

# Metasurface Design for Monostatic and Bistatic RCS Reduction in X-Band

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**Abstract-** In this contribution, a metasurface has been designed capable of reducing the radar cross section in X-Band. To this end, the analysis and optimisation of its unit cells and, subsequently, of the complete structure has been carried out. Furthermore, it has been designed in such a way that its response is independent of polarization and target size and works for an incidence range of  $[-60,60]^\circ$ . For both monostatic and bistatic, a radar cross section reduction below -12 dB is achieved, which means a reduction in distance of 50%, in a bandwidth of 22.22% (9.2 – 11.5 GHz) for the monostatic case and 19.72% (9.6 – 11.7 GHz) for the bistatic case.

## I. INTRODUCTION

In recent years, stealth technologies have become a field of great interest in both military and civil applications. To address this problem, the scenario must first be analysed from the radar's point of view in order to know exactly what requirements a target has to meet to avoid detection. Thus, reducing the distance at which a target can be detected means reducing its radar cross section (RCS).

To analyse and quantify the RCS, it has to be taken into account that it depends on the size of the target, the angle of incidence, the polarisation and the frequency [1].

There are several methods of RCS reduction that can be generally classified in two categories: absorption [2], [3] and scattering [4], [5], [6], [7]; in addition to physically modify the target. This study focuses on reducing the RCS by scattering the incident waves on the target, so that they are not received by the radar. This is addressed by using metasurfaces, which are artificial flat structures composed of arrays of conductive elements placed on a substrate and capable of manipulating the electromagnetic waves impinging on them. The behaviour of these structures is determined by the design of the unit cells of which they are composed, and which are replicated periodically.

Analysing the published material, the existing works define the RCS reduction as -10 dB compared to a metallic plane. In [4], it is achieved in the 4.1 - 7.6 GHz band (60%), however, this is accomplished by using unit cells with a thickness of 6.35 mm. Another important aspect is that these structures will be shaped over the target, so it is necessary that their thickness is not very high. The works [5] and [6] achieve a 10 dB reduction in the 4.8 - 19.6 GHz (121%) and 7.34 - 64.85 GHz (159%) bands, respectively. Their designs involve varying the thickness of the substrate between the cells, but this complicates fabrication. In addition, the repetition

patterns between cells are not periodic, so the size of the structure is fixed. As already mentioned, the RCS depends on the size of the target, but throughout this study the RCS reduction will be made independent of the target size, which requires a certain periodicity between cells. The same happens with the design of [7], which manages to reduce the RCS below 10 dB in the 5 - 40 GHz band (155%), but only for a given size.

Another aspect to consider is the difference between monostatic and bistatic RCS, where the difference lies on the position of the receiver relative to the transmitter. In a monostatic radar, the transmitting and receiving antenna are the same or are in the same emplacement, whereas in a bistatic radar they are in different locations [8]. This results in two different analyses, since, from the point of view of the target, in a monostatic radar the position of the receiving antenna is known, and the reflection angle of interest is the angle of incidence. However, in a bistatic radar, the target does not know the position of the receiving antenna and, therefore, it is necessary to consider all the angles of reflection. This study will work with both definitions.

In all the above-mentioned articles, it is analysed the reduction of monostatic RCS for a normal angle of incidence and the reduction of bistatic RCS in the specular direction by varying the angle of incidence. Although these are a priori the worst cases, it is necessary to check the behaviour at the other angles of incidence in monostatic and at all angles of reflection in bistatic due to the proper definition of the radar system, since it could be the case that the target is detected in another direction not analysed. In this work the RCS will be reduced both monostatic and bistatic below 12 dB compared to a metal plane of the same size. This ensures that the detection distance of the radar is reduced to 50% in any condition.

Finally, although most of the radar systems work with horizontal polarization, the behaviour for both polarizations will be ensured.

## II. DESIGN METHODOLOGY

A metasurface is composed of unit cells that are periodically replicated, in this case two types of them are combined to create a chessboard metasurface. Therefore, the first step is to study the response of each of the cells both in amplitude and phase. Then, once the structure is complete, its behaviour in RCS is analysed, which is the objective of the study.

The cells of which the metasurface is composed are shown in Fig. 1, where the complete metasurface can also be seen.

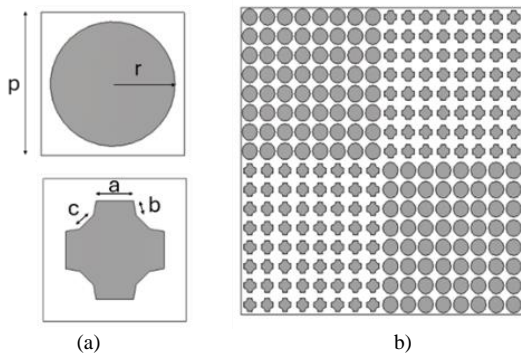


Fig. 1. (a) Unit cells that compose the metasurface. (b) Chessboard metasurface.

Each of the unit cells is composed of three layers: ground plane, substrate and the conductive element. Therefore, the key point of analysis and design is the phase of the reflected waves.

In order to achieve reflection cancellation, a phase difference between the cells of  $180^\circ \pm 45^\circ$  is required. This results in a RCS reduction of 10 dB when surveying the entire metasurface [4]. However, based on the radar equation [8], the maximum detection distance varies at a rate of  $\sqrt[4]{\sigma}$  as the signal travels back and forward. Therefore, in this work the reduction bandwidth is defined more strictly, at -12 dB, so that a reduction in detection distance of 50% is ensured. For this purpose, the aim is still to achieve a phase difference between the cells of  $180^\circ$ , so that their reflections are cancelled, but the critical factor is the margin of phase variation that can be accepted to achieve the 12 dB reduction. Starting from [9] and adapting the conditions to this problem, this deviation can be calculated mathematically by subtracting two vectors. Thus, by relating the phase difference to the minimum required RCS reduction (RCSR), the following equation is obtained.

$$RCSR = \frac{1}{4} [1 + \delta^2 - 2\delta \cos(\theta)] \quad (1)$$

where  $\delta = A_2/A_1$  is the ratio between the amplitudes of the reflection coefficient of each of the unit cells, and  $\theta$  is the phase variation from  $180^\circ$  to ensure a reduction of 12 dB with respect to the metallic plane. Considering  $\delta \cong 1$ , a phase deviation margin of  $30^\circ$  is obtained. From this data, it is possible to deduce a priori the bandwidth in which the metasurface will reduce the radar section of the target. In Fig. 2. it can be seen the phase difference of  $180^\circ \pm 30^\circ$  in the bandwidth from 9 to 11.73 GHz (26.3%) and Fig. 3. shows the phase of the field at 10.35 GHz.

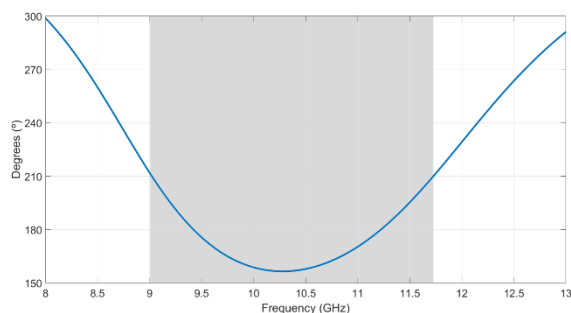


Fig. 2. Phase difference between the unit cells.

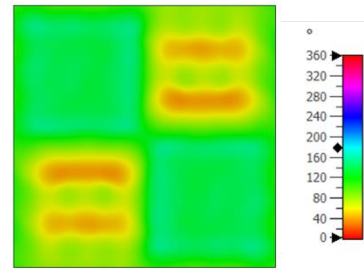


Fig. 3. Distribution of phase.

With these premises, the design consists of a parametric study to characterise each of the unit cells in phase, as shown in Fig. 4. as an example, and their optimisation to achieve the greatest bandwidth within the defined phase margin. For the optimisation, the *MATLAB* optimization algorithm based on surrogates has been used, interacting with *CST Microwave Studio* in order to obtain the best solution.

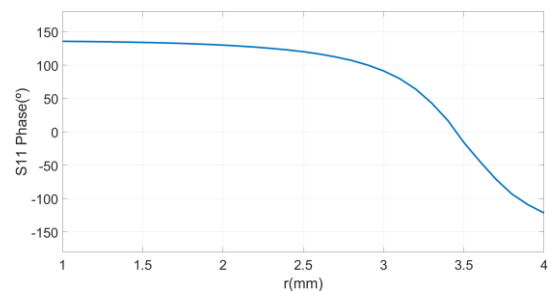


Fig. 4. Phase of the reflection coefficient of the circle cell as a function of its radius.

After the parameter study and the whole optimisation, these are the final parameters of both unit cells, that are simulated with RO4350B substrate ( $\epsilon_r = 3.66, \tan \delta = 0.0037$ ) with a thickness of 1.524 mm.

p (mm)	r (mm)	a (mm)	b (mm)	c (mm)
9.19	4	2.41	0.92	1.26

Table I. Optimized parameters.

### III. MONOSTATIC RCS

Once a first approximation of the metasurface behaviour is obtained from the response of each of its unit cells, it is necessary to analyse the RCS reduction in order to further optimise it. When combining the cells to create the chessboard metasurface, a new optimisation parameter appears: the repetition period of the same unit cell type to form the chessboard design. This parameter, together with all the parameters that make up each of the cells, have been analysed and optimised to achieve the greatest RCS reduction in the widest possible bandwidth.

Fig. 5. shows the monostatic scenario, where the angle of reflection of interest is the angle of incidence.

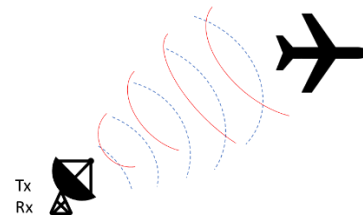


Fig. 5. Monostatic scenario.

As a first step to analyse this monostatic reduction, it will be studied in band with an angle of incidence normal to the surface. For this purpose, the response of the metasurface is compared with a metallic plane of the same dimensions, which is equivalent to the behaviour of the target with and without the metasurface. In Fig. 6. it is shown the result of subtract the RCS produces by the two structures. In addition, unlike the references discussed above, the structure is symmetrical, so it is deduced that the response is the same for both polarizations.

The RCS is a unit of area, so it depends on the size of the target. Therefore, it is important to ensure that the response of the metasurface is maintained regardless of its size. For this purpose, the metasurface in Fig. 1. (b) will be replicated infinitely ensuring that it does not change its behaviour. This ensures that depending on the size of the target on which the metasurface needs to be placed, the size of the metasurface can be adapted, ensuring a 12 dB reduction in the RCS of the target. This can also be seen in Fig. 6, showing the response of the 2x2 and 3x3 replicates. In addition, the response does not depend on the structure being square as can be seen for a 2x3 structure.

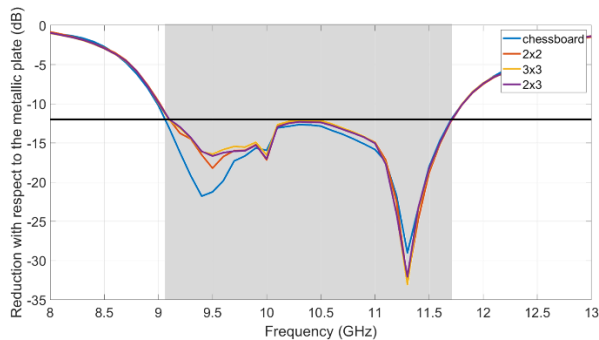


Fig. 6. Monostatic RCS reduction for different replicates varying the metasurface size.

Once the independence with polarisation and size has been assured, it is necessary to analyse the behaviour of the monostatic RCS as the angle of incidence is varied. The problem is that a metallic plane reflects all incident waves towards the specular direction, but this is not the case for the metasurface, as it scatters the waves. Therefore, it is necessary to study the behaviour for all angles of incidence to ensure that none of them worsen the situation. For this purpose, the RCS produced by a metallic plane and the metasurface have been studied by varying the angle of incidence in the range  $[-60, 60]^\circ$  in the main plane  $\varphi = 0^\circ$  at specific frequencies within the operating band. From the radar perspective, to calculate the range, the average RCS of the target is considered and not at a specific point. To translate this to our study, the average RCS reduction has been calculated by taking into account these angles of incidence. Finally, the bandwidth where this value remains below -12 dB has been reduced to 9.2 - 11.5 GHz (22.22%). Fig. 7. shows the RCS produced by the metallic plane and the metasurface, normalised to the plane maximum, at these two frequencies and at the central frequency (10.35 GHz). As discussed above, the RCS of the plane drops significantly as the angle of incidence is varied, and when compared to the RCS of the metasurface, over the whole range it remains below -12 dB with respect to the maximum of the metallic plane. Therefore, it can be concluded that in the whole range  $[-60, 60]^\circ$  the detection distance is reduced to 50%.

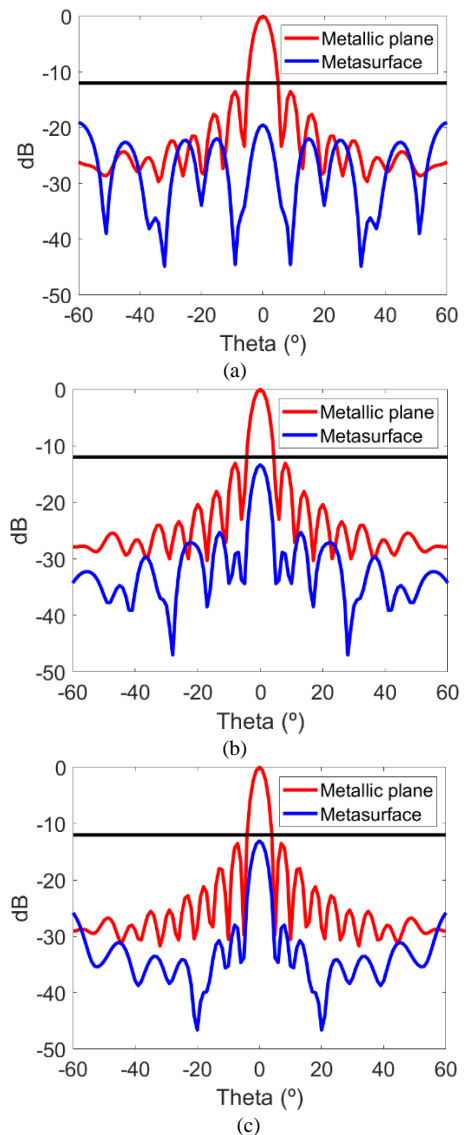


Fig. 7. Comparison between monostatic RCS of the metallic plate and the metasurface for  $\varphi = 0^\circ$  at different frequencies: (a) 9.2 GHz, (b) 10.35 GHz, (c) 11.5 GHz

#### IV. BISTATIC RCS

For the case of a bistatic radar, it is first necessary to understand the scenario under study, since the transmitting and receiving antennas are not located in the same place.

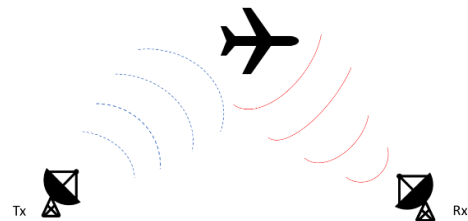


Fig. 8. Bistatic scenario.

When studying the response of the metasurface by varying the angle of incidence it is important to analyse all the reflection angles as the position of the receiver is unknown. Usually, the more critical reflection angle is considered to be the specular with respect to the angle of incidence since this is where the greatest reflection occurs when dealing with a metallic target. Under these conditions, if the receiver is offset

from that angle, the RCS of the target drops drastically, and the radar is not able to detect it [10]. As the metasurface scatters the incident waves in different directions, in this specular angle, the RCS will be reduced. The key point is to ensure that at all other reflection angles, the RCS is not as high as in the specular when illuminating a metallic target. To achieve this, the goal is to generate a diagram as much lobulated as possible.

Analysing the RCS in the specular direction over the same incidence range,  $\theta = [-60, 60]^\circ$ , Fig. 9. shows how the bandwidth below -12 dB decreases as the angle of incidence increases, resulting in a bandwidth of 19.72% from 9.6 to 11.7 GHz for an angle of  $60^\circ$ .

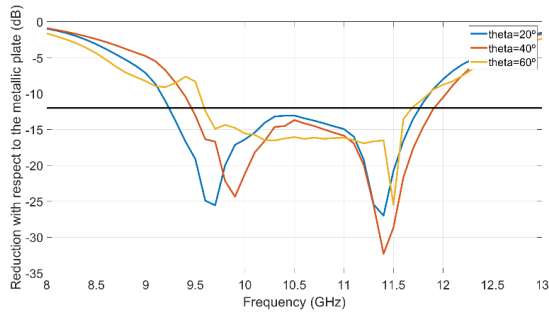


Fig. 9. Bistatic RCS reduction for different incidence angles.

As mentioned above, it is important to ensure that the reflection is not concentrated in another direction since, from a bistatic point of view, all reflection angles have to be taken into account and, in case the reflected wave is concentrated in another direction, the bistatic RCS is not reduced, but simply the direction in which the target is detected is changed. For this purpose, the aim is to generate a multilobed reflection pattern, so that the power is split into different beams. Fig. 10 shows the diagrams obtained with the designed metasurface and it can be seen that this is accomplished and there is no direction at which the RCS is greater than the maximum generated by the metallic plane.

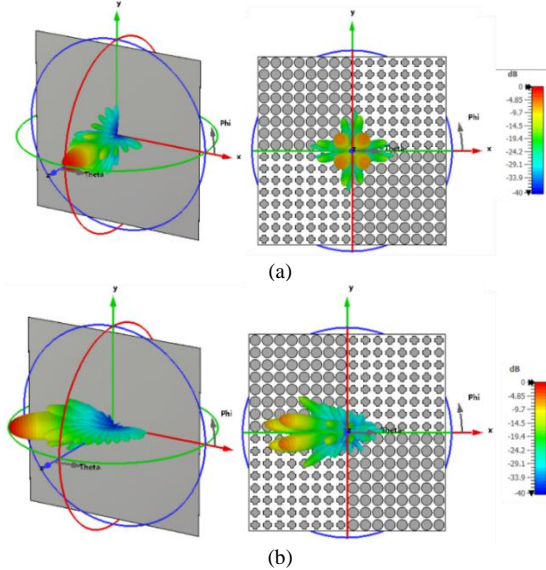


Fig. 10. 3D diagrams of the metallic plane and metasurface at 10.5 GHz (a) with  $\theta = 0^\circ$  (b) with  $\theta = 60^\circ$ .

Further results will be presented at the congress URSI 2024, as well as the manufacture and measurement of the prototype of Fig. 11.

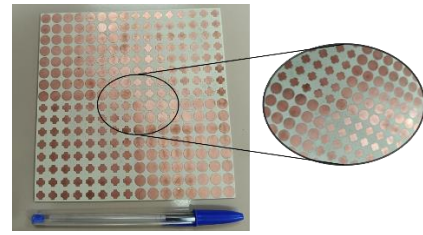


Fig. 11. Prototype.

## V. CONCLUSIONS

The objective of this study was to reduce the RCS in the X-band to at least -12 dB, thus reducing the detection distance versus radar to 50%. After a process of analysis and optimisation, two unit cells have been designed to form the complete metasurface which achieves the objective from both monostatic and bistatic points of view in bandwidths of 22.22% and 19.72%, respectively. This response is achieved independently of polarisation and target size for a range of incidence angles  $[-60, 60]^\circ$ .

## ACKNOWLEDGEMENTS

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