Optimization-driven design of a 90° metasurface phase shifter at 60 GHz

Pablo H. Zapata Cano
School of Electrical and Computer Eng.
Aristotle University of Thessaloniki
Thessaloniki, Greece
pablozapata@auth.gr

Evangelos Vassos
Department of Electrical, Electronic and Systems Eng.
University of Birmingham
Birmingham, UK
e.vassos@bham.ac.uk

Zaharias D. Zaharis
School of Electrical and Computer Eng.
Aristotle University of Thessaloniki
Thessaloniki, Greece
zaharis@auth.gr

Pavlos Lazaridis
School of Computing and Engineering
University of Huddersfield
Huddersfield, UK
p.lazaridis@hud.ac.uk

Traianos V. Yioultsis
School of Electrical and Computer Eng.
Aristotle University of Thessaloniki
Thessaloniki, Greece
traianos@auth.gr

Nikolaos V. Kantartzis
School of Electrical and Computer Eng.
Aristotle University of Thessaloniki
Thessaloniki, Greece
kant@auth.gr

Alexandros Feresidis
Department of Electrical, Electronic and Systems Eng.
University of Birmingham
Birmingham, UK
a.feresidis@bham.ac.uk

***Abstract*—The exigent demands imposed by future generations of high-speed cellular and satellite communications claim for low-loss and wideband phase shifters at mm-Wave frequencies. Pixelated metasurfaces provide large design versatility and constitute an attractive solution for wave manipulation. However, their design often implies the simultaneous tuning of a large number of geometrical parameters. In this article, multi-objective optimization is used together with full-wave simulation to design a low-loss 90° phase shifter operating on the 57-63 GHz frequency band. Among the set of optimal individuals provided by the algorithm, a final solution has been selected according to the electromagnetic response of the device, achieving less than 0.06 dB of reflection loss and a constant phase shift with an absolute error less than 2° over the whole frequency band.**

***Index Terms*—phase-shifter, multi-objective optimization, genetic algorithm, metasurface**

I. Introduction

Phase shifting is considered to be one of the most crucial functionalities in microwave components. Phased array antenna systems and their real-time beam steering capability are considered a key enabler for applications in future high-speed cellular communications, satellite communications, or automotive radars, among others [1]. This has recently fuelled the interest of the research community on the design of wideband phase shifters operating at mm-Wave frequencies, in which some 5G new radio bands are defined as an extension of the sub-6-GHz frequency range [2].

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In the same way, optimization-driven design is a recurrent technique for the conception of various electromagnetic devices. Among the used strategies, natured-inspired techniques like a genetic algorithm (GA) or particle swarm optimization (PSO) have been widely employed for the design of phased array antennas [3], frequency selective surfaces [4], and microwave absorbers [5], among others.

Existing design techniques for this frequency range often involve complex circuitry or the necessity of switching elements [6], and they often suffer from high losses. The utilization of metasurfaces consisting on an ordered metallic geometry patterned onto a dielectric substrate, and the incorporation of active devices or materials that enable dynamic tuning contributes for a simultaneous control of the magnitude, phase and polarization of electromagnetic (EM) waves. However, the design of the unit cell that conforms the metasurface often implies the simultaneous finding of a large number of geometrical parameters. This emphasizes even more the importance of the optimization phase in the design process [7].

In this work, a GA is used to design a wideband phase shifter consisting of a pixelated metasurface and a mechanical actuator. Due to the nature of the optimization problem, the design of the pixelated metasurface is changing on every iteration of the algorithm, which signifies an extra degree of complexity compared to a simple parameter-tuning problem. This constitutes a NP-complete problem that is addressed by the joint utilization of an optimization framework implemented in Python and full wave electromagnetic simulation, carried out by CST Microwave Studio [8].

The rest of the paper is organized as follows: First, Section II introduces the design and working principle of the device. Second, Section III presents the formulation and configuration of the optimization problem. Next, Section IV includes the results obtained from the experiments. Finally, Section V contains some concluding remarks.

II. Design principle

The structure of the phase manipulating device is depicted in Fig. 1.

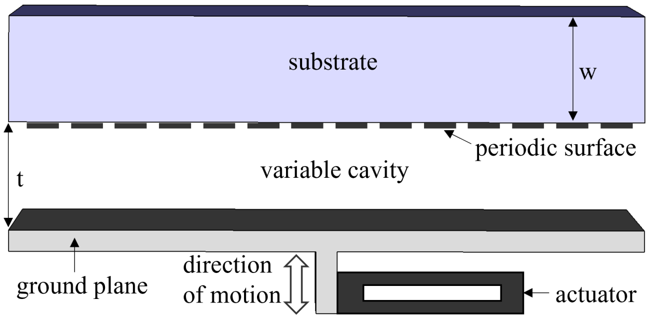

Fig. 1. Schematic design of the proposed device.

The phase shifter consists of a square block of a dielectric material presenting a relative permittivity of $\varepsilon_r = 2.2$ and dielectric losses of $\tan\delta = 0.0009$. A periodic surface conformed by the grid of metallized pixels is then deposited on the substrate. A metal plate that acts as a ground plane is positioned at a distance t from the periodic surface. Finally, the ground plane is mounted on a mechanism that provides a linear displacement.

The working principle of the device consists on controlling the phase of the reflected electromagnetic wave. In order to achieve this phase difference, the metal plate is displaced by means of a piezoelectric actuator, making the air cavity between the periodic surface and the metal plate variable. As the mechanism is positioned under the ground plane, the phase shift is achieved without introducing extra losses.

Fig. 2 shows the phase and magnitude of the reflected wave in absence of the periodic surface. It can be observed how a phase shift of around 30° is produced by a 0.15 mm displacement of the metal plate, i.e. the change of volume contained within the air cavity, which can be performed thanks to the piezoelectric actuator. Moreover, losses are kept very low in both cases (below 0.1 dB). However, the objective of the design is to be able to achieve a higher phase difference while maintaining the metal plate relatively close to the rest of the structure. In order to do that, an specific design of the periodic surface will be conceived for a given value of the target phase difference. On the following, an optimization problem is formulated and addressed with the objective of finding the most suitable configuration of the pixed grid conforming the periodic surface in order to control the phase

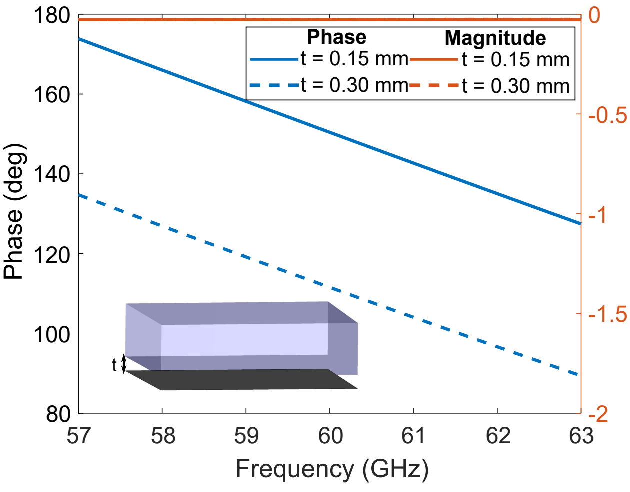

Fig. 2. Phase and magnitude of the reflected wave without periodic surface.

difference induced by a given variation of the position of the metal plate.

III. Optimization problem

A. Problem formulation

Let $\mathcal{G}$ be the set of pixels forming the grid of the metasurface. Then, the solution of the addressed optimization problem will be a binary array of the form $p \in \{0,1\}^{|\mathcal{G}|}$, where p_i corresponds to the state of each pixel. If the i pixel is chosen to be metallized, then p_i is set to 1, being equal to 0 for non-metallized pixels.

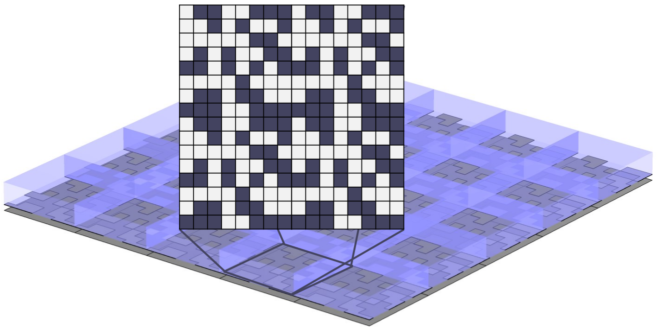

Fig. 3. Schematic of the periodic structure and example of a random 64x64 pixel grid (unit cell).

The first objective to be minimized is the one corresponding to the flatness of the phase over the frequency bandwidth $F = [f_{min}, f_{max}]$. Let $shift_{target}$ be the target phase difference between the reflected waves obtained for the initial position of the ground plane (ph_{t1}), and the displaced position (ph_{t2}). Then the first objective function is then calculated as

$$\min q_{ph} = \sum_{j=f_{min}}^{F} \left[shift_{target} - \left| ph_{t1_j} - ph_{t2_j} \right| \right]^2 \quad (1)$$

The second objective consists on the minimization of the magnitude of the reflected wave for both displacements of the metal plate, t_1 and t_2. It is obtained as follows:

$$\min q_{mag} = \sum_{j=f_{min}}^{F} mag_{t1}^2 + mag_{t2}^2 \quad (2)$$

with mag_{t1} and mag_{t2} being the magnitude of the reflected waves in dB.

By the joint optimization of both objective functions, the problem will consist on the search for the configuration of the pixel grid that provides both a flat reflection phase (of a given target value), and a minimum reflection loss.

B. Optimization framework

Figure 4 includes a flowchart of the optimization procedure. The jMetalPy [9] framework is used as optimization engine. Thus, both the algorithm and the post-processing of the objective function values are implemented in Python. In order to evaluate the fitness of the solutions generated by the algorithm, the CST Microwave Studio commercial software is used to perform a full-wave simulation of the structure and obtain the resulting reflection phase and magnitude.

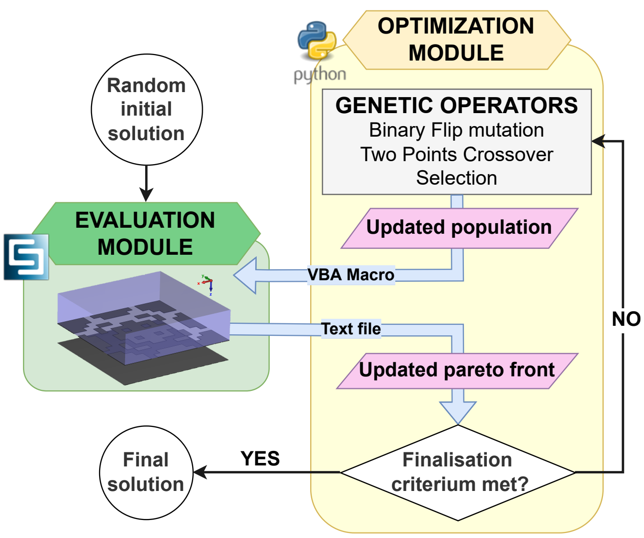

Fig. 4. Flowchart of the followed optimization process.

In order to build the CST model that corresponds to the solution generated by the algorithm, a VBA script is created in Python and passed to CST. In a similar way, the simulation results are written into a text file after simulation, and then interpreted in by the optimization module. This configures the optimization loop, that is repeated until a finalisation criterion (such as a given running time, number of iterations, quality indicator value) is met. After that, the final solution(s) is(are) retrieved and a physical interpretation of the results can be carried out.

C. Optimization algorithm

The algorithm that has been used for optimization is the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) [10]. It is an evolutionary technique that consists on the generation of new populations from the original one by the application of genetic operators (selection, crossover, and mutation). Then, the individual of both the new and the old population are evaluated and sorted out according to the value(s) of the fitness function(s). After this step, a new population is formed with the best solutions.

The binary nature of the solution of the optimization problem is determinant for the choice of the genetic operators used by the algorithm. According to this, the mutation operator is chosen to be the Bit Flip Mutation, being the selection operator the Simplex (SPX) Crossover.

IV. Experimentation and Results

In order to test the performance of the optimization framework on the formulated problem, an experiment has been conducted, with the aim of designing a 90° phase shifter between 57 and 63 GHz. The configuration of the problem and the optimization framework is the one included in Section III. A maximum of 2500 evaluations has been chosen as finalization criterion for the optimization algorithm, with a population size of 20 individuals. The SPX Crossover is applied with a probability of r_c = 0.9, whereas the bit flip mutation probability is chosen to be $1/|\mathcal{G}|$.

The periodic surface to optimize consists of a squared pixel grid of 256 pixels (i.e. $|\mathcal{G}|$ = 256 pixels). In order to make the response of the device polarization invariant and reduce the complexity of the simulation, diagonal symmetry is imposed to the unit cell. This reduces the optimization problem to one of 36 variables (one octave of the unit cell including the pixels on the diagonal). Then, mirroring operations are applied to obtain the 256-pixels unit cell. The rest of the elements composing the structure are disposed as shown in Fig. 1, with a substrate thickness of w = 0.78 mm and a pixel size of 0.1875 mm, which results on a squared grid of 3x3 mm (unit cell).

Due to the multi-objective nature of the proposed problem, a Pareto front representation has been chosen for the visualization of the results. The resulting Pareto front after 2500 evaluation is depicted in Fig. 5. By definition, the Pareto front is a representation of a set of non-dominated optimal solutions. However, after the interpretation of the solutions considering their electromagnetic response, some of them might not be of interest for the desired application. This is the case of the solutions appearing on the right part of the Pareto front in Fig. 5. Despite of providing an ultra-low loss, these solutions are significantly far for the targeted phased shift, which will lead to an undesired performance of the device.

Indeed, by analyzing the value of both objective functions of the solutions of the front, one can easily realize that the integrity of the solutions present a very low reflection magnitude: a value of q_{mag} = 6 corresponds to an average reflection of -0.055 dB, which is more than acceptable.

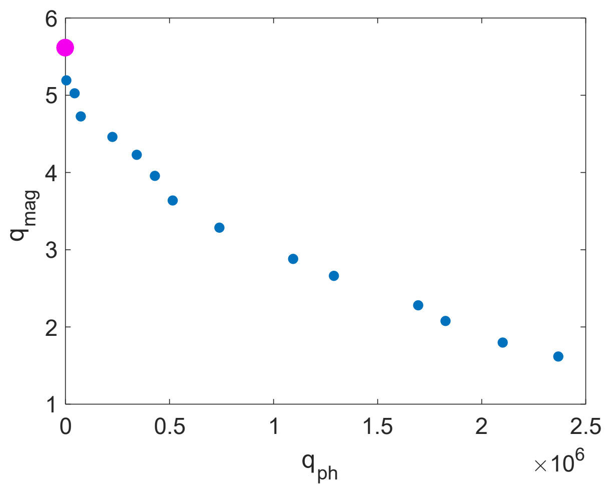

Fig. 5. Obtained Pareto front after 2500 evaluations. The purple big point corresponds to the selected optimal solution from the front.

According to this, the solution providing the better phase difference has been chosen as the most suitable one (purple point in Figure 5).

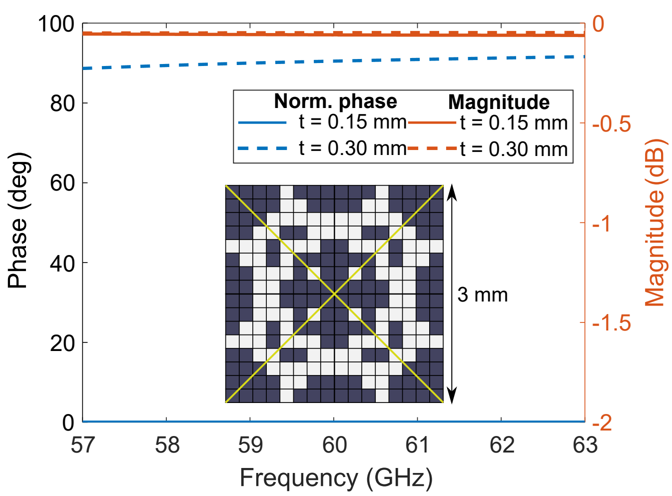

Fig. 6. Normalized phase (w.rt. ph_{t1}) and magnitude of the selected solution. Configuration of the pixel grid of the selected solution and symmetry axes.

Fig. 6 depicts the reflection magnitude and normalized phase difference (taking the reflection phase obtained for $t = t_1$ = 0.15 mm as a reference) of the selected best solution. As is it observed on the figure, the response of the device presents an ultra-low level of losses (less than 0.06 dB for both mag_{t_1} and mag_{t_2} in the whole 57-63 GHz band). With respect to the phase shift, a constant 90° with an absolute error less than 2° is achieved for the entire frequency range.

V. Conclusions

In this work, a phase shifter working at mm-Wave frequencies has been designed using an optimization-based approach. A periodic pixelated metasurface presenting an unit cell containing a pixel grid of 265 elements is optimized, minimizing the losses of the reflected wave and targeting a constant phase shift of 90° over the 57-63 GHz frequency band. A multi-objective genetic algorithm, NSGA-II, integrated on a optimization framework using full-wave simulation is used for the evaluation of the fitness function. The obtained results have been illustrated in the form of a Pareto front, and the most suitable element has been selected after physical interpretation of the electromagnetic response of the solutions. An ultra-low response, together with a constant 90 ° phase shift (with less than two degrees of absolute error) have been achieved. As future continuations of the work, a wider frequency range and different targeted phase shifts could be considered.

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