International Journal of Microwave and Wireless Technologies

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Research Paper

Cite this article: Tiwari AK, Ahmed A, Bharti M, Sheoran G (2025) A wide-band frequency-selective surface for enhancing the performance of microstrip antenna. *International Journal of Microwave and Wireless Technologies* **17**(1), 132–139. https://doi.org/10.1017/S1759078725000212

Received: 28 September 2024
Revised: 27 January 2025
Accepted: 29 January 2025

Keywords:
5G; frequency-selective surface; gain tuning; microstrip antenna; Wi-Fi; WLAN

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A wide-band frequency-selective surface for enhancing the performance of microstrip antenna

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Abstract

This work presents the design of a wide-band frequency-selective surface (FSS) with its analysis for the performance enhancement of a microstrip antenna. To demonstrate the concept, a dual-band microstrip antenna is also designed and combined with the proposed FSS to investigate its advantages and performance enhancement capabilities. The proposed FSS is designed for a frequency range of 3.5–6.5 GHz, whereas the designed antenna operates in dual frequency bands of 3.5 and 5 GHz. The combined effect of the antenna and FSS is investigated at 5 GHz for improving the gain of the antenna from 2.8 to 3.2 dBi. The outcome of the measured performance validates that the proposed surface has potential capability for enhancing the gain of an antenna for 5G, WLAN, and Wi-Fi communication.

Introduction

In the past several years, Wi-Fi and WLAN communication have become essential modes for data or information transmission in daily life. Researchers are working extensively in the field to make this communication proficient with improved and cost-effective solutions. Generally, the hardware part of such a communication system includes transmitters, receivers, power amplifiers, repeaters, and control circuit assemblies. The transmitters and receivers are basically antennas that may be designed with various methodologies (i.e., wire, horn, Yagi, MIMO, etc.). Recently, a variety of methodologies have been engaged to improve the performance of antennas [1–4] (i.e., metamaterial surfaces, reconfigurable intelligent surfaces, intelligent reflective surfaces, and frequency-selective surfaces [FSSs]). Among all these techniques, FSS is currently one of the most used methodologies in wireless communication for the enhancement and reconfiguration of various parameters of the trans-receivers [5–11], radar cross section reduction [12–14], synthetic aperture radar [15], and absorbers [16]. Generally, an FSS is a two-dimensional periodic structure of metallic elements on dielectric materials that either transmits, reflects, or even absorbs the incoming waves at the designed frequency. FSS structures that are controlled by the external circuitry and power supply are called the active FSS [5]. Active FSS is costly because of the use of extra circuit components and supply arrangements. However, such structures are frequently used for automated tuning of antenna parameters. Whereas a passive FSS is a fixed periodic structure that does not use such electronic arrangements for tuning applications as compared to active FSS. Generally, FSS comprises of a periodic array of metallic elements designed on dielectric materials. When an electromagnetic (EM) wave is incident on the surface, the FSS's elements start resonating at the designed frequency. Based on the design parameters, the FSS can be operated for reflection and transmission modes. Recently, multiple FSS structures have been designed and employed with different types of antennas to improve their functionality in terms of their performance parameters [11, 17–20]. These parameters include gain, isolation, absorption, polarization, directivity, beam directionality, etc. The FSS structures are specifically designed based on the required applications; for example, isolation and absorption require the attenuation of incident waves within the FSS [10, 16, 17]. Whereas, the FSS structures that are used to enhance gain and directionality [24–28] require controlled transmission of waves through the structure. The advantage of including FSS for gain enhancement is that it does not require an alteration in the physical structure of the antenna, and it can also be used for any antenna within the designed frequency range. Therefore, FSS structures are widely used in modern wireless communication technology.

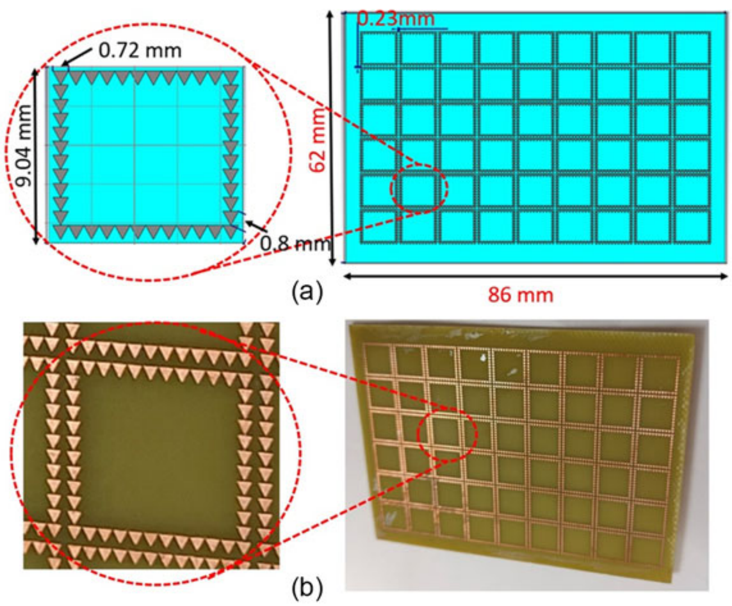

Figure 1. (a) Proposed FSS structure along with its unit cell; (b) fabricated FSS structure.

This work presents a passive FSS for wide-band frequency applications that covers the operating frequency from 3.5 to 6.5 GHz. The designed FSS is capable of enhancing the gain of an antenna for 5G, WLAN, and Wi-Fi ranges of frequencies single-handedly. To demonstrate the proof of concept, a dual-band microstrip patch antenna is designed at 3.5 and 5 GHz frequency bands. Further, this designed antenna is used analogously with the proposed FSS to observe the improvement in its performance. The main advantage of a passive FSS is that the parameters of the antenna can be tuned without affecting the physical structure of that antenna. Moreover, the presented methodology does not require any external passive or active components, electronic switching, or an external power supply. This advantage makes it cost-effective and easy to manufacture.

Design and analysis of proposed FSS

The proposed FSS is a periodic array of metallic structures integrated on FR-4 base material with a thickness of 1.6 mm and a dielectric constant of 4.4, where the maximum dimension of a unit cell structure is less than $\lambda_g/4$. The proportions of the proposed FSS are designed based on the concepts and equations given in the literature [23,24]. All these dimensions are evaluated at 5 GHz.

The structure and the parameters of the proposed FSS are given in Fig. 1(a), and the corresponding fabricated prototype of the same is given in Fig. 1(b). The dimension of a unit cell is 9.04 mm × 9.04 mm, whereas a 6 × 9 array of this structure is designed in simulation mode with overall dimensions of 62 mm × 86 mm. This structure is designed and simulated in the CST Studio software environment. For analysis of FSS's operating frequency and reflection coefficients, the structure is designed inside a waveguide environment. The corresponding EM field and the direction of field propagations are illustrated in Fig. 2(a). The reflection curve of the proposed FSS is given in Fig. 2(b), which gives the peak reflection at the designed frequency of 5 GHz with an operating bandwidth of 3.5–6.5 GHz. The scattering (S) parameters of the fabricated FSS are measured using the experimental setup consisting of R&S ZNB 20. A two-port vector network analyzer along with coaxial to waveguide transitions is used to record the reflection and transmission parameters of the FSS. The assessment of the simulated and measured outcomes of the proposed FSS is given in Fig. 2(e), which gives a good agreement of the operating frequency range. The working frequency of the proposed FSS structure is from 3.5 to 6.5 GHz, with measured peak reflections of −26.8 dB at 5 GHz. The designed FSS is also compared with the simulated outcome of the equivalent microstrip rectangular lines, which is given in Fig. 2(c). It is cleared from the graph that the rectangular structure covers a large bandwidth. However, the resonant frequency of the structure is shifted from 5 to 5.5 GHz frequency with the same dimensions of both the FSS. Therefore, the size of the rectangular strip needs to be increased to bring the resonant frequency to 5 GHz. This will increase the size of unit structure of FSS. Therefore, we can say that the proposed FSS is a miniaturized structure as compared to the general rectangular FSS. Further, the designed triangular FSS is also analyzed for the polarization sensitivity of the incident EM waves. Therefore, the reflection parameter of the FSS is observed for various incident angles and given in Fig. 2(d). The graph shows the approximately similar resonance for all the incident angles.

Enhancement of antenna performance

The concept presents a combination of FSS along with the planar microstrip antenna to modify the overall performance of that antenna. To validate the concept, initially a coplanar microstrip patch antenna is designed and validated with various performance parameters for the frequency range of mobile communication. In the next step, the presented FSS is combined with the proposed microstrip antenna to enhance its performance parameters.

Design of microstrip antenna

A microstrip antenna is designed for dual-band applications that cover the frequency range of WLAN, Wi-Fi, and WiMAX applications. Thus, it shows the effective application area of the proposed antenna. This antenna is designed on an FR-4 epoxy substrate with a dielectric constant [ε_r]) of 4.4 and a loss tangent factor of 0.02. The design constraints of the antenna are inspired by the literature

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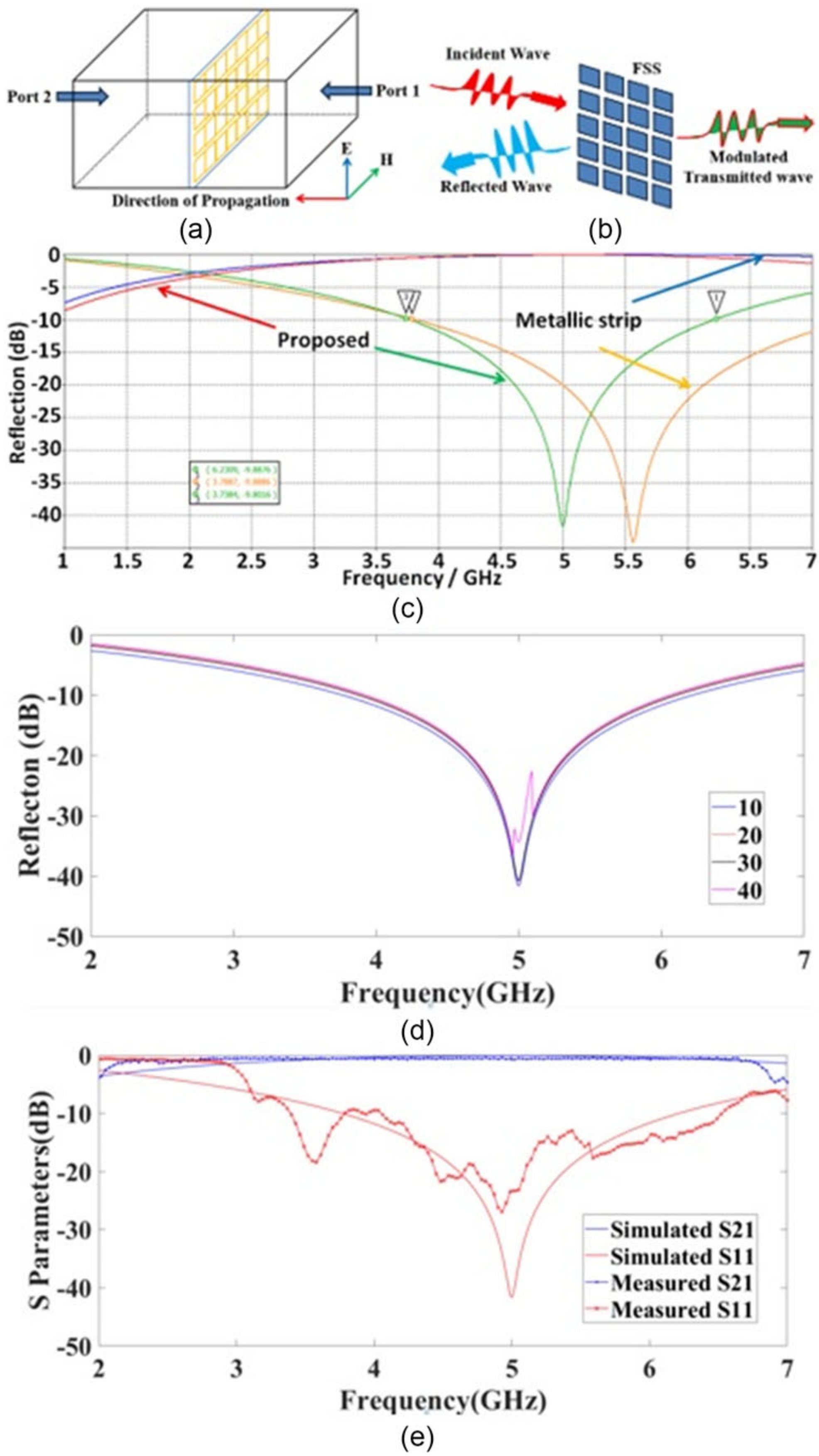

Figure 2. (a) Fields environment for simulation of FSS; (b) conceptual mechanism of FSS; (c) comparison of proposed and general rectangular FSS; (d) reflection graph for different polarization angles of incident waves; (e) simulated and measured s parameters.

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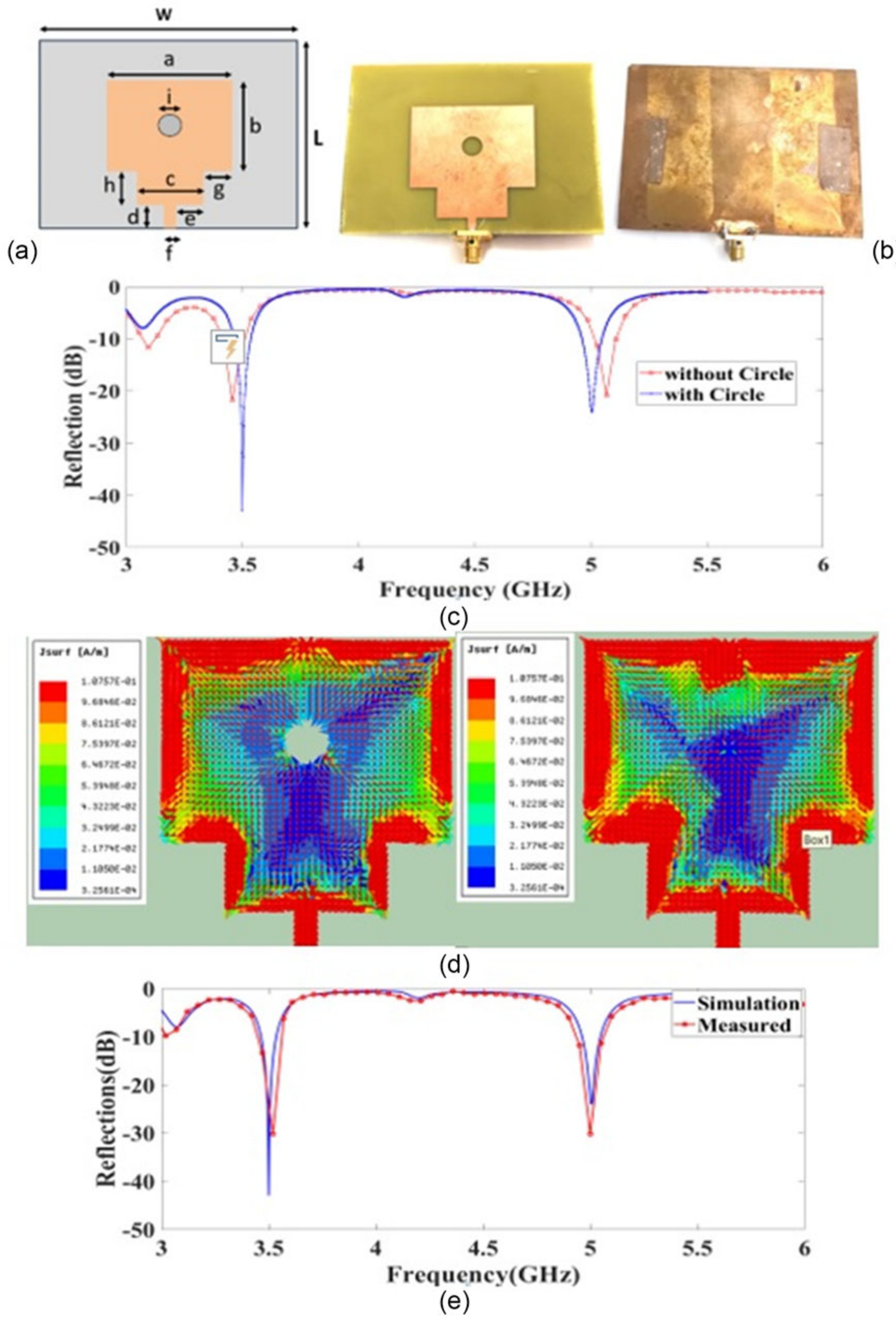

Figure 3. (a) Cross-sectional view of proposed antenna, where dimensions are given as $a = 42.7$ mm, $b = 29.6$ mm, $w = 86$ mm, $l = 62$ mm, $h = 10.5$ mm, $c = 23.8$ mm, $d = 5.7$ mm, $f = 3$ mm, $i = 7$ mm, 9.45 mm. $e = 10.4$ mm; (b) fabricated antenna; (c) comparison of reflection graph for the effect of circle; (d) surface current graph for with and without circle; (e) simulated and measured reflection graphs.

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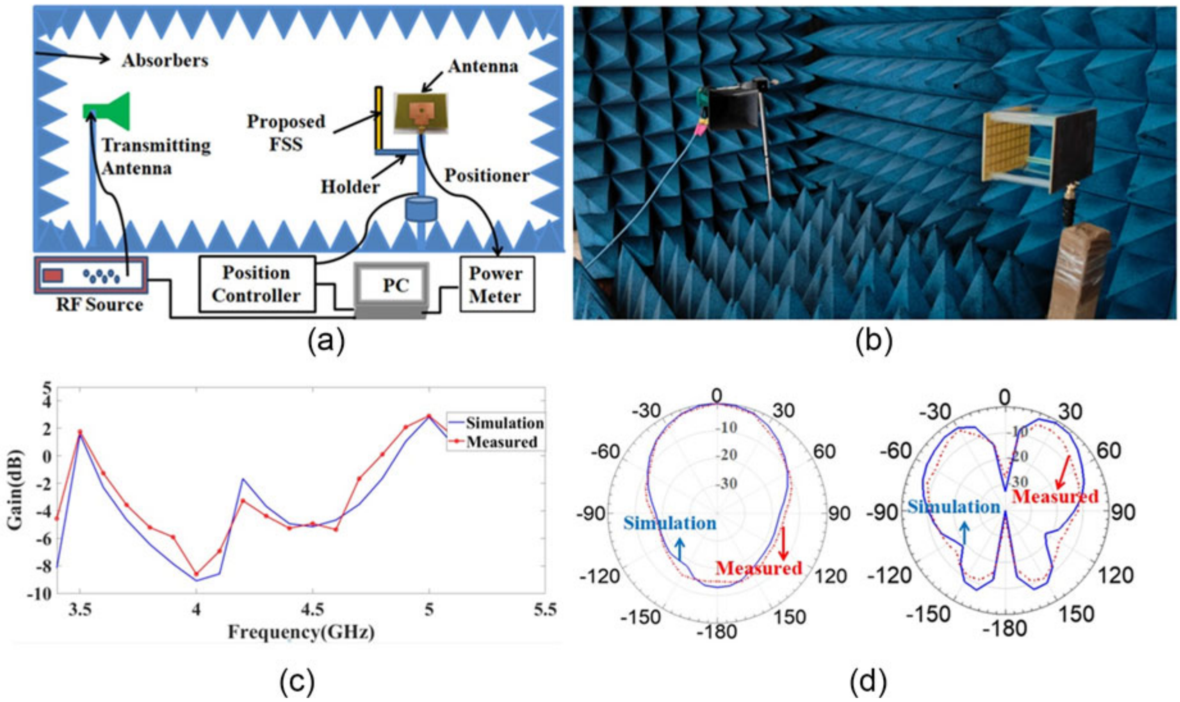

Figure 4. (a) Conceptual setup for measurement of radiation pattern and gain; (b) experimental setup; (c) gain; (d) radiation patterns of the proposed antenna.

[24]. The cross section of the designed antenna is given in Fig. 3(a). The corresponding dimensions of the proposed antenna are calculated using the equations (1–3) available in the literature [28, 29], where ε_{re}, $c_{0,}$ and f_0 are the effective dielectric constant, speed of light, and operating frequency, respectively.

$$\varepsilon_{\mathfrak{R}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12H}{W}\right)^{-1/2} \quad (1)$$

$$\mathrm{W} = \frac{c_0}{2f_{r0}}\sqrt{\frac{\varepsilon_{\mathfrak{R}} + 1}{2}} \quad (2)$$

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{\mathfrak{R}}}\left[\frac{W}{H} + 1.393 = \frac{2}{3}\ln\left(\frac{W}{H} + 1.444\right)\right]} \quad (3)$$

The composition of the antenna is designed, simulated, and optimized in the CST Suite software environment, and the finalized antenna is then fabricated in-house using a chemical etching process on a FR-4 substrate and shown in Fig. 3(b). Whereas, Fig. 3(c) gives the comparison of improvement of the reflection curve over a basic optimized microstrip patch. Introduction of circle creates a discontinuity in the path of the current and thus improves the resonance value with a very slight shift of frequency. This positive shift makes this antenna to operate simultaneously in 3.5 and 5 GHz frequency bands. The corresponding surface current graph is given in Fig. 3(d). The assessment of the simulated and measured reflection is given in Fig. 3(e) that shows considerable similarity between both the outcomes of the antenna. The designed antenna operates in dual frequency bands of 3.4–3.52 and 4.9–5.1 GHz, with a peak gain of 2.8dBi at 5 GHz. Therefore, this antenna has possible applications in Wi-Fi and WLAN frequency band.

The conceptual and experimental setup for the radiation field measurement of the antenna is illustrated in Figs. 4(a) and 4(b), respectively. A reference linearly polarized directive antenna antenna is connected to the R&S SMB100 signal source to generate the radio frequency signal, whereas the surface and antenna are mounted over a rotational stage to rotate the arrangement for measurement of the field patterns. An R&S NRP-40T power sensor is connected to the antenna to record the strength of the received signal. All of these arrangements are enclosed with absorbers to remove the effect of external fields for better measurement accuracy. The radiation patterns (theta and phi) of the antenna are then recorded for every rotational angle of the antenna and given in Fig. 4(d). Whereas, the gain of antenna is recorded for different frequencies using the Friis formula for free space propagation. The measured gain of the fabricated antenna is 1.8 and 2.82 dBi at 3.5 and 5 GHz, respectively.

Performance reconfiguration of antenna using FSS

The designed antenna is associated with the FSS to enhance its various parameters. For this, a 6×9 array is developed and placed along the direction of the main radiation of the antenna. The conceptual representation of the position and functioning of the antenna and FSS is illustrated in Fig. 5(a). For this investigation, the FSS is placed at a distance from the antenna, and this distance (Dis) is varied to record the effect on the performance of the antenna. Figures 5(b) and 5(c) give the outcome of reflection and gain for parametric analysis of the distance (Dis) of the antenna. Whereas, Fig. 5(d) gives the assessment for reflection parameters of the antenna and FSS combination at an optimized distance of 42 mm. The reflection curves show that the combination of the FSS and antenna gives the effective required reflections within the operating frequency range and with an improved gain. The gain of the combination is improved to 3.2 dBi from 2.8 dBi at the 5 GHz frequency. The corresponding surface current and radiation pattern graphs of antenna and FSS combination are given in Fig 5(e) and 5(f),

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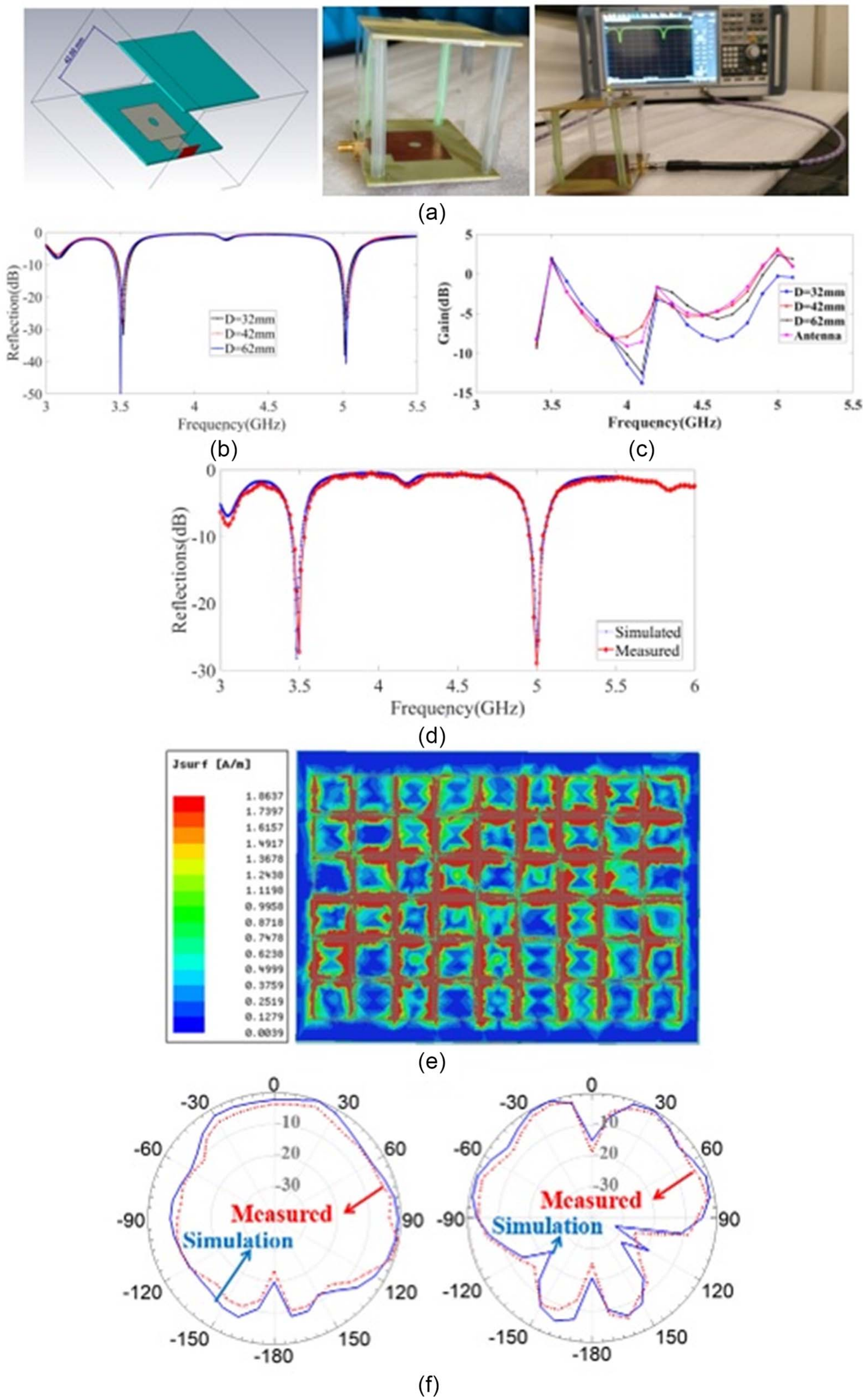

Figure 5. (a) Antenna and FSS arrangement along with the measurement setup of reflections; (b) performance of antenna for different value of distance (Dis); (c) variation of gain for different values of distance (Dis); (d) reflection parameter of antenna along with FSS at Dis = 42 mm; (e) surface current graph of FSS; (f) the radiation patterns of antenna and FSS combined.

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Table 1. Comparison of the proposed FSS with the recent available literature

Ref.	Frequency (GHz)	Unit cell dimension	Application
[18] 2017	5.1–5.25 GHz	9.6 × 9.6 × 1.6 mm^3	Antenna gain enhancement
[19] 2020	3.8 and 5 GHz	16.67 × 16.67 × 1.5 mm^3	WLAN and Wi-Fi
[20] 2021	3.8 and 5 GHz	11.2 × 11.2 × 2.56 mm^3	Antenna stealth
[21] 2022	3.5 GHz	10 × 10 × 1.6 mm^3	High angular and polarization stability
[22] 2024	3.5 and 5.8 GHz	38.5 × 38.5 mm^2	5G and Wi-Fi
[30] 2023	5 GHz (BW: 1.45 GHz)	8.6 × 8.6 × 0.1 mm^3	Electromagnetic shielding
[31] 2022	5 GHz	16 × 16 × 1.6 mm^3	Band stop absorber
[32] 2021	700 MHz and 3.5 GHz	87 × 43.5 mm^2	Fractal 5G
[33] 2022	4.1–5.2 GHz and 5.73–5.89 GHz	15.9 × 14.5 mm^2	5G, WLAN
Proposed	**FSS: 3.5–6.5 GHzAntenna: 3.4–3.52 and 4.9–5.1 GHz**	**9.04 × 9.04 × 1.6 mm^3**	**5G, WLAN, and Wi-Fi**

respectively. Further, the proposed FSS is compared with the recent available literature and listed in Table 1.

The outcome shows that the proposed FSS has the capability of enhancing the gain of an antenna. The work concept is demonstrated with a dual-band, narrow-band antenna. However, the FSS has a wide bandwidth of 3.5–6.5 GHz. Therefore, the proposed FSS has the potential capability for wireless communication for 5 G, WLAN, and Wi-Fi applications.

Conclusion

The presented FSS is designed for wide bandwidth, with peak resonance at 5 GHz. Further, a dual-band patch antenna is also designed and investigated to improve the performance of the antenna in the presence of the FSS. The advantage of the methodology is that the improvement of antenna performance (i.e., gain and return loss) is achieved without any change in the physical structure or dimensions of the antenna. Moreover, there is no need for an external switching circuit to tune the performance. The designed FSS is a generalized structure that can be used with different types of antennas (i.e., microstrip, waveguide, etc.) to reconfigure their performances. Therefore, FSS is an efficient and cost-effective solution for antenna reconfiguration.

Data availablility statement. Data are available based on the reasonable request from the authors.

Funding statement. Authorsdid not receive any funding to carry out this research work.

Competing interests. Authors do not have any conflict of interest.

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