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SCATTERING BEHAVIOUR OF FRACTAL BASED METALLO-DIELECTRIC STRUCTURES

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Abstract—The scattering behaviour of fractal based metallo-dielectric structures loaded over metallic targets of different shapes such as flat plate, cylinder and dihedral corner reflector are investigated for both TE and TM polarizations of the incident wave. Out of the various fractal structures studied, square Sierpinski carpet structure is found to give backscattering reduction for an appreciable range of frequencies. The frequency of minimum backscattering depends on the geometry of the structure as well as on the thickness of the substrate. This structure when loaded over a dihedral corner reflector is showing an enhancement in RCS for corner angles other than 90°.

1. INTRODUCTION

Fractal has found an intricate place in science as a representation of some of the unique geometrical features occurring in nature. Fractal geometry is described as an arrangement of identical or similar elements repeated in different magnifications, orientations and positions. There are a number of geometric properties used to depict fractals [1]; self similarity, fractional dimension and the space filling property. The blend of fractal geometry and theory of electromagnetism paved the way to a new research area known as fractal electrodynamics. Structures based on fractal geometries are finding applications especially in the design of antennas for multiband applications, due to their inherent self similarity and space filling properties [2, 3]. The Sierpinski antenna was the first example of a multi band radiator based on fractal geometry. These antennas keep the same behaviour at several bands in terms of input impedance and radiation pattern. It features as many bands as scales levels in geometry [4, 5]. Some of the other areas of study include frequency selective surfaces, diffraction by band limited fractal screens, the reflection and transmission properties of fractal multilayers, the side lobe computation of fractal arrays, the scattering of electromagnetic wave from corrugated random surfaces with fractal slopes etc. [6–10].

The study of radar cross section (RCS) is of great importance as it is used in modeling many portions of aircrafts and missiles. The development of smart radar systems triggered the scientists to the field of radar cross section reduction during the past few years. Recent interest in RCS is to reduce the detectability of targets. Elimination of specular reflection over a wide range of aspect angle using a strip grating surface of two dimensional periodicity for TE polarization is reported in [11]. Studies for the elimination of backscattering and specular reflections were studied extensively by many researchers [12, 13]. All these structures employ metallization based on conventional Euclidean geometry backed by a flat metallic plate.

Electromagnetic scattering problems of perfectly conducting cylinder and parallel metamaterial cylinders are studied in [14, 15]. RCS of a target with lossy background has been calculated using parabolic equation method in [16]. In order to show the validity of the method the RCS of a conducting cylinder computed using the parabolic equation method is compared with the analytic results. Various techniques are available in the literature for the reduction of RCS of cylindrical bodies. The method of loading impedance as a means of controlling the RCS of objects has been extensively investigated by many researchers. This technique consists of loading the body with lumped or distributed impedances. Its main objective is to calculate the optimum impedance and to position it in the object in order to attain the necessary control of RCS. The minimization of backscattering of a cylinder by loading lumped impedances at two points is reported in [17]. The technique for minimizing the RCS of a moderated cylindrical structure using central impedance loading has been discussed in [18]. Michielssen et al. have reported the reduction of RCS of solid dielectric cylinders using simulated annealing technique [19]. Electromagnetic scattering from corrugated cylinders of circular cross section has been described in [20]. Arvas et al. have reported RCS of dielectric and conducting cylinders of arbitrary cross section using the method of moments [21].

Missiles and aircrafts are complex targets that can be represented as collections of basic geometric elements such as cylinders, cones and flat plates. Studies of the backscattering cross section of corner reflectors are important for many radar applications and are often used as an RCS standard. Corner reflectors are inadvertently formed on ships and military vehicles wherever flat surfaces meet at right angles and form major scattering centers of these objects. They are highly retrodirective and the return persists in angles. An aircraft dihedral effect involves the upper surface of the wing and the curved side of the fuselage. Another similar dihedral occurs between the upper surface of the horizontal stabilizer and the side of the tail fin. Dihedrals increase the probability of radar detection. Right angled dihedral corner reflector provides a large radar cross section over a wide angular range in a plane normal to its wedge, which makes it a suitable reference target in remote sensing and synthetic aperture radar applications. These large echoes from these targets arise from multiple reflections between the two mutually orthogonal flat surfaces dominating the backscattered pattern in forward region, forming the reflectors [22–25]. In recent years several papers dealing with the backscattering by perfectly conducting as well as loaded dihedral corner reflector structures have been published. Dihedral corners have been proposed by many workers in RCS reduction studies and also in RCS calibration target [26–29]. It has also been reported that RCS reduction of dihedral corners can be achieved by altering the mutual orthogonality of the flat surfaces [30]. This technique involves changes in original engineering design of the target. The consequence of non orthogonality on the scattering properties have been analysed in [31].

The large RCS of a 90° dihedral corner over a wide angular range makes it a suitable reference target in remote sensing and synthetic aperture radar applications. The RCS of dihedral corner reflector with acute and obtuse corner angles are less. A slight variation from the 90° corner angle reduces the RCS drastically. This is a major drawback in designing corner reflectors for the applications aforementioned. The backscattered power is appreciably lower for dihedral corner reflector with corner angle other than 90°.

Recently the authors have reported the use of fractal based metallization for the elimination of backscattered power from targets. The maximum reduction in backscattered power is obtained when the metallization is based on the third iterated stage of Sierpinski carpet fractal geometry [32]. The frequency tunability is also possible in this type of structure [33]. This paper deals with the study of the scattering behaviour of different targets such as metallic flat plate, cylinder surface and dihedral corner reflector loaded with metallo-dielectric structures (MDS) based on fractal geometries. The study encompasses three parts. First, the scattering behaviour of Sierpinski carpet fractal structures with different basic geometries etched on substrates of different thickness is presented along with a description of the measurement setup. The second part deals with the backscattering properties of a cylinder loaded with Sierpinski carpet fractal structure and finally the effect of fractal loading over dihedral corner reflector is discussed.

2. METHODOLOGY

The metallo-dielectric structures based on fractal geometries are fabricated by photo etching the metallizations on a dielectric sheet ($\epsilon = 2.56$) of size $30 \times 30\,\mathrm{cm}^2$ and thickness h. The targets of interest (metallic flat plate, metallic cylinder and dihedral corner reflector) are loaded with these metallo-dielectric structures and placed on a turn table inside an anechoic chamber. The structure is illuminated using a horn antenna and the backscattered power is measured using an identical horn antenna kept at the side of the transmitter. The backscattered power at various angles of incidence is measured by rotating the target. The measurements are performed using an HP 8510C network analyzer. The backscattered power from these structures is compared with that of unloaded targets of same dimension.

3. FLAT PLATE

Scattering properties of a flat plate loaded with metallo-dielectric structures are discussed in this section. The schematic of reflector backed metallo-dielectric structure and its cross sectional view are shown in Figures 1 and 2 respectively. Top view of the third iterated stage of Sierpinski carpet fractal geometry using different generators like octagon, circle, hexagon and square are shown in Figure 3.

The variation of backscattered power with frequency for different structures in the frequency range from 4.5 GHz to 16 GHz is illustrated in Figure 4. From the graph it is seen that out of various carpet structures, hexagonal Sierpinski carpet is giving a maximum reduction in backscattered power of $\sim$38 dB at 8.24 GHz for TM polarization for a dielectric thickness $h = 5\,\mathrm{mm}$. Also, this structure is giving a reduction in backscattered power over an appreciable range of frequencies in X-band. Since the structure is not symmetric, the backscattered power obtained is different for TE polarization. A maximum bandwidth (below $-10\,\mathrm{dB}$) of 2.83 GHz is obtained by using square Sierpinski carpet simultaneously for both TE and TM, since the structure is symmetrical.

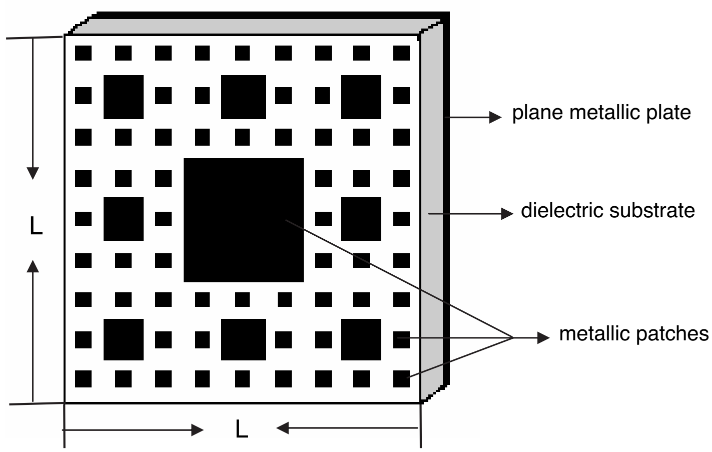

Figure 1. Schematic diagram of reflector backed metallo-dielectric structure of third iterated stage of Sierpinski carpet, $L = 30\,\text{cm}$.

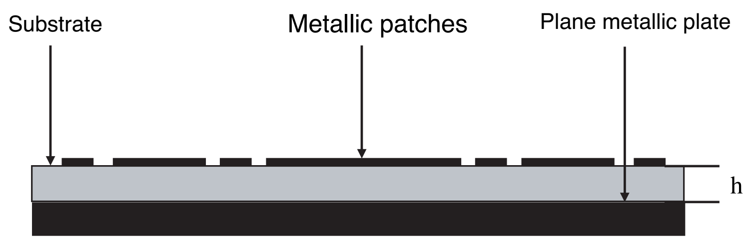

Figure 2. Cross sectional view of metallo-dielectric structure, $h =$ dielectric substrate thickness.

Figure 5 presents the variation of received power with angle of incidence for hexagonal Sierpinski carpet at TM polarization. It is found that the scattered power is distributed symmetrically with respect to normal.

The metallo-dielectric structure can be optimized to give minimum backscattering at a different frequency by varying the thickness of the substrate. Figure 6 illustrates the variation of backscattered power with frequency for the structures fabricated on a dielectric substrate thickness of $h = 10\,\text{mm}$. It is observed that a maximum reduction in backscattered power of about 45 dB at 13.04 GHz is obtained for the structure based on hexagonal Sierpinski carpet for TM polarization. The observations indicate that the reduction in backscattered power is a function of dielectric thickness and it is observed that the reduction at

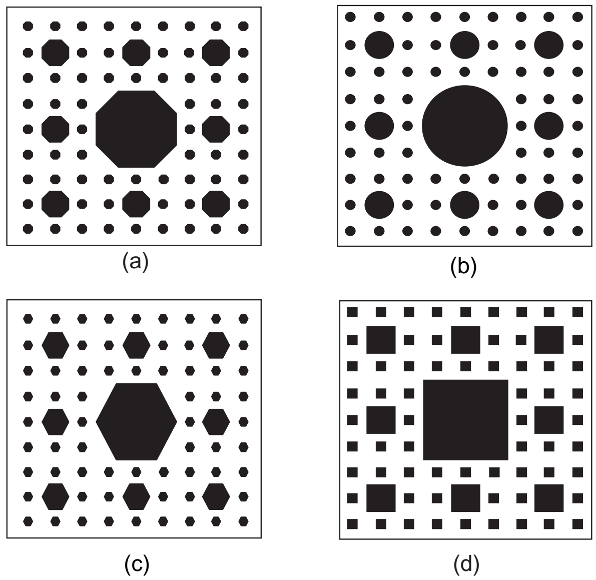

Figure 3. Top view of the modified form of the third iterated stage of the Sierpinski carpet fractal geometry with metallization (a) octagon (b) circle (c) hexagon (d) square.

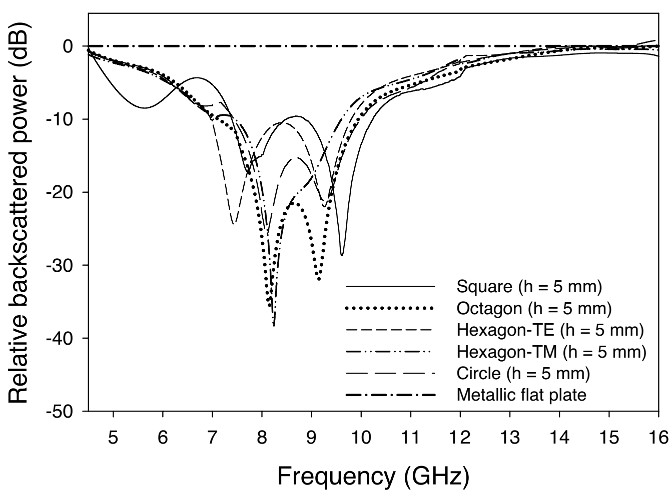

Figure 4. Variation of backscattered power with frequency for different structures of Sierpinski carpet fractal geometry with respect to a metallic flat plate calibrated to 0 dB.

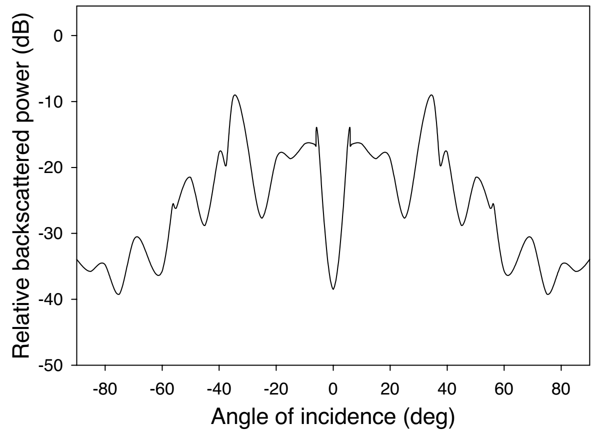

Figure 5. Variation of backscattered power with angle of incidence for hexagonal structure at TM polarization $f = 8.24\,\text{GHz}$, $h = 5\,\text{mm}$.

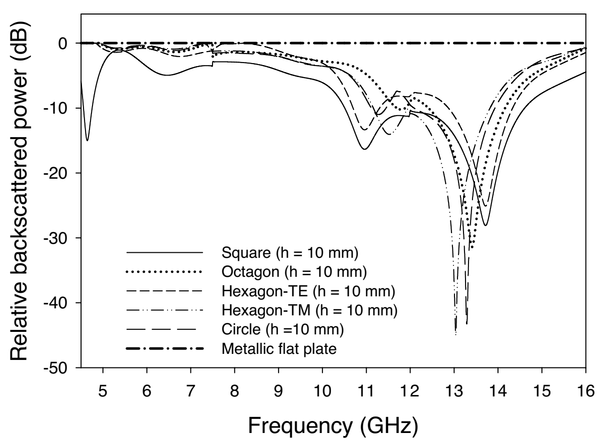

Figure 6. Variation of backscattered power with frequency for different structures of Sierpinski carpet fractal geometry with respect to a metallic flat plate calibrated to 0 dB.

higher frequencies is obtained at a higher substrate thickness. Figure 7 shows the variation of backscattered power with angle of incidence for this configuration. A maximum backscattered power of $-9.5\,\text{dB}$ is obtained at an angle of incidence of $20°$.

The backscattering reduction is obtained simultaneously for both TE and TM polarizations of the incident field for structures that

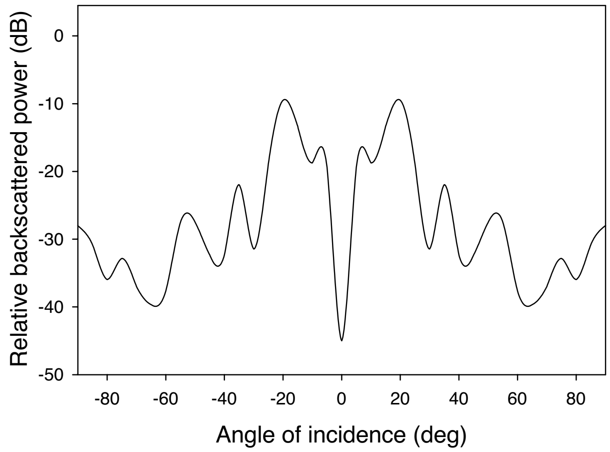

Figure 7. Variation of backscattered power with angle of incidence for hexagonal structure at TM polarization $f = 13.04$ GHz, $h = 10$ mm.

have symmetrical geometries. Table 1 shows the comparison of scattering behaviour of different modified geometries of Sierpinski carpet structures studied in the present work.

Table 1. Optimum dielectric thickness giving minimum backscattered power for different structures.

Fractal structures	Optimum Dielectric Thickness (h)	-10 dB Bandwidth (4.5 GHz–16 GHz)
Sierpinski carpet	5 mm 10 mm	2.83 GHz 4.1 GHz
Octagonal Sierpinski	5 mm 10 mm	2.8 GHz 1.75 GHz
Hexagonal Sierpinski TE-polarization	5 mm 10 mm	2.82 GHz 1.51 GHz
Hexagonal Sierpinski TM-polarization	5 mm 10 mm	2.13 GHz 2.67 GHz
Circular Sierpinski	5 mm 10 mm	2.57 GHz 1.82 GHz

4. METALLIC CYLINDER

The effect of loading fractal based metallo-dielectric structure on a metallic cylinder is discussed in this section. A metallic cylinder loaded with the metallo dielectric structure is shown in Figure 8.

Figure 9 illustrates the variation of the backscattered power with frequency for TE polarization of the incident field for different dielectric thickness. As expected, the reduction in backscattered power depends

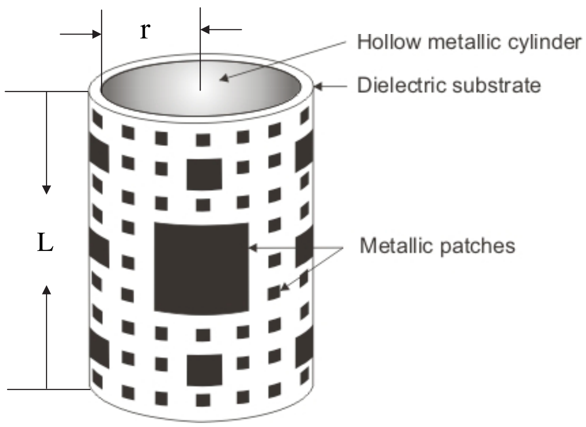

Figure 8. Schematic of metallic cylinder loaded with fractal based metallo-dielectric structure, $L = 30\,\text{cm}$, $r = 9.55\,\text{cm}$.

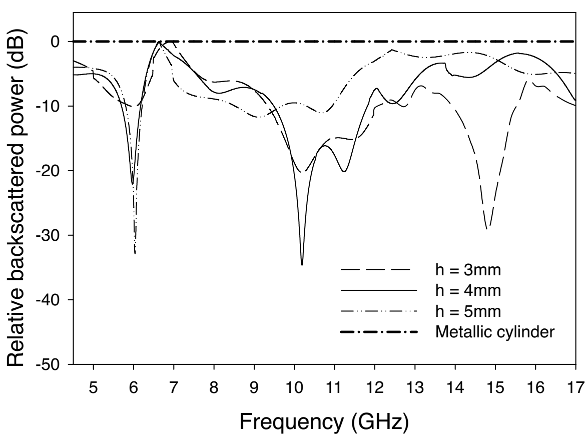

Figure 9. Variation of backscattered power with frequency for TE polarization of the incident field with respect to a metallic cylinder to 0 dB.

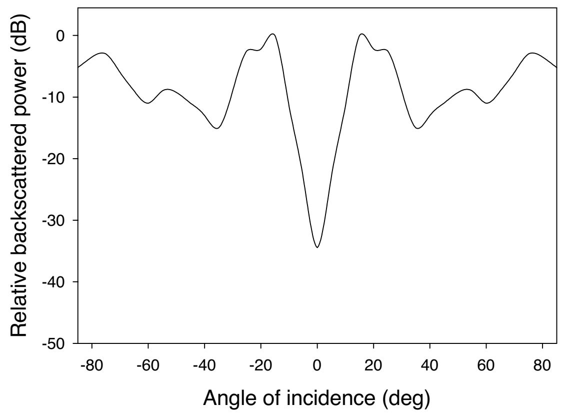

Figure 10. Backscattered power with angle of incidence $f = 10.18\,\text{GHz}$, $h = 4\,\text{mm}$, TE polarization.

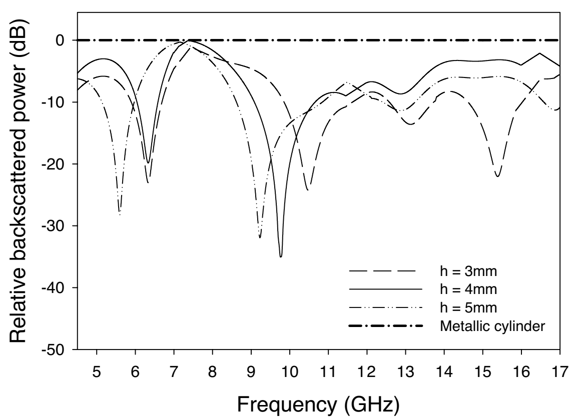

Figure 11. Backscattered power variation with frequency for TM polarization of the incident field with respect to a metallic cylinder calibrated to 0 dB.

on the thickness of the substrate material. A reduction of $\sim 35\,\text{dB}$ in the backscattered power is obtained at 10.18 GHz for a dielectric thickness $= 4\,\text{mm}$. The frequency of minimum backscattered power is also changing with thickness of the substrate. Backscattered power for different angles of incidence for the configuration giving minimum backscattered power is plotted in Figure 10. It is found that, at an angle of incidence of 15°, backscattering is maximum.

Backscattered power at different frequencies for TM polarization of the illuminated wave is plotted in Figure 11. Maximum reduction in the backscattered power of -35 dB is obtained for dielectric thickness ($h = 4$ mm) at 9.78 GHz. Figure 12 shows the backscattered power for different angles of incidence. Maximum backscattered power is obtained at an angle of incidence of 7°. It can be seen that the reflected power is distributed symmetrically with respect to normal. In this case also, reduction in backscattered power is obtained at multiple frequency bands.

Figure 12. Variation of backscattered power with angle of incidence $f = 9.78$ GHz, $h = 4$ mm, TM polarization.

5. DIHEDRAL CORNER REFLECTOR

In this section, technique to enhance the radar cross section of a dihedral corner reflector by loading fractal based metallo-dielectric structures is demonstrated.

The dihedral corner reflector is formed by attaching two square plates of side $L = 30$ cm along a common edge and is so designed that the corner angle (α) can be varied from 0 to 180°. The metallo-dielectric structure attached to the corner reflector as shown in Figure 13. The backscattering from this structure is measured as before by keeping it on a turn table.

Figure 14 presents the variation of backscattered power against frequency with and without loading MDS, for a dihedral corner reflector with 80° corner angle. Maximum backscattered power is obtained at 9.55 GHz for a substrate thickness $h = 3$ mm. The

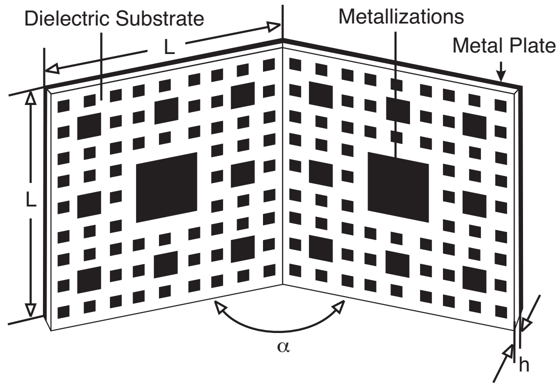

Figure 13. Dihedral corner reflector loaded with metallo-dielectric structure based on Sierpinski carpet fractal, $L = 30\,\text{cm}$.

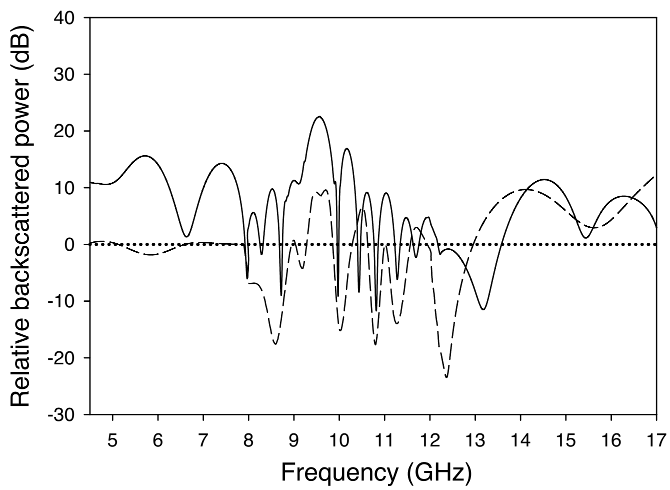

Figure 14. Variation of backscattered power against frequency for a dihedral corner reflector, $\alpha = 80°$, $h = 3\,\text{mm}$. —— MDS loaded, TM polarization, ---- MDS loaded, TE polarization, ······ Plain dihedral corner reflector calibrated to 0 dB.

backscattered power as a function of angle of incidence for this configuration is shown in Figure 15. An enhancement of backscattered power in the range of 15–25 dB is achieved by loading MDS.

The measured results indicate that a maximum enhancement in backscattered power is obtained for TM polarization. The variation in RCS with corner angle at $f = 9.55\,\text{GHz}$ is shown in Figure 16. It

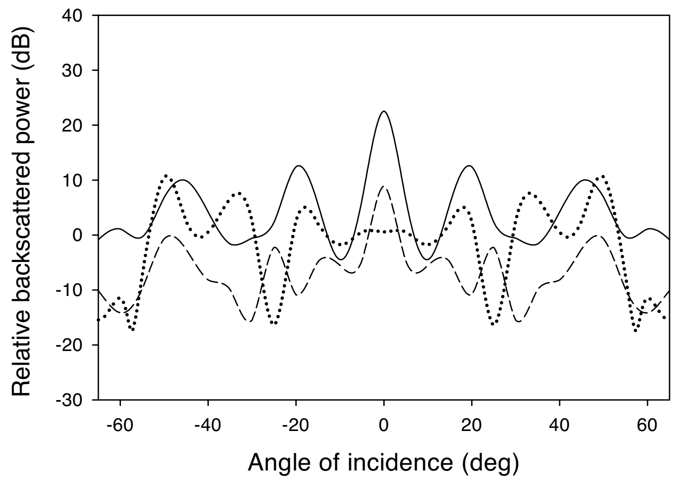

Figure 15. Variation of backscattered power with angle of incidence $\alpha = 80°$, $f = 9.55\,\text{GHz}$, $h = 3\,\text{mm}$. —— MDS loaded, TM polarization, - - - - MDS loaded, TE polarization, $\cdots\cdots$ Plain dihedral corner reflector.

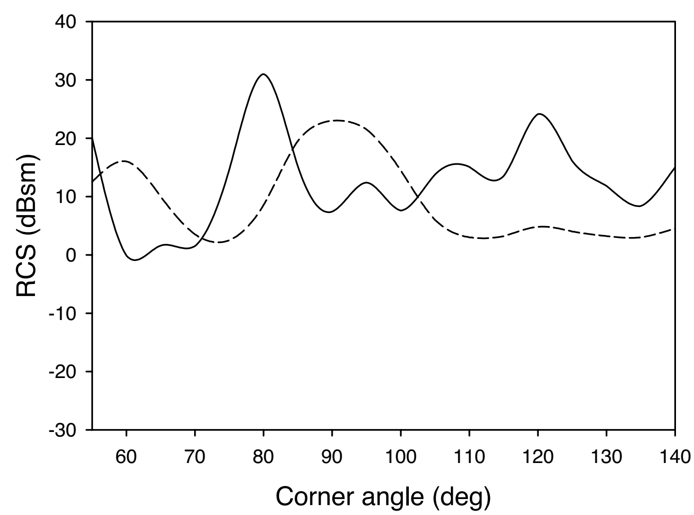

Figure 16. Variation of RCS with corner angle (α), $f = 9.55\,\text{GHz}$. —— MDS loaded, $h = 3\,\text{mm}$, - - - - Plain dihedral corner reflector.

is clear from the graph that RCS enhancement is obtained at certain acute and obtuse corner angles of the dihedral corner reflector when MDS is loaded. The results also show that, maximum enhancement in RCS of 20–30 dBsm is obtained for TM polarization of the incident field, for certain corner angles.

The photographs of the metallo-dielectric structure based on Sierpinski carpet fractal geometries loaded over flat plate, cylinder and diheadral corner reflector are shown in Figure 17.

(a) (b) (c)

Figure 17. Photographs of the metallo-dielectric structure based on Sierpinski carpet fractal geometry loaded over (a) flat plate (b) cylinder (c) dihedral corner reflector.

6. CONCLUSION

Fractal based metallizations on a dielectric substrate are useful in reducing the backscattered power to an appreciable extent from a flat metal plate or cylindrical body. The frequency of minimum backscattered power is a function of dielectric thickness. These properties are observed for both TE and TM polarizations of the incident field for the structures that have symmetry in their geometry. Also, this method is effective in enhancing the radar cross section of a normal dihedral corner reflector over a specific range of aspect angles, above the normal cross section. It is useful when a strong, relatively steady return is desirable for good tracing accuracy, in tracking an aircraft or missile by ground radar.

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