Design of FSS-antenna-radome system for airborne and ground applications

Hafiz Usman Tahseen1 | Lixia Yang2 | Xiang Zhou3

1 School of Computer Science and Communication Engineering, Jiangsu University, Zhenjiang, China
2 School of Electronic and Information Engineering, Anhui University, Hefei, China
3 School of Computer Science and Communication Engineering, Jiangsu University, Zhenjiang, China

Abstract
Radome being an RF window and support structure for an antenna system is a very critical element of terrestrial and airborne radar systems. This paper presents an efficient X-band frequency select surface (FSS)-antenna-radome system for airborne and ground applications. In the first step, an optimum wall configuration with lowest insertion loss is found out of A-sandwich, C-sandwich and multilayers wall configurations. In the second step, two 5×5 arrays (FSS screens) are designed that cover the whole antenna face in the broadside direction for a controlled and secure communication system. A slotted array on a dielectric substrate gives a bandpass feature with antenna for radome operation. A dipole array on a dielectric substrate gives a broader bandwidth with antenna somewhat different from antenna alone. It makes the antenna to stop radiating for a specific band. So, it gives band-stop feature. This proposed FSS-antenna-radome system is demonstrated with an X-band high directional horn antenna over the frequency range 9.4–16 GHz under a sandwich-wall dielectric radome. The bandpass and bandstop features make this proposed FSS-antenna-radome a good candidate for ground and airborne applications for secure communications. In bandpass feature, antenna becomes inaccessible to other antennas/radars except a narrow band.

1 INTRODUCTION
Radome (derived from RADAR + Dome) protects the radiating element (antenna) of a system from wind, rain, rays, ice and high temperature [1]. Radomes are used for protection of terrestrial, airborne, Sat Com and underwater antenna systems. Airborne radomes are used for aircrafts and missiles to protect the antennas inside from severe external environmental conditions [2, 3]. For high speed applications, the radome coating layers protect radome against excessive temperature increments [4]. The radome is an electromagnetic window that protects the exposed parts of an antenna from serious damages. By reducing the external wind/other environmental loads; radome reduces the operational cost of the system too. Radome is an essential part of a radar system. The size and geometrical shape of radome depends on the antenna size and application environment. For ground applications, antenna may be on static platform (fixed earth stations, ground radars) or mobile platform (ground vehicles, ships in sea etc.). For airborne applications, antennas are mounted on commercial and military aircrafts. Radome shape, weight and size are very critical for airborne platform, as the flight platform is highly dynamic and environmental loadings are very high. Most of the large aircrafts and some fighters have blunt shape rounded nose cone whereas supersonic fighters have the sharp tip for a nose cone. Sharp nose cone reduces the drag that makes the shock as weak as possible. A few examples of radome enclosed antenna/radar systems are used for terrestrial, maritime and airborne applications. Internal reflection also causes mismatch that increases the insertion loss too. As the radome is the last element in the transmit chain and first element in the receiving chain in RF path of a radar or any other antenna system; low loss is a critical requirement of any radome for better system design (high transmission efficiency and low noise figure).

A number of methods and techniques have been presented to develop the EM performance parameters of radomes using resonant, anisotropic structures, metamaterials and frequency selective services (FSS) etc. [5–7]. Controllable dielectric structures are also used in the radome wall configurations [7, 8]. In [9] the efficiency and performance of a graded
dielectric inhomogeneous wall configuration for a streamlined nose cone radome is proposed. Radome is designed at 10 GHz and performance analysis is given as a comparison with the constant thickness radome and variable thickness radome.

In [10] a dual band A-sandwich radome is presented for airborne applications where a 3D ray tracing numerical technique is used for antenna radome interaction. In [11] a number of techniques and methods are presented for designs and EM analysis of airborne radomes. It also discusses the challenging EM issues to airborne radome structures.

Furthermore it also discusses the rapid progress in the field of FSS and metamaterials and their impact on radomes. In [12] A-sandwich radome is optimized with genetic algorithm for frequency range 2–27 GHz. In [13] phase distortions are described, caused by inhomogeneous radomes to reveal boresight error (BSE) in the first part and proposes a method to estimate insertion phase delay and BSE. It also describes the performance analysis of an inhomogeneous radome through comparison with the variable thickness radome. The variable thickness radomes are half-wave wall radomes that are known to be narrow banded inherently and are sensitive to errors during manufacturing process [14].

The bandwidth compensation technique and binary particle swarm optimization algorithms are suggested to get flat band-pass response [30–32]. The comparison of BSE and transmission loss (TL) with variable thickness radomes is presented in [15]. The multiobjective particle swarm optimization and 3-D ray-tracing techniques are combined in [16] to optimize BSE and transmission loss for airborne radome applications.

In [17], a 13 × 13 FSS screen array is used over a patch antenna operating at 10.8 GHz to enhance the antenna directivity and passband characteristic. Frequency selective surfaces (FSS) are extensively used in radomes, spatial filters, shielding structures and electromagnetic absorbers due to their resonant structural property either as stopband [18–22] or passband [23–28] performance.

In [29] a metamaterial based FSS dielectric sheet is embedded in the mid-plane of a radome wall structure to analyse the EM performance through comparison with the monolithic radome wall configuration over the frequency range 8.5–10.3 GHz. The bandwidth compensation technique and binary particle swarm optimization algorithms are suggested to get flat band-pass response [30–32].

Based on the literature review [5–32], this paper presents a novel controllable and secure communication technique for an antenna-radome system. It is not only applicable to airborne radomes but also to ground applications. A 5 × 5 slotted array on a FR4 dielectric substrate and dipole array on Quartz Polycyanate dielectric substrate (FSS screens) are used over a high directional antenna surface for a frequency range 9.4–16 GHz in the broadside direction for bandpass and bandstop features respectively. This whole assembly is covered under a dielectric sandwich-wall radome as shown in Figure 1. In the first step, the insertion loss for various sandwich radome configurations is simulated to find optimum radome structure. In the second step, an antenna gain is measured with FSS screens under a dielectric radome. The expected bandwidth variation from large to a small and then small to a narrow band makes this FSS-antenna-radome a controllable and secure communication system. For bandpass feature, antenna becomes inaccessible for other radars/antennas for the entire band except a very narrow band. The EM analysis of the proposed FSS antenna-radome system is performed using ANSYS 18.2 HFSS and validated through experimental results.

The paper is organized as follows: Section II begins with the design and EM analysis of antenna-radome system. Section III discusses the design and EM analysis of FSS-antenna-radome system. The fabrication and measurement of FSS-antenna-radome system lies in the section IV. The final summary is in section V.

2 | DESIGN AND EM ANALYSIS OF ANTENNA-RADOME SYSTEM

A WR-90 high directional horn antenna is designed under a sandwich wall radome to demonstrate the FSS-antenna-radome system for frequency range 9.4–16 GHz. There are many radome wall configurations either monolithic or sandwich. X-band Monolithic or A-sandwich configuration is considered a better choice for radome structures [10, 12]. Half wave radomes have λ/2 or a multiple of λ/2 wall thickness while radomes with thin walls have almost λ/10 thickness.

These radomes have narrow bandwidth however they are structurally rigid and are popular for airborne and ground applications. In A-sandwich wall configuration, high εr skins are separated by low εr core. A-sandwich radome has a very high strength to weight ratio and it has very good electrical performance at various incident angles that makes it a strong candidate for airborne applications. C-sandwich structure has two A-sandwiches back to back. It has five layers and residual reflections from individual A-sandwiches which are further cancelled [33].

Multilayers radomes have more than five layers with very thin skins and suitable cores that can give more strength and
wide-band transmission properties for small angles of incidence [33]. These radomes are often used for broadband applications and have more design flexibility. Radome layers can be represented by an equivalent transmission line. Single layer radome can be considered as a small length of low impedance line. Multilayer radome can be made equivalent to multiple small lengths of a transmission line in series (cascaded configuration). Dielectric layer has an interface on both sides. So, it is a cascaded circuit of three transmission lines (air-dielectric-air), each represented by its characteristic impedance and longitudinal propagation constant. Dielectric layers have different impedances for vertical and horizontal polarization [33]. For A-sandwich (three layers; skin-core-skin), for C-sandwich (five layers; skin-core-skin-core-skin) and for multilayers sandwich (seven layers; skin-core-skin-core-skin-core-skin) are used.

If each skin layer has equivalent ABCD matrix \[
\begin{bmatrix}
A & B \\
C & D \\
\end{bmatrix}
\]
and core has ABCD matrix \[
\begin{bmatrix}
A_c & B_c \\
C_c & D_c \\
\end{bmatrix}
\]
then the overall \[
\begin{bmatrix}
A & B \\
C & D \\
\end{bmatrix}
\]
will be the product of individual ABCD matrices of all layers for A-sandwich radome [11]. With the same pattern, additional matrices for skin and core are added for C-sandwich and multilayer radomes. All these Equations (1)–(7) are radome design equations [11, 12, 33].

Voltage transmission coefficient is:

\[
T = \frac{2}{A + B + C + D}
\]

(2)

Voltage reflection coefficient is:

\[
R = \frac{A + B - C - D}{A + B + C + D}
\]

(3)

ABCD matrix of single layer is:

\[
\begin{bmatrix}
\cos \phi & j \frac{\varepsilon}{\varepsilon_0} \sin \phi \\
\frac{\varepsilon}{\varepsilon_0} \sin \phi & \cos \phi \\
\end{bmatrix}
\]

(4)

Here, the electrical length is:

\[
\varphi = \frac{2\pi d\sqrt{\varepsilon - \sin^2 \theta}}{\lambda}
\]

(5)

where \(d\) = thickness of wall, \(\lambda\) = free space wavelength, \(\varepsilon\) = dielectric constant, \(\theta\) is incident angle and \(\frac{Z}{Z_0}\) is the ratio of impedance in the medium to free space.

For parallel polarization:

\[
\frac{Z}{Z_0} = \frac{\sqrt{\varepsilon - \sin^2 \theta}}{\varepsilon \cos \theta}
\]

(6)

For perpendicular polarization:

\[
\frac{Z}{Z_0} = \frac{\cos \theta}{\sqrt{\varepsilon - (\sin \theta)^2}}
\]

(7)

Transmission loss increases with the incident angle variation for one value of skin thickness. There is a small range of thicknesses of core that offer low transmission loss. In typical construction, a fiberglass skin is used with dielectric constant about 4 and loss tangent 0.015, while the sandwich core of dielectric constant 1.15 and loss tangent 0.002 is used [33]. In sandwich wall configurations, the skin material with 0.03 thicknesses to wavelength ratio is used for variable core thickness [33]. At 9.4 GHz design frequency and 0.0319 meter wavelength, the skin thickness is found to be 0.957 mm with 0.03 thicknesses to wavelength ratio factor [33]. It is observed that more than 95% transmission efficiency is achieved for the incident angle up to 80° at 4.2 thicknesses to wave length ratio from the graphs power transmission versus thickness to wavelength ratio for parallel and perpendicular polarizations [33]. So, the ultimate core thickness is found to be 13.4 mm.

A unit cell is simulated with this core and skin thickness to verify this synthesis as shown in Figure 2. A minimum insertion loss is found with the optimum core thickness 8.5 mm and 0.5 mm skin with dielectric constant 1.15 and 3.23 respectively. Unit cell simulation of A-sandwich, C-sandwich and multilayer radomes at optimum skin and core thicknesses show very low insertion loss for incident angle 0°–80°.

Figure 3 shows the insertion loss for optimum skin and core thicknesses for various incident angles. It is observed that A-sandwich wall configuration has low insertion loss constantly for incident angle 0°–60° like other configurations with a little difference. Then it has a little drop from 60°–80°. Overall A-sandwich wall configuration looks like a better candidate for radome structure, for airborne and ground antenna applications where it can receive better signal with low insertion loss for incident angle 0°–80°. With an optimum A-Sandwich wall configuration, radome is simulated with a high directional horn antenna for antenna-radome demonstration. Antenna is designed for the frequency range 9.4–16 GHz with 5k radome radius and 10λ height. A-Sandwich wall configuration (skin-core-skin) is made with Quartz-Polycyanate skin material and Rohacell_110WF core material.

A little difference is observed in antenna gain with and without radome as shown in Figure 4. It has 20.55 dB gain for radome-antenna structure and 20.21 dB gain without radome.

FSS screens are either used to stop or pass a specific band depending upon the required application. They are designed to transmit, reflect or absorb the electromagnetic waves based on frequency. This paper has one FSS screen as a 5x5 slotted array on an FR4 substrate for a bandpass feature, as shown in Figure 5(a). The second FSS screen is a 5x5 dipole array on a 2 mm Quartz-Polycyanate substrate (Figure 5(b)). FR4 substrate is a 4.4 mm thick sheet and has dimensions 142.65 mm × 111.05 mm. Each slot/dipole size is 5 mm×16.53 mm either in width side or length side crossing the other slot at mid. Slotted and dipole substrate dimensions are same. Inter-element
distances are 10 mm and 4.73 mm in x-axis and y-axis for both FSS arrays. Both FSS screens have dimensions with respect to the size of horn to cover the antenna signals.

3 1 DESIGN AND EM ANALYSIS OF FSS-ANTENNA-RADOME SYSTEM

On the present section, a floquet port is developed on HFSS to study the frequency response of both FSS screens to confirm the synthesis. For floquet port analysis, the frequency responses of unit cells and complete FSS screens both are studied. (Figure 6) Frequency response of both screens in floquet port

FIGURE 2  Unit cells (a) A-Sandwich, (b) C-Sandwich, (c) multilayers

FIGURE 3  Insertion loss with optimum skin and core thicknesses

FIGURE 4  Simulated antenna gain with and without A-Sandwich radome

FIGURE 5  FSS screens: (a) slotted array, (b) dipole array
FIGURE 6 FSS unit cells: (a) slotted unit and (b) dipole unit. Floquet ports for FSS screens: (c) slotted array and (d) dipole array

FIGURE 7 Frequency responses of FSS slotted unit cell

FIGURE 8 Frequency responses of FSS dipole unit cell

FIGURE 9 Frequency responses of 5 × 5 slotted array

analysis shows bandpass and bandstop features for slotted and dipole unit cells and array screens respectively as shown in Figures 7–10.

It is observed from Figures 7 and 9 that slotted unit cell and array screen gives transmission for a very narrow band during floquet port analysis while dipole array screen develops a transmission for a large band (Figures 8 and 10). Figure 11 shows the simulated results of antenna gain with both FSS screens. The antenna gives 20.38 and 19.82 dB gains with FSS dipole array and slotted array screens respectively.

Not much insertion loss is observed in the antenna gain with FSS screens application. Figure 12 shows the simulated reflection parameter of the proposed FSS-antenna-radome system. There is a large continuous band for the horn antenna under A-sandwich radome without FSS screens. The antenna gives a very little and narrow band with slotted array FSS screen under A-sandwich radome for communications as shown in Figure 12. It is observed that antenna impedance bandwidth for dipole array FSS screen operation starts from a point where slotted array screen ends. So, antenna covers the rest of the band with dipole FSS screen. Hence, FSS screens give bandpass and bandstop features with antenna radome system that makes a controllable, reliable and secure antenna communication.
The prototype of FSS-antenna-radome system is made in two steps. In the first step, A-sandwich radome along with a horn antenna is made. In the second step, FSS screens are made and antenna measurements are taken with and without FSS screens.

In A-sandwich radome structure, there are three layers (skin-core-skin). Skin is made with 0.5 mm thick and $\varepsilon_r = 3.23$ Quartz-Polycyanate dielectric material while the core is a Rohacell_110WF material with 8.5 mm thickness and $\varepsilon_r = 1.16$. In Figure 13a, $5 \times 5$ slotted array on a 4.4 mm thick FR4 substrate FSS screen and $5 \times 5$ dipole array on 2 mm thick Quartz-Polycyanate substrate are shown. These both FSS screens are used for bandpass and bandstop features in the proposed antenna-radome system. These screens are used to cover the antenna horn to face the whole signals in the broadside direction.

The antenna-radome system gain is measured in the microwave chamber in a free space measurement as shown in...
So, the complete antenna band is divided into two sub bands (narrow band and wide band) with FSS screen applications. The same antenna can operate in two different bands within the original impedance bandwidth under a dielectric radome. The antenna operation for a narrow band gives a secure communication operation source for airborne and ground applications. The application of FSS screens give bandpass and bandstop features in a good agreement with simulated results. The proposed work combines the features of [10, 12] for an optimum A-sandwich wall configuration with high gain and low transmission loss and the feature of electromagnetic absorbers due to the resonant structure as bandstop [18–22] and bandpass [23–28] operation. The optimum A-sandwich dielectric radome operation with metamaterial based FSS screens for a secure controllable band operation makes this proposed FSS-antenna-radome system a good candidate for airborne and ground applications.

A little difference or discrimination is observed between simulated and measured results due to fabrication. It is also observed that the measured and simulated results follow the same pattern over the selected band (9–16 GHz) as shown in Figure 17. Simulated and measured antenna results with no evident difference describe the feasibility and validity of the FSS-antenna-radome system.

In all reference papers mentioned in Table 1, the insertion loss/transmission loss of antenna-radome system is measured with various radome sandwich configurations (A-sandwich, C-sandwich or multi-layered). It is observed that the insertion loss is taken for scan angle $0^\circ$–$60^\circ$ maximum. The proposed antenna-radome system gives the minimum value of insertion loss with the profile skin and core thickness, and materials of the radome structure.

A little bandpass increment is proposed in [29] with the metamaterial-element based FSS antenna-radome system. The proposed FSS-antenna-radome system gives reasonable bandpass and bandstop features with FSS slotted array and dipole array screens. This novel feature makes this profile FSS-antenna-radome system an attractive candidate for airborne and ground applications.
Table 1: Comparison of related works

| No. | Ref. | Frequency | Insertion loss | Bandpass % | Bandstop % |
|-----|------|-----------|----------------|------------|------------|
| 1   | 9    | 10 GHz    | 0.5–0.62 dB    | Nil        | Nil        |
| 2   | 10   | 1.53–1.6 | 1.6 dB         | Nil        | Nil        |
| 3   | 13   | N.A.      | 0.75–0.93 dB   | Nil        | Nil        |
| 4   | 29   | 8.5–10.3 GHz | 0.3–0.6 dB  | A little increment | Nil        |
| 5   | This work | 9.4–16 GHz | 0.1–0.3 dB  | 2.5 % (slotted array) | 83.33 % (dipole array) |

Figure 17: Simulated and measured gain curves for FSS-antenna-radome system

5 | Conclusion

An FSS-antenna-radome system is presented in this paper. The frequency selection characteristic of FSS materials is used to modify the antenna structure under dielectric radome protection. Out of all three sandwich wall configurations, A-sandwich wall configuration is the optimum one with lowest insertion loss for FSS-antenna-radome system. The development of bandpass and bandstop features of FSS screens in the antenna-radome system makes this proposed structure a good candidate for airborne and ground applications. This article develops a hypothesis for a phased antenna radome system with metamaterial based FSS screens for airborne and ground applications. In phased antenna-radome systems, antenna can change the scan angle of radiation pattern with frequency switching and it can develop band pass and band stop features at different frequencies within the same band. This makes antenna-radome system a more controllable and secure communication system.

References

1. Kraus, J.D.: Antennas. McGraw-Hill, New York (1988)
2. Kozakoff, D.J.: Analysis of Radome Enclosed Antennas. Artech House, Norwood (1997)
3. Yurchenko, V.B., et al.: Numerical optimization of a cylindrical reflector-in-radome antenna system. IEEE Trans. Antennas Propag 47(4), 668–673 (1999)
4. Nair, R.U., et al.: Temperature-dependent electromagnetic performance predictions of a hypersonic streamlined radome. Prog. Electromagn. Res. 154, 65–78 (2015)
5. Chen, F., et al.: Electromagnetic optimal design and preparation of broadband ceramic radome material with graded porous structure. Prog. Electromagn. Res. 105, 445–461 (2010)
6. Pei, Y., et al.: Electromagnetic optimal design for dual-band radome wall with alternating layers of staggered composite and Kagome lattice structure. Prog. Electromagn. Res. 122, 437–452 (2012)
7. Nair, R.U., Jha, R.M.: Novel A-sandwich radome design for airborne applications. Electronics Lett. 43(15), 787–788 (2007)
8. Nair, R.U., Jha, R.M.: Electromagnetic performance analysis of a novel monolithic radome for airborne applications. IEEE Trans. Antennas Propag. 57(11), 3664–3668 (2009)
9. Mohammed Yazeen, P.S., et al.: Electromagnetic performance analysis of graded dielectric inhomogeneous streamlined airborne radome. IEEE Trans. Antennas Propag. 65(5), 2718–2723 (2017)
10. Zhou, L., et al.: Dual-band A-sandwich radome design for airborne applications. IEEE Antennas Wirel. Propag. Lett. 15, 218–221 (2015)
11. Raveendranath, U.N., Rakesh, M.J.: Electromagnetic design and performance analysis of airborne radomes—Trends and perspectives. IEEE Antennas Propag Mag. 56(4), (2014)
12. Ismail, C.O.R., Birsen, S.: Geniş bandlı radom analizi ve eniylenmesi analisisi ve optimizasyonu. In: 26th signal processing and communications applications conference, Izmir (2018)
13. Xu, W., et al.: Study on the electromagnetic performance of inhomogeneous radomes for airborne applications—Part II: The overall comparison with variable thickness radomes. IEEE Trans. Antennas Propag. 63(6), 3175–3183 (2017)
14. Xu, W., et al.: EM performance analysis of radomes with material properties errors. IEEE Antennas Wirel. Propag. Lett. 13, 848–851 (2014)
15. Nair, R.U., et al.: Graded dielectric inhomogeneous streamlined radome for airborne application. Electron. Lett. 51(11), 862–863 (2015)
16. Xu, W., et al.: Multiobjective particle swarm optimization of boresight error and transmission loss for airborne radomes. IEEE Trans. Antennas Propag. 62(11), 5880–5885 (2014)
17. Kurra, L., et al.: FSS properties of a uniplanar EBG and its application in directivity enhancement of a microstrip antenna. IEEE Antennas Wirel. Propag. Lett. 15, 1606–1609 (2016)
18. Foroozesh, A., Shafai, L.: Investigation into the effects of the patch-type FSS superstrate on the high-gain cavity resonance antenna design. IEEE Trans. Antennas Propag. 58(2), 258–270 (2010)
19. Pirhadi, H.B., Nasri, J.: Wideband high directive aperture coupled microstrip antenna design by using a FSS superstrate layer. IEEE Trans. Antennas Propag. 60(4), 2101–2106 (2012)
20. Wu, Z.-H., Zhang, W.-X.: Broadband printed compound air-fed array antennas. IEEE Antennas Wirel. Propag. Lett. 9, 187–190 (2010)
21. Moharamzadeh, E., Javan, A.: Triple-band frequency-selective surfaces to enhance gain of X-band triangle slot antenna. IEEE Antennas Wirel. Propag. Lett. 12, 1145–1148 (2013)
22. Natarajan, R., et al.: A compact frequency selective surface with stable response for WLAN applications. IEEE Antennas Wirel. Propag. Lett. 12, 718–720 (2013)
23. Xu, R., et al.: Dual-band capacitive loaded frequency selective surfaces with close band spacing. IEEE Microw. Wirel. Compon. Lett. 18(12), 782–784 (2008)
24. Chiu, C.-N., Chang, K.-P.: A novel miniaturized-element frequency selective surface having a stable resonance. IEEE Antennas Wirel. Propag. Lett. 8, 1175–1177 (2009)
25. Kim, Y.-J., et al.: Frequency selective surface superstate for wideband code division multiple access system. In: European wireless technology conference (EuWiT), Rome (2009)
26. Yang, G., et al.: A novel stable miniaturized frequency selective surface. IEEE Antennas Wirel. Propag. Lett. 9, 1018–1021 (2010)
27. Deng, F., et al.: Design and performance of a double-layer miniaturized-element frequency selective surface. IEEE Antennas Wirel. Propag. Lett. 12, 721–724 (2013)
28. Yan, M., et al.: A novel miniaturized frequency selective surface with stable resonance. IEEE Antennas Wirel. Propag. Lett. 13, 639–641 (2014)
29. Narayan, S., et al.: Novel metamaterial-element based FSS for airborne radome applications. IEEE Trans. Antennas Propag. 66(9), 4695–4707 (2018)
30. Liu, N., et al.: A feasible bandwidth compensation technique for FSS radome design. IEICE Electron. Exp. 14(13), 20170510 (2017)
31. Yuan, J., et al.: A novel high-selective bandpass frequency selective surface with multiple transmission zeros. J. Electromagn. Waves Appl. 28(17), 2197–2209 (2014)
32. Liu, N., et al.: Design of FSS radome using binary particle swarm algorithm combined with pixel overlap technique. J. Electromagn. Waves Appl. 31(5), 522–531 (2017)
33. Rudge, A.W.: Radomes. In: The Handbook of Antenna Design, vol. 2. IET, London (1982)

How to cite this article: Tahseen HU, Yang L, Zhou X. Design of FSS-antenna-radome system for airborne and ground applications. IET Communications. 2021;1–9. https://doi.org/10.1049/cmu2.12181.