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Design of Wideband Metasurface Structure with the Aid of Bottom-Up Optimization

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***Abstract*—This paper presents a design methodology leading to optimize an electromagnetic metasurface structure usable in a wide band frequency. The structure consists of identical unit cells realized in microstrip technology, being one of them fed by a coaxial cable. The employed approach is the bottom-up optimization (BUO) that is implemented by increasing the number of radiators following a squared scheme of $n \times n$ nature. The proposed methodology leads to design optimal complex structures exhibiting a wideband feature. For validating the use of BUO method, the number of radiators has been increased from 1 to 25, i.e., n has been varied form $n = 1$, to $n = 5$. The initial design parameters of antennas are obtained through particle swarm optimization (PSO) algorithm. The simulation results show that the optimized metasurface with the aid of BUO method has a wideband frequency answer in the range from 13 GHz to 22.66 GHz.**

***Index Terms*—Antenna, bottom-up optimization (BUO), metasurface, particle swarm optimization (PSO), wideband.**

I. INTRODUCTION

Day after day, mobile communication systems develop exponentially, generating more and more technical challenges. Antennas, one of the main parts of these systems, are at the forefront of this process, as broadband radiators with reconfigurable radiation patterns are needed to improve energy efficiency in the complex communication environment [1], [2]. Recently, metasurface structures have proved their ability in controlling waves in which electromagnetic (EM) metasurfaces can provide beam scanning features obtained by proper phase modulation on the aperture [3], [4]. Usually, the metasurface is constructed by a periodic repetition of subwavelenght metallic pattern(s) which can be built on single or multi-layer substrate(s) [5].

Various methodologies have recently been suggested to improve the overall performances of metasurfaces. In [3], a technique for designing metasurface aiming controlling the beam width and its direction is presented. The impedance model is employed for synthesizing a lossless and reciprocal metasurface impedance. Application of a metasurface is demonstrated in [6] for wireless power transfer systems that is realized with the combination of a 2-bit amplification within the unit cell of the metasurface. In [7], a dual-band multifunctional metasurface is presented leading to provide a methodology for realizing angular-asymmetric transmission. A conformal holographic metasurface for evaluating circularly polarized beams is presented in [2]. For enhancing radiation behavior of the polarized metasurface antenna array, a method consisting of introducing L-feeding patches along the orthogonal direction is presented in [8]. Metasurface structures are also considered for array applications where multiple modes are used for wideband radiations [9]. In [10], a hybrid multilayer impedance-sheet model is presented leading to analyze and simulate the characteristic modes. An interface field optimization methodology is presented in [11] for designing and optimizing a planar periodic metasurface combing with three-layer admittance sheets. A wideband programmable metasurface is proposed in [12] for realizing reflection phase difference of 170° ± 10° between the cases when diodes are in ON and OFF states, respectively.

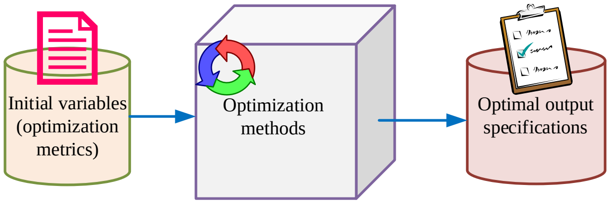


Fig. 1. General view of optimization method.

The use of optimization methods is often considered, as they can improve the performance of systems and increase the efficiency of high-dimensional designs. The general view of an optimization flow is represented in Fig. 1: the input data and optimization metrics are given as inputs to the optimization algorithms, which in turn will generate the optimal output specifications.

This paper devotes to present a methodology making use of the bottom-up-optimization (BUO) leading to enhance the overall performance of a metasurface in terms of optimal largeness bandwidth. Firstly the optimization starts with the a single unit cell, and its number is sequentially increased following a square rule to $n \times n$. Here, the particle swarm optimization (PSO) has been employed for achieving the optimal design parameters of this single unit cell. In a second step this unit cell is repeated in 2D forming a metasurface, where only one of the cells are fed by a coaxial cable. The resulting metasurface antenna has a wide bandwidth of 9.6 GHz.

The remaining of this work is structured as follows: Sec. II introduces the summary of proposed method. Section III presents the practical implementation of the proposed method for designing and optimizing the metasurface antenna structure. Finally Sec. IV concludes this presentation.

II. PROPOSED METHOD

In high-dimensional designs, employing advanced optimization methods are required for achieving the targeted output specifications. In this paper, BUO is introduced leading to design an electromagnetic periodic structure. This section devotes to present the implementation of the methodology as depicted in Fig. 2.

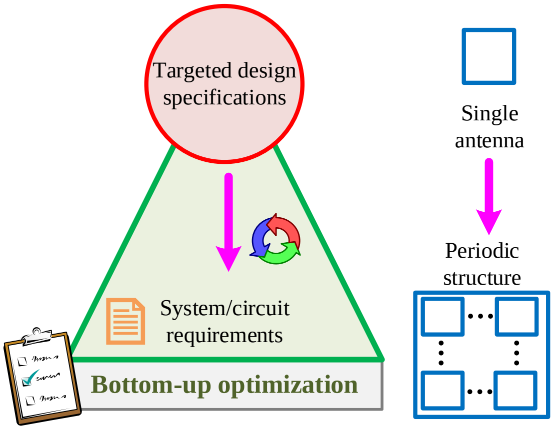


Fig. 2. Implementation of BUO method for designing the periodic structures.

The BUO optimization is the method that starts with the smallest/single section and increases the number of single parts [13]. As Fig. 2 shows, firstly one single antenna is designed and optimized, and afterwards sequentially the number of single antennas in terms of $n \times n$ ($n \geqslant 2$) is increased. The value of n can be determined with respect to the targeted output results. When the required specifications are achieved, the overall optimization is stopped.

III. SIMULATION RESULTS

This section aims presenting the practical implementation of BUO method for designing and optimizing a periodic metasurface structure. Firstly the single antenna is designed and simulated and after that 2×2, 3×3, and 4×4 configurations are considered, simulated and optimized.

The sequential increment is performed in the number of unit cells up to achieving the targeted frequency bandwidth from 13 GHz up to 22.6 GHz. Figure 3 presents the practical implementation of BUO method for designing and optimizing the metasurface antenna. The structure of initial single antenna is started by getting a view from the presented design in [14]. Afterwards the value of n is increased with a step of 1, up to $n = 4$. The design parameters of these antennas are achieved through the PSO method.

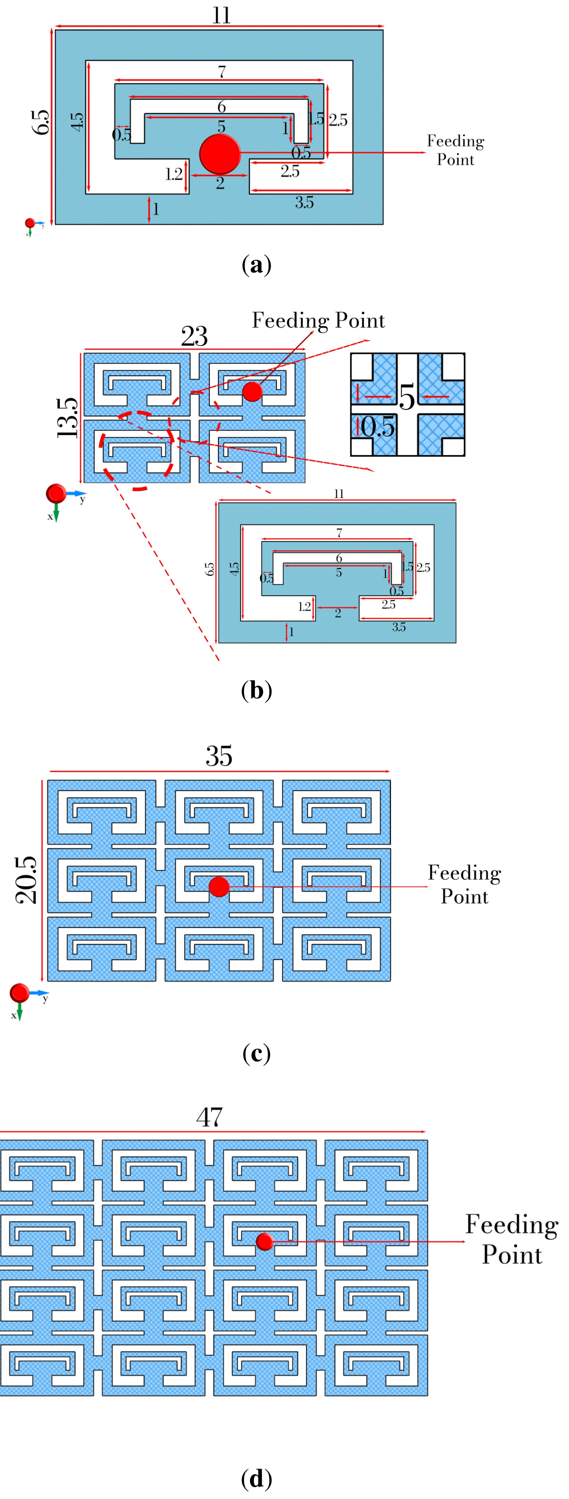


Fig. 3. (**a**) single antenna; (**b**) 2×2 metasurface antenna; (**c**) 3×3 metasurface antenna; (**d**) 4×4 metasurface antenna; dimensions are in mm unit.

The optimized metasurface antenna shown in Fig. 4 is implemented on the ground with the size of 47 × 27.5 mm^2

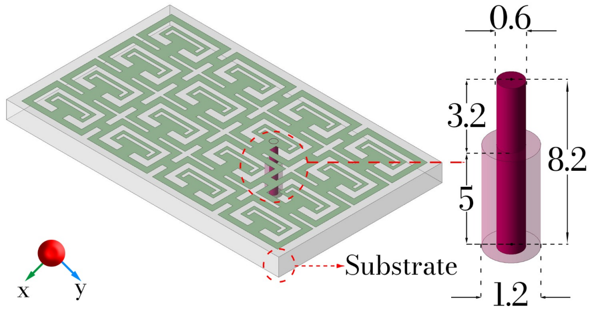
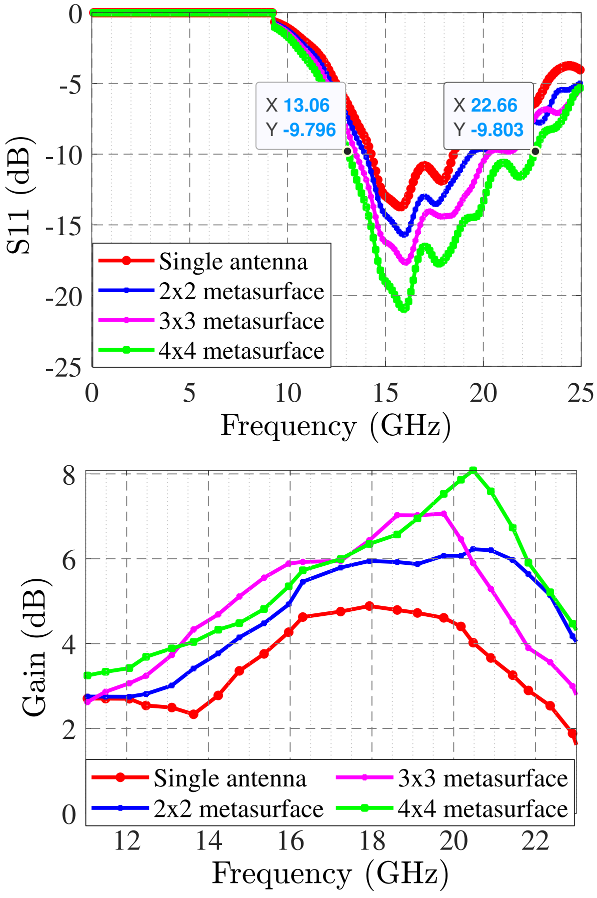


Fig. 4. Illustration of coax feeding for metasurface structures; dimensions are in mm unit.

where the employed substrate is Rogers with thickness of 3.2 mm, relative permittivity (ε_r) of 3.66, and loss tangent ($\tan\delta$) of 0.004. Additionally, the geometry of the coaxial feeding of the metasurface structure is illustrated.



(a)

Fig. 5. Comparison performance form single unit cell up to 4×4 metasurface antenna; a) S_{11} performance, b) gain performance.

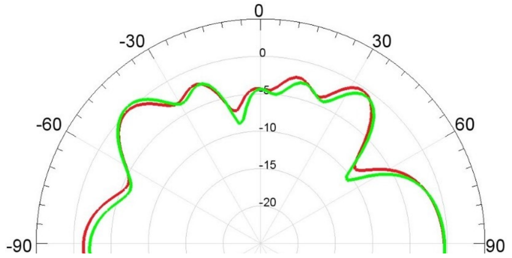


Fig. 6. Radiation pattern at 13 GHz; Phi=0° (red) and Phi=90° (green).

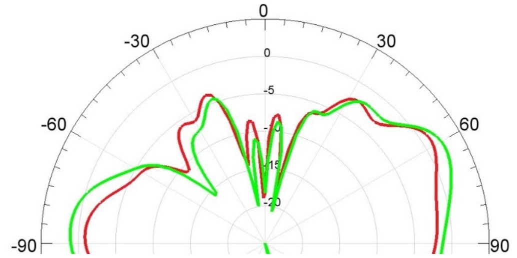


Fig. 7. Radiation pattern at 17.5 GHz; Phi=0° (red) and Phi=90° (green).

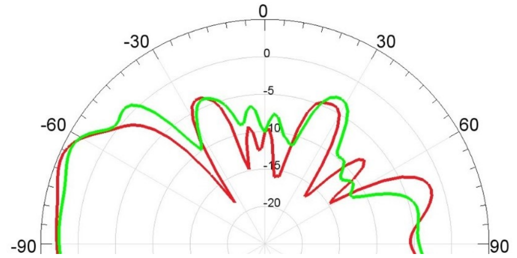


Fig. 8. Radiation pattern at 22 GHz; Phi=0° (red) and Phi=90° (green).

Figure 5 presents the S_{11} with gain performances respectively for a single antenna, 2×2, 3×3, and 4×4 metasurface antennas. It demonstrates that the bandwidth from 13.06 GHz to 22.66 GHz is achieved in the 4×4 structure. Also it is proved that the bandwidth of metasurface is increasing by improving the overall configuration. Additionally, the radiation pattern for the three frequencies namely for 13 GHz, 17.5 GHz, and 22 GHz are presented in Fig. 6, 7, and 8, respectively for the 4×4 configuration.

IV. CONCLUSION

In this work, EM-based BUO method is employed for designing and optimizing a wideband metasurface antenna. The BUO approach in this study, is based on increasing the number of unit cells following a rule of $n \times n$ aiming to achieve the optimal targeted results. Here, we design a wideband metasurface antenna with the bandwidth of 9.6 GHz in which the PSO algorithm is employed for achieving the initial design parameters. It is proved that the bandwidth of metasurface is increasing in comparison with a single antenna.

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