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Exploitation of Floquet analysis for anomalous reflection : experimental validation of a RCS optimisation method.

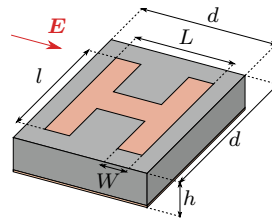
Matthieu Elineau, Renaud Loison, Stéphane Méric, Raphaël Gillard, Pascal Pagani, Geneviève Mazé-Merceur, Philippe Pouliguen

This letter proposes the experimental validation of an optimisation method for periodic metasurfaces. A previous study showed the design and simulation of a classical anomalous reflecting metasurface and enlightened the parasitic reflection induced by the translational invariances of the structure. The method applies to periodic structures, in the framework of the Floquet analysis. It consists of the exploitation of the Floquet type simulation outputs of a periodic element of the structure to predict the behaviour of the complete structure in terms of radar cross section (RCS). The proposed application focuses on the reduction of the RCS level of the structure in one particular Floquet direction. The fabricated metasurfaces and experimental setup are presented with the associated measurements. The well-agreeing simulation and experimental results validate the proposed optimization procedure.

Introduction: The radar cross section (RCS) is a measure of the reflective ability of a target [1]. For stealth purposes, one may want to reduce the RCS of an object. A classical way to do this is to shape the object or to use absorbing volumetric materials for its conception. To address this issue, another possibility recently emerged : metasurfaces. They have generated a wide variety of applications for wave front shaping [2]. Among them, the classical gradient metasurface leading to anomalous reflection has been particularly studied [3]. It allows reflecting an incoming illumination in a non specular direction, which may prove useful for stealth purposes. Such a metasurface consists of the juxtaposition of sub-wavelength scattering elements (the cells) introducing a linearly varying phase shift at the surface of the object. However, these classical gradient metasurfaces exhibit parasitic reflection directions because of the periodic nature of the phase gradient [4]. The scatterers used to cover a gradient period form a supercell that, when periodically replicated to pave the overall surface, excites Floquet harmonics [5]. Translational invariances and associated symmetries in metasurfaces are now widely studied [6].

Recently, we proposed a method [7] to mitigate parasitic reflections of an anomalous reflecting metasurface with a monodimensionally varying gradient, using Floquet analysis. Simulating a supercell in a Floquet environment allows the computation of the $S_{m,n}$ scattering parameters between the different Floquet modes. Assuming $n = 0$ corresponds to the fundamental mode impinging on the metasurface, there is a direct correlation between $S_{m,0}$ and the resulting RCS level in the propagation direction of reflected mode m , defined by an angle θ_m . This means that the outputs of the Floquet simulation (light to simulate) are sufficient to correctly describe the behaviour of the whole structure (requiring a much heavier simulation) in terms of RCS. Going further in this direction, the Floquet simulation S parameters has been incorporated into an analytical model to calculate the total RCS of the structures. This approach has been successfully validated by simulation in [8]. The purpose of the present letter is to provide a complete experimental demonstration and, more generally speaking, to address practical fabrication and measurement issues.

Fabricated metasurfaces: The metasurface initial objective is to reflect a normally incident plane wave into the $\theta_1 = 60^\circ$ direction, with a classical gradient metasurface. The wave reflection occurs in the plane normal to the surface and containing the direction of the gradient. Incoming plane wave is TM polarised and working frequency is 8 GHz. The initial surface is created by designing three cells that produce the linear phase variation required along a gradient period, constituting the supercell. Each cell phase response is simulated using local periodicity assumption, under normal illumination. Cells dimensions are found in the table of Figure 1, with the description of the cell geometrical parameters. The surface is created by replicating the supercell nine times to create an array that is approximately 10λ long. Figure 4 shows the simulated RCS of the initial surface, in blue dashed line. The surface mainly radiates in the intended $\theta_1 = 60^\circ$ direction but also shows a quite high parasitic reflection level in the Floquet direction



		Cell dimensions (mm)		
		Initial		Optimised
q	l_q	L_q	l_q	L_q
1	3	9.881	4.418	9.372
2	3	11.075	3.224	11.119
3	3	11.619	3.132	12.189

Fig. 1 The H shape phase shifting cell. Fixed parameters are $\epsilon_r = 2.17$, $h = 1.6$ mm, $d = 14.43$ mm and $W = 2$ mm. The l and L dimensions are used as degrees of freedom to produce the required phase values.

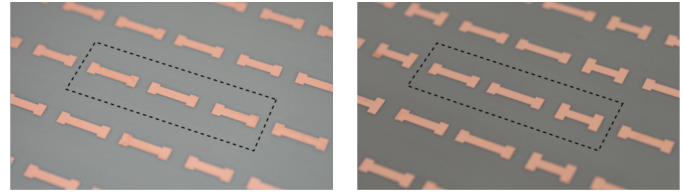


Fig. 2 Close view of the fabricated metasurfaces. Initial (left) and optimised (right) surfaces. A supercell is represented with dashed lines.

$$\theta_{-1} = -60^\circ.$$

An optimised surface is proposed by following the optimisation procedure in [8]. The optimisation is performed at a unique frequency $f = 8$ GHz and consists of the maximisation of the difference between the $S_{1,0}$ and $S_{-1,0}$ parameters, using cell dimensions as degrees of freedom. This process gives an optimised supercell whose dimensions are also listed in figure 1. The use of this optimised supercell results in a 6.80 dB reduction of the RCS level in the $\theta_{-1} = -60^\circ$ direction, as shown in figure 4. Dashed line corresponds to the initial surface and plain line corresponds to the optimised one. Both surfaces, initial and optimised are fabricated with printed copper patches on a Neltec NY9217 copper backed substrate. A 27×27 cells surface is fabricated and gives an array of approximately $10\lambda \times 10\lambda$ (or approximately 40×40 cm²). A close view of each surface is found in Figure 2 where a supercell is enclosed by a dashed line.

Measurement facility: The RCS measurements have been made with a specific 3D measurement facility at the CEA-CESTA, presented in [9]. It consists of an antenna attached on an armature, mounted on a rotating axis. A motor drives the rotation of the whole structure giving access to bistatic RCS measurements. This facility is usually exploited in a monostatic configuration, but, for the current study, an transmitting antenna was added, illuminating the metasurface under normal incidence. The situation is depicted in Figure 3 where both antennas are at a distance $r = 4$ m from the target.

For obvious obstruction reasons, bistatic angles θ for which $|\theta| < 10^\circ$ are not accessible. This is not a problem since the incidences of interest are $\theta = \pm 60^\circ$. The facility in this configuration then gives access to angles from 10° to 90° . The target was flipped after the first angular sweep to reach negative incidences. Despite the fact that the optimisation has been performed at a unique frequency, measurements are made over a 2 GHz

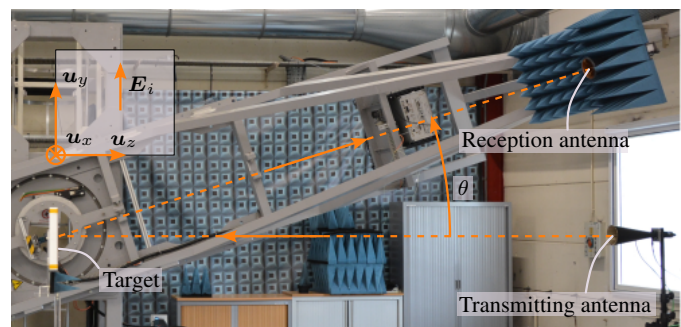


Fig. 3 RCS measurement facility with target under test. Transmitting and reception antennas, bistatic angle θ and \mathbf{E} field polarisation.

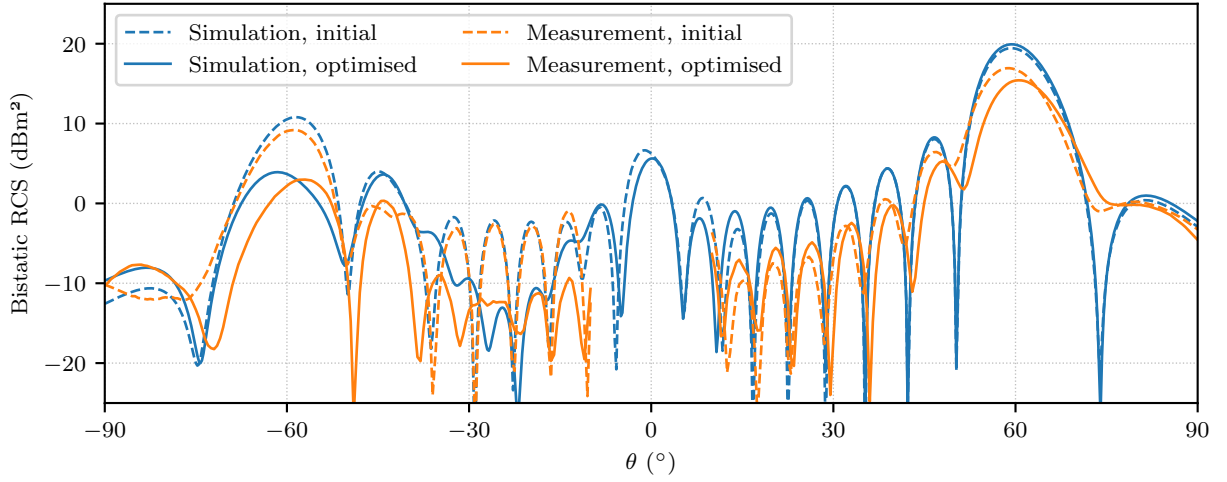


Fig. 4. Bistatic RCS of both initial and optimised metasurfaces, obtained with a full wave simulation of with RCS measurement.

to 18 GHz frequency range to apply spatial filtering, hence removing the contribution of the measurement environment to the received signal.

Results: The measured RCS of the initial and optimised surfaces are represented in Figure 4, with the simulated ones. The measured RCS in the $\theta = -60^\circ$ direction is 9.05 dB for the initial surface and 2.20 dB for the optimised one. This is a 6.85 dB reduction while the simulation shows a 6.80 dB reduction. The agreement between the simulated reduction and the measured reduction is excellent. Globally, the simulation is overestimating RCS values. Actually, the number of assumptions for the synthesis of the surfaces is important (local periodicity, infinite environment, description with only a phase response, phase response computed at only one frequency). This large amount of assumptions makes the optimisation process very efficient. For the synthesis and simulation steps, every computation is made with far field considerations. From a measurement point of view, with an object that is approximately 40 cm long and an antenna at 4 m from the target, the far field hypothesis is not accurate. This would be the first hypothesis to address in order to explain the simulation to measurement disagreement.

Figure 5 shows the evolution of ΔRCS , the optimisation performance. It is defined as $\Delta\text{RCS}(f, \theta) = \text{RCS}_{\text{opti.}}(f, \theta) - \text{RCS}_{\text{init.}}(f, \theta)$ where f is the working frequency and θ is the direction of observation (*i.e.* the bistatic angle). The evolution of $\Delta\text{RCS}(f, \theta = -60^\circ)$ is in orange thick line in Figure 5. For clarity purposes the trace domain is restricted to the 6 GHz to 10 GHz frequency band, while the measurement was, as said earlier, conducted in the 2 GHz to 18 GHz band. It is observed that the optimisation is performing in a very narrow frequency band. We report a 3 dB reduction in a thin 0.2 GHz band, that is represented by a grey rectangle in Figure 5. A large region around 9 GHz interestingly shows a very good performance over a 1 GHz band. It should be kept in mind that no design rule has been followed toward the synthesis of a wide band device. More generally, metasurfaces devices fail to handle wideband phenomena, or at a cost of sophisticated synthesis procedures (multi scales or multi layer devices [10]) that are not practical for stealth applications. For completeness, $\Delta\text{RCS}(f, \theta = \theta_{-1})$ has been calculated, where θ_{-1} is the $m = -1$ Floquet mode direction which varies with frequency. This curve is shown as a thin grey line in the same figure. The trace shows a similar behaviour around the central frequency.

Conclusion: This study demonstrates the relevance of the optimization method by proposing a measurement of an optimised surface. The simulation and measurement exhibit a RCS reduction of almost 7 dB, in the direction of the parasitic lobe, with an excellent agreement between them. It has been made possible by the simplicity of the Floquet type simulation and the correct use of its outputs to predict the behaviour of the surface. The method should not be limited to the RCS reduction in a particular direction. One could consider applying this method for any power repartition, in other directions or multiple ones, as long as one stays in the framework of the Floquet analysis.

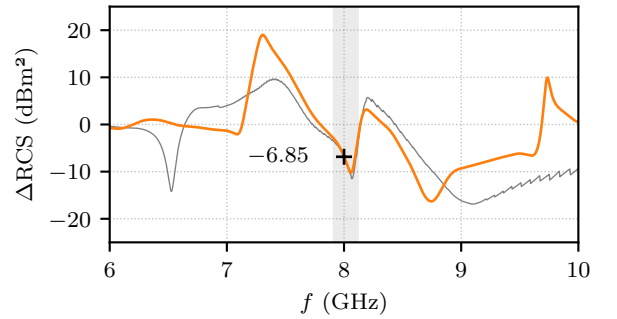


Fig. 5 Evolution of the RCS reduction over the frequency range, in the $\theta = -60^\circ$ direction (thick orange line) or in the $\theta = \theta_{-1}$ direction (thin grey line).

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