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Inverse design of sub-wavelength metadeflectors for an ultra-flat antenna system in Ka-Band

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Résumé — A inverse design methodology is developed to optimize a sub-wavelength metadeflector structure used on an ultra-flat antenna system in Ka-band. The strategy adopted combines two ingredients : a high order HDGFD (Hybrid Discontinuous Galerkin Frequency-Domain) solver of the frequency-domain Maxwell equations coupled to a Floquet modes decomposition for the numerical characterization of the infinite periodic Macro-cell design of the deflector and the EGO algorithm for the optimization of the geometrical characteristics of constituting dielectric pillars. The deflector was specifically designed for Ka-band operation, achieving a 30° deflection at 29GHz, which enables a maximum scan angle of 66° by employing two deflectors using the Risley scanning concept.

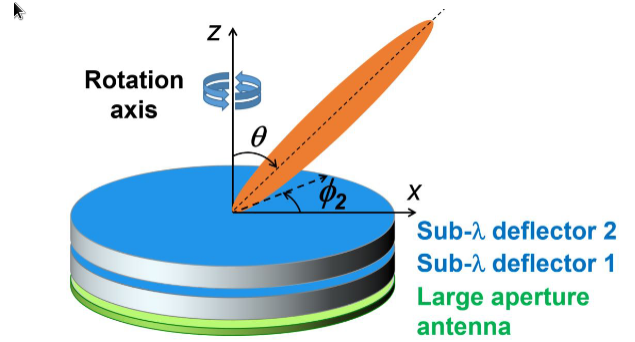


FIGURE 1. (a) The proposed 2D-beam-steering antenna (b) Risley scanner concept

1. Introduction

Enabling the Internet accessibility in mobility, in particular on board of public land and air transport (trains, buses, airliners), as well as the access to secure communication servers (for combat aircraft or military vehicles, etc.) requires the development of agile, ultra-flat and low-cost Ka-band antennas. Nonetheless, meeting the targeted performance while ensuring a low-profile and cost-effective antenna is a major challenge. To address it, the antenna architecture proposed in this paper consists of a planar radiating panel associated with two compact metadeflectors, whose rotation ensures the beam-steering capacity. Moreover, the compactness and the moderate cost of the deflectors can be obtained thanks to the subwavelength structuration of a dielectric matter by using additive manufacturing. Indeed, the sub-wavelength patterning technique has recently shown the possibility to realize antenna components much thinner than their homogeneous bulk counterparts, with equivalent or even better radiofrequency performance.

The objective of this work is to develop an advanced numerical methodology for the virtual design of subwavelength structured deflectors and their cascading to achieve an ultra-flat Ka-band antenna system composed of two such metadeflectors. Our recent initiatives focus on addressing this objective through the utilization of two leading numerical a high order discontinuous finite element method for the simulation of the electromagnetic problem,

and a statistical learning-based global optimization technique.

2. Methodology

2.a. Risley concept

The proposed antenna architecture is inspired by optical approaches based on Risley scanners [1, 2]. The typical system contains a RF feed and two independently rotatable prisms. This configuration enables 2D-beam steering within a wide angle scanning by manipulating the individual rotations of the prisms. Figure 1 presents a general view of our proposed system based on Risley concept. It composed of a radiating source emitting a linearly TE/TM polarized electromagnetic wave in Ka-band and a pair of rotatable compact sub-wavelength all-dielectric deflectors positioned in the near-field region above the antenna to steer the beam to a desired angle. The direction of the 2D-scanning beam can be analytically predicted using the phase method [3]. To achieve a full coverage of the solid conical area, it is necessary to employ the same deflection angle α for both deflectors. Thus, the elevation and azimuth angles of the beam can be calculated using

$$\theta = \arcsin(\sin(\alpha) \sqrt{2 [\cos(\phi_2 - \phi_1) + 1]}) \quad (1)$$

$$\phi = \arctan\left(\frac{\sin(\phi_1) + \sin(\phi_2)}{\cos(\phi_1) + \cos(\phi_2)}\right) \quad (2)$$

where ϕ_1 and ϕ_1 are the rotation angles from x-axis of the two reflectors respectively (see Figure 1)

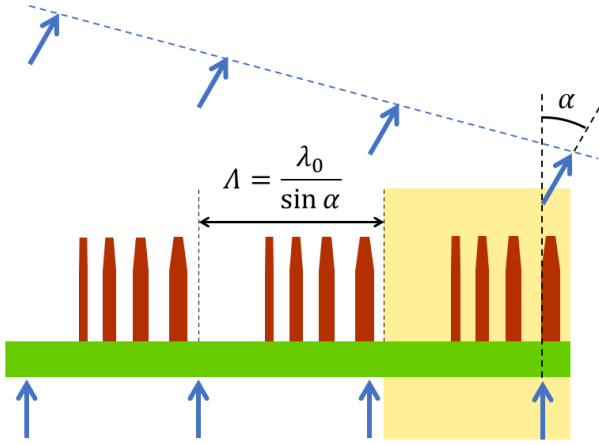


FIGURE 2. Profile view of a part of a sub-wavelength deflector. The periodic Macro-cell is highlighted in red

2.b. Design of the Sub-wavelength deflectors

The deflector was specifically designed for Ka-band operation, achieving a 30° deflection at 29GHz. This design enables a maximum scan angle of 66° by employing two deflectors within the Risley scanning system. To generate the beam deflection, the required phase profile along the deflection plane (along y-axis for example) is calculated for the desired deflection angle α at the design wavelength λ_0 using

$$\varphi(y) = \frac{2\pi}{\lambda_0} \sin(\alpha)y \quad (3)$$

To respect the compactness of the deflector, the repeated phase profile over a 2π -cycle is used instead of the absolute phase. The period Λ of the sub-wavelength deflector corresponding to a 2π -cycle, is calculated from the designed wavelength λ_0 and the desired deviation angle α , as follows

$$\Lambda = \frac{\lambda_0}{\sin(\alpha)} \quad (4)$$

The deflectors is designed to refract an incoming plane wave of normal incidence by an angle of 30° at 29 GHz. This lead to period $\Lambda=20\text{mm}$ (with 4 pillars per period). In our case, cylindrical sub-wavelength pillars are used to synthesize the computed phase profile. This way, we can locally control the phase and generate a desired phase profile. A composite material with high permittivity and low loss ($\epsilon_r = 7$, $\tan \gamma = 0.001$) is used for the deflector design.

2.c. Full-wave analysis

A full-wave approach is used to characterize metadeflectors based on cylindrical pillars by solving the complete system of 3D frequency-domain Maxwell equations. The simulations were performed with a Hybrid Discontinuous Galerkin Frequency-Domain (HDGFD) solver that we have recently developed [4, 5, 6] and which is implemented in the DIOGENeS software suite [7], programmed in Fortran 2008 and tailored for high-performance computing systems.

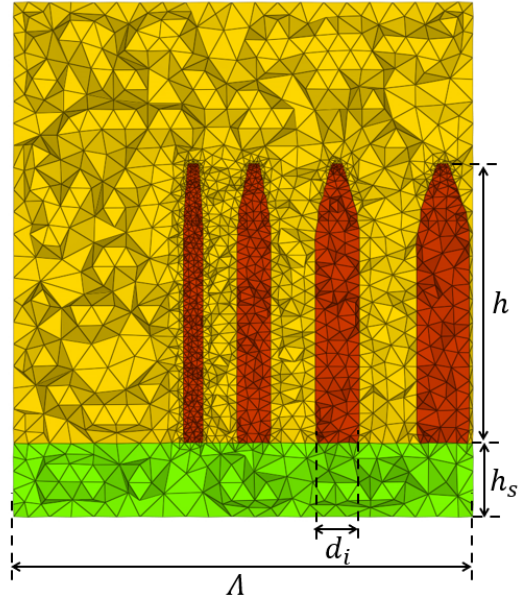


FIGURE 3. The design configuration of the full-wave simulation

In this cas, the grating structure can be modeled as infinite periodic structure with linearly phased periodic electromagnetic field. Therefore, we can describe how the transmitted electromagnetic field divides between diffraction orders modes by using Floquet modal decomposition, which yields to define and compute the mode diffraction efficiency $\eta_{m,n}$ on the Ka-band frequency ranges. An illustration of the periodic Macro-cell of the metadeflector simulated by HDGFD is shown in Figure 3. A linearly polarized plane wave used as incident wave, excited at the lower Floquet port. Therefore, the diffraction efficiencies are computed at the upper Floquet port. The objective is to enhance the diffraction efficiency of the $(0,+1)$ mode order which correspond to the desired angle of the beam steering, while concurrently minimizing the efficiency level for other diffraction modes.

2.d. Optimization method

A inverse design problem is formulated to optimize the deflector's Macro-cell structure. In this case, the diffraction efficiency $\eta_{0,1}$ in the desired diffraction ordre $(0,+1)$ and for the intended linear polarization (TE/TM) serves as an objective cost function. This inverse problem aims to determine the shape and dimensions of cylindrical pillars to maximize the cost function's value. Solving this inverse problem requires rigorous and computationally efficient optimization techniques capable of handling a large number of parameters while minimizing solver calls.

Therefore, we consider one of the most advanced optimization techniques based on a statistical learning approach, which is known as Efficient Global Optimization (EGO) [8, 9] and belongs to the class of Bayesian optimization methods. The EGO algorithm is a global optimization algorithm that substitutes the complex and costly iterative electromagnetic evaluation process with a simpler

and cheaper model. Contrary to the traditional common global optimization strategies like genetic algorithm, EGO is not based on adaptive sampling, but on a surrogate model to built on the basis of available fitness observations, which is employed to decide which new design should be tested next. This surrogate model utilizes a statistical learning criterion related to the optimization target (usually called merit function) in order to identify which design (set of parameters) should be tested in the next iteration that would provide better results close to the predefined goal.

In general, the EGO is based on two phases. The first one is the Design Of Experiment (DOE), in which an initial database is generated. In essence, a uniform sampling strategy is deployed in order to generate different designs in which the cost function is evaluated using our electromagnetic HDGFD solver. In the second, phase, using the data obtained from the DOE, a Gaussian Process (GP) model, is constructed to fit these data. This GP model allows us to predict the values of the cost function in the parameter space without the need to perform additional simulations. Therefore, one can estimate at any point of the design space, the objective function (mean of the GP model) and an uncertainty value (variance of the GP model). The mean and the variance are used together to determine a statistical merit function. In our case, we rely on the expected improvement, which is a function whose maximum defines the next design parameters set to be evaluated. That is to say, in the search parameter space where this function is maximized, we extract the corresponding parameter values, and the corresponding design will be simulated using the HDGFD solver. Then the database is updated accounting for this new observation (construction of a new GP model based on the updated database). We repeat this process until a predefined convergence criterion is reached, or when the expected improvement is sufficiently small.

3. Numerical Results

3.a. Simulation configuration

The objective is to optimize the design of a metadeflector into the frequency range of $[27.5GHz, 31GHz]$ in the ka-band. The period of the Macro-cell along y is given by $P_y = \Lambda = 20mm$ and the period along x is chosen $P_x = 2.6mm$. A substrate support base of 3-mm-thickness is added to ensure the mechanical rigidity of the deflector. The excitation is a plane wave with linear TE/TM polarization.

The design parameters to optimize include the radius r_i and height h of the pillars : $d_i \in [0.8mm, 2.4mm]$ and $h \in [6mm, 15mm]$ with $i \in \{1, \dots, 4\}$, leading to 5 optimized parameters. For a linear polarization, which combines both TE and TM polarizations, the objective is to maximize their sum $S_\eta = (\eta(0, +1)_{TE} + \eta(0, +1)_{TM})/2$ and minimize their difference $D_\eta = |\eta(0, +1)_{TE} - \eta(0, +1)_{TM}|/2$. Thus, the optimization problem can be written as

$$\text{Minimize } f_\eta(\mathbf{d}, h) = 1 - S_\eta + D_\eta \quad (5)$$

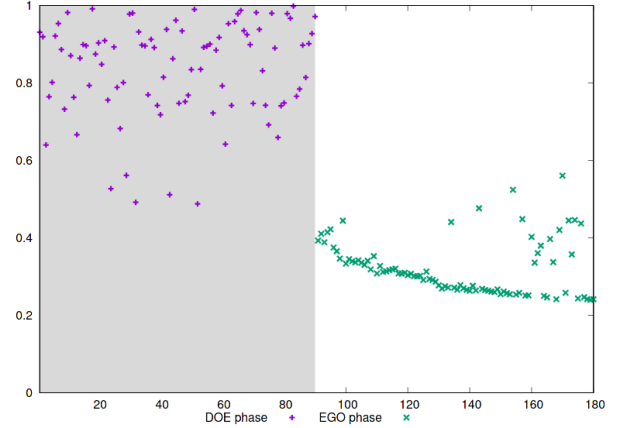


FIGURE 4. Optimization using the EGO method as a function of the number of full-wave solver calls

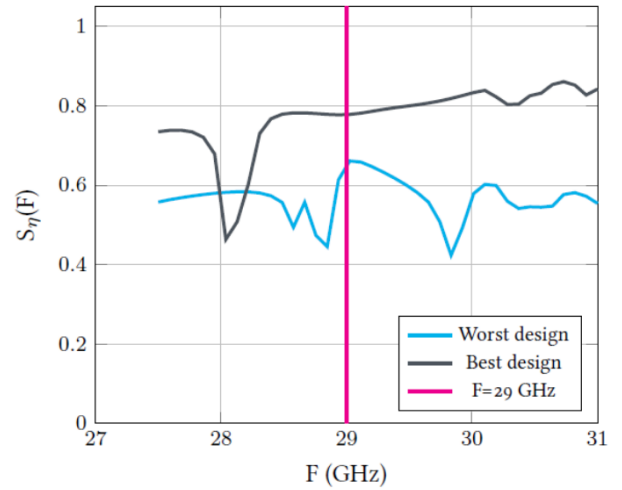


FIGURE 5. The design configuration of the full-wave simulation

3.b. Macro-cell optimization results

As explaining previously, the optimization has been realized using the EGO method. At the first phase, we built a DOE database with 50 points. In the second phase, EGO phase, a surrogate model is constructed based on these DOE designs and is used during the optimization process to find a global minimum. Figure 4 summarize the optimization process, in which the objective function evaluations of the DOE are presented by the purple points and the evaluations obtained during the EGO phase are presented by the green points. The results have been obtained using a finer mesh and a HDGFD- \mathbb{P}_2 .

The evaluation of the diffraction efficiency S_η as a function of the frequency is represented in figure 5. A comparison is depicted between the optimized best design and the least effective design. The best one achieves a notably high diffraction efficiency, reaching approximately 80% at around 29 GHz, compared to 65% in the worst-case scenario. The parameter values of the optimized structure are presented in Table 1.

Best design			
i	y_i	d_i	h
1	1.282	2.364	12.18
2	5.895	1.994	12.18
3	9.539	1.532	12.18
4	12.189	0.882	12.18

TABLEAU 1. Best design parameters

3.c. Correlation between the infinite Macro-cell and the finite complete deflector

To validate the periodic Macro-cell results, the diffraction efficiency obtained from the optimized structure is compared to the results from a finite full-deflector simulations for two diameters : $D = 9cm$ and $D = 26cm$. The complete deflector system was simulated with the Transient Solver of CST Microwave. The excitation used is a linearly polarized Gaussian source. Figure 6 shows the diffraction efficiency and the Side Lobes Level (SLL) as a function of frequency obtained from the three simulations.

The results indicate a good agreement among the three simulations in terms of diffraction efficiency levels. Additionally, the SLL are even lower in the finite case, further validating the approach of optimizing the Macro-cell using periodic boundary conditions (PBC).

4. Conclusion

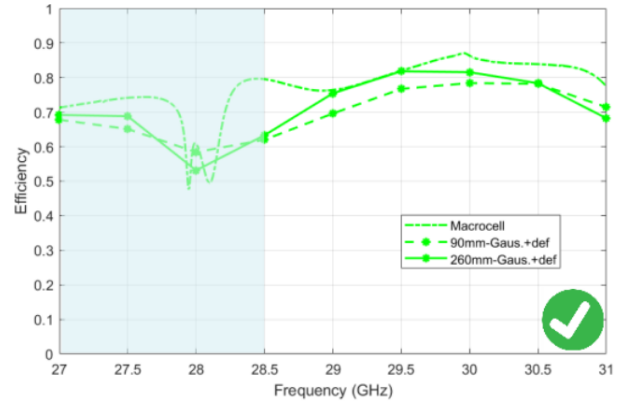
The inverse design methodology discussed in this study demonstrates the capability to generate optimal designs with a reasonable number of full-wave solver iterations. The results obtained for cylindrical nanopillar arrays can achieve more than 80% of diffraction efficiency for TE/TM polarization using only 180 full-wave simulations. This facilitates the creation of antenna systems with efficient deflectors capable of 2D beam steering within a large conical volume. Additionally, employing high-permittivity and low-loss composite materials gives deflectors with wider band and much cheaper. Consequently, the proposed design illustrates the potential to realize low-cost low-profile highly directive 2D-scanning antennas significantly thinner than their solid bulk counterparts, offering comparable or superior performances.

Références

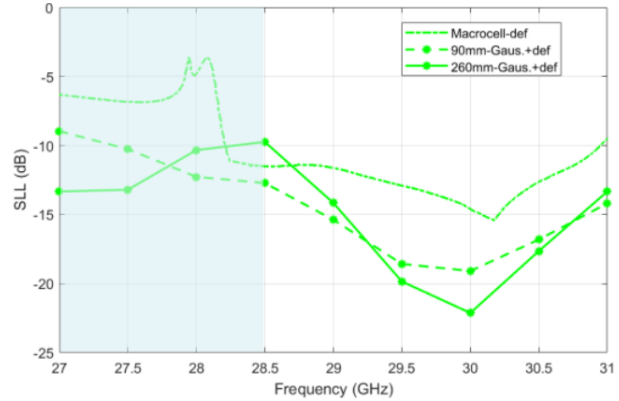
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(a) Diffraction efficiency



(b) SLL

FIGURE 6. Comparaion of simulations between the Macro-cell, full-deflector structure with $D = 90mm$ and with $D = 260mm$

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