3$-dB transmission BW that extends from 2.72 to 4.62 GHz, and thus, the FBW is about 51.8%. The measured result in the TE mode shows a $-3$-dB transmission BW of 1.76 GHz extending from 2.64 to 4.40 GHz. Thus, in the TE mode, the structure exhibits a 50% FBW. In the TM mode, extending from 2.72 to 4.70 GHz, it has a 53.3% FBW.

The discrepancy among simulated and measured results in TE and TM modes has been observed. In general, for the angular incidence, the TM mode offers a wider BW. However, for the normal incidence, the response of TE and TM should be identical under the ideal simulation and measurement environment. However, in the present case, the deviation in the result is attributed to mainly three facts. The relative permittivity of the FR-4 substrate has a wide range of tolerance. Second, the accuracy depends on the fabrication process, and in this case, wet-etching was used to develop the prototype. Third, the discrepancy arose from the parallax error in the alignment of two horn antennas when the FSS was placed in between. The simulated result shows a deviation of 2.2% with respect to the predicted FBW from Figure 6. Similarly, the measured response in TE and TM modes deviates from the predicted value by 5.6% and 0.3%, respectively. Thus, the maximum deviation of 5.6% is noted in this measurement, which is within the predicted tolerance of 10% as discussed before. The simulated and measured responses in Figure 9 show a poor skirting in the stopband, which may be improved by increasing the number of substrate and metallic layers.

To estimate the effect of the distance between excitation and FSS structure on the bandpass response, in 2 to 5-GHz range, the response of the FSS for different values of $h$ in Figure 8B has also been measured and it is shown in Figure 10. The measured result shows that the bandpass characteristic is identical in all the cases. Only with the increase in the
distance, due to the increase in the free-space loss, the bandpass magnitude drops maximum to $-5\text{dB}$ for $h = 1.4\text{m}$.

However, it clearly discriminates between bandpass and bandstop regions of the response, which is needed in the spatial filters.

## 7 | STATE-OF-THE-ART COMPARISON

The state-of-the-art comparison of the proposed FSS to recently proposed structures is shown in Table 3. In addition to the topology, the FBW also depends on the periodicity of the unit-cell and the number of substrate and metallic layers, and thus, a comparison in terms of these parameters is presented in this table. It is noted that in Reference 8, a $63\%$ transmission BW has been achieved. However, it uses three metallic layers in which two are placed at certain distance from the dielectric layer, and thus increases the overall size of the unit-cell. When it is compared with respect to the single-dielectric layered FSS in References 20, 27, a significant improvement in the BW is noted. Similarly, it also offers wider BW with respect to the other multilayered FSSs. In this table, $\lambda_0$ is the free-space wavelength corresponding to the center frequency $f_0$.

## 8 | CONCLUSION

In this article, the relationship between the phase range and the transmission BW has been developed. It is found that FBW is proportional to the phase range. Based on the analysis and simulation, an equation to calculate the phase range and a design curve with an accuracy of $\pm 10\%$ to relate these quantities are developed. To validate the concept, a two-metallic layered prototype on the low-cost FR-4 substrate has been tested. The measured result shows a $53.3\% -3\text{-dB}$ FBW in the S-C band of the electromagnetic spectrum. The proposed method has also been used to analyze the single-metallic layered FSS, in which the phase range and the corresponding BW have been reduced. The state-of-the-art comparison is also presented to show the enhanced FBW of the structure designed using the proposed method. In future, the method may be tried on different topologies and multilayered structures to optimize the FBW of the bandpass FSS. With the increase in the phase range, the tolerance increases and it affects the estimated FBW. The accuracy of the method depends on the accuracy of the phase range calculation and it may further be improved in future.
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REFERENCES
1. Munk BA. Frequency Selective Surfaces: Theory and Design. New York, NY: John Wiley and Sons; 2005.
2. Mittra R, Chan C, Cwik T. Techniques for analyzing frequency selective surfaces—a review. Proc IEEE. 1988;76(12):1593-1615.
3. Jha KR, Singh G, Jyoti R. A simple synthesis technique of single-square-loop frequency selective surface. Prog Electromagn Res B. 2012;45:165-185.
4. Panvar R, Lee JR. Progress in frequency selective surface-based smart electromagnetic structures: a critical review. Aerosp Sci Technol. 2017;66:216-223.
5. Costa F, Kazemzadeh A, Genovesi S, Monorchio A. Electro-magnetic absorbers based on frequency selective surfaces. Forum Electromagn Res Methods Appl Technol. 2016;37(1):1-23.
6. Li Y, Li L, Zhang Y, Zhao C. Design and synthesis of multilayer frequency selective surface based on antenna-filter-antenna using Minkowski fractal structures. IEEE Trans Antennas Propag. 2015;63(1):133-141.
7. Amin SM, Abadi MH, Li M, Behdad N. Harmonic-suppressed miniaturized-element frequency selective surfaces with higher order bandpass responses. IEEE Trans Antennas Propag. 2014;62(5):2562-2571.
8. Lv Q, Jin C, Zhang B, Mittra R. Wide-passband dual-polarized elliptic frequency selective surface. IEEE Access. 2019;7:558833-555840.
9. Yu Y-M, Chiu C-N, Chiou Y-P, Wu T-L. A novel 2.5-dimensional ultra-miniaturized-element frequency selective surface. IEEE Trans Antennas Propag. 2014;62(7):3657-3663.
10. Shi Y, Zhuang W, Tang W, Wang C, Liu S. Modeling and analysis of miniaturized frequency selective surface based on 2.5-dimensional closed loop with additional transmission pole. IEEE Trans Antennas Propag. 2016;64(1):346-351.
11. Hussain T, Cao Q, Kayani JK, Majid I. Miniaturization of frequency selective surfaces using 2.5-dimensional knitted structures: design and synthesis. IEEE Trans Antennas Propag. 2017;65(5):2405-2412.
12. Shi Y, Tang W, Zhuang W, Wang C. Miniaturised frequency selective surface based on 2.5-dimensional closed loop. Electron Lett. 2014;50(23):1656-1658.
13. Barton JH, Garcia CR, Berry EA, Salas R, Rumpf RC. 3-D printed all-dielectric frequency selective surface with large bandwidth and field of view. IEEE Trans Antennas Propag. 2015;63(3):1032-1039.
14. Zhu J, Tang W, Wang C, Huang C, Shi Y. Dual-polarized bandpass frequency-selective surface with quasi-elliptic response based on square coaxial waveguide. IEEE Trans Antennas Propag. 2018;66(3):1331-1339.
15. Li D, Li T-W, Hao R, et al. A low-profile broadband bandpass frequency selective surface with two rapid band edges for 5G near-field applications. IEEE Trans Electromagn Compat. 2017;59(2):670-676.
16. Liu X, Wang Q, Zhang W, Jin M, Bai M. On the improvement of angular stability of the 2nd-order miniaturized FSS structure. IEEE Antennas Wirel Propag Lett. 2016;15:826-829.
17. Al-Joumayly M, Behdad N. A new technique for design of low-profile second-order bandpass frequency selective surfaces. IEEE Trans Antennas Propag. 2009;57(2):452-459.
18. Abbaspour-Tamijani A, Sarabandi K, Rebeiz GM. Antenna-filter-antenna arrays as a class of bandpass frequency-selective surfaces. IEEE Trans Microw Theory Tech. 2004;52(8):1781-1789.
19. Li W, Li Y. A high selectivity, miniaturized low profile dual-band bandpass FSS with a controllable transmission zero. Int J Antennas Propag. 2017;2017:7983567.
20. Li B, Shen Z. Synthesis of quasi-elliptic bandpass frequency-selective surface using cascaded loop arrays. IEEE Trans Antennas Propag. 2013;61(6):3053-3059.
21. Zhong T, Zhang H, Min X–L, Chen Q, Wu G-C. Wideband frequency selective surface with a sharp band edge based on mushroom-like cavity. *Prog Electromagn Res Lett*. 2016;62:105-110.

22. Yang L-L, Wei X-C, Yi D, Jin J-M. A bandpass frequency selective surface with a low cross-polarization based on cavities with a hybrid boundary. *IEEE Trans Antennas Propag*. 2017;65(2):654-661.

23. Yan M, Qu S, Wang J, et al. A miniaturized dual-band FSS with second-order response and large band separation. *IEEE Antennas Wirel Propag Lett*. 2015;14:1602-1605.

24. Zhang S, Yin Y, Fan J, Yang X, Liu W. Analysis of miniature frequency selective surfaces based on fractal antenna–filter–antenna arrays. *IEEE Antennas Wirel Propag Lett*. 2012;11:240-243.

25. Zhao P-C, Zong Z-Y, Wu W, Fang DG. A convoluted structure for miniaturized frequency selective surface and its equivalent circuit for optimization design. *IEEE Trans Antennas Propag*. 2016;64(7):2963-2970.

26. Zhao P-C, Zong Z-Y, Wu W, Li B, Fang D-G. Miniaturized-element bandpass FSS by loading capacitive structures. *IEEE Trans Antennas Propag*. 2019;67(5):3539-3544.

27. Jin C, Lv Q, Wang J, Li Y. Capped dielectric inserted perforated metallic plate bandpass frequency selective surface. *IEEE Trans Antennas Propag*. 2017;65(12):7129-7136.

28. Liu N, Sheng X, Zhang C, Guo D. Design of frequency selective surface structure with high angular stability for radome application. *IEEE Antennas Wirel Propag Lett*. 2018;17(1):138-141.

29. Pozar DM. *Microwave Engineering*. New York, NY: John Wiley and Sons; 2005.

30. Balanis CA. *Advanced Engineering Electromagnetics*. 2nd ed. New York, NY: Wiley; 2012.

31. Abdelrahman AH, Yang FZ, Elsherbeni A. Analysis of multilayer frequency selective surfaces for transmitarray antenna applications. In *Proc. 29th Annual Review of Progress in Applied Computational Electromagnetics (ACES)*. Monterey, CA: ACES; 2013:135-140.

32. Lee CK, Langley RJ. Equivalent-circuit models for frequency-selective surfaces at oblique angles of incidence. *IEE Proc. 1985;132(6):395-399.

33. Rahmati B, Hassani HR. High-efficient wideband slot transmitarray antenna. *IEEE Trans Antennas Propag*. 2015;63(11):5149-5155.

34. Jha KR, Mishra G, Sharma SK. Analysis and design of a microwave absorber using non-resonance constituent parameter retrieval method for wireless communication applications. *IET Microw Antennas Propag*. 2018;12(6):977-985.

35. Jha KR, Sharma SK. Combination of frequency agile and quasi-elliptical planar monopole antennas in MIMO implementations for handheld devices. *IEEE Antenna Propag Mag*. 2018;60(1):118-131.

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