Antenna Design on Periodic and Aperiodic Structures

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1. Introduction

Frequency selective surfaces (FSSs) have been studied extensively in widespread microwave and optical applications [1]. They can be arranged in either a single layer or multiple layers to eliminate resonant crosstalk and dispersive behavior. Although literature abounds in numerical analysis and electromagnetic applications of FSSs, little has been done on the design optimization approaches for them. Published results include a hybrid genetic algorithm (GA)-Powell technique on polarizer structures design[2] and several filter designs using neural networks [3] or GAs [4], respectively. In [3], Davis, et.al. applied neural networks to optimize the surface dimensions of a chosen element shape. Also in [4], Michielssen, et.al. has designed highpass and lowpass filters using GAs by choosing from a database consisting of different element types and dielectric materials. In this paper we examine a multilayered FSS design using gradient-based optimization methods such as sequential quadratic programming (SQP) to tune both the unit cell dimensions and dielectric layer parameters to achieve desired frequency responses.

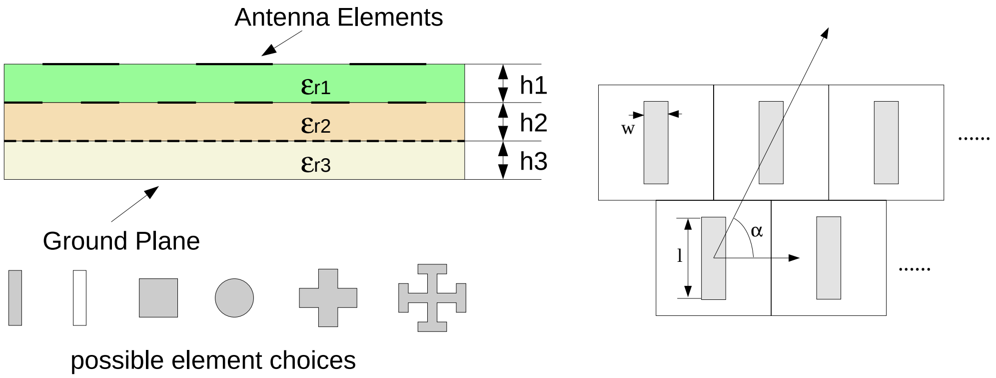
Photonic bandgap (PBG) materials consist of printed elements on perforated (usually periodic) substrates, which makes it an ideal fit for FSS applications. Antennas with PBG substrates have shown improved performance over uniform substrates [5]. More specifically, PBGs can increase gain and bandwidth and reduce loss. However, design approaches for these antennas have yet to be developed and furthermore, there is great interest for a better understanding of bandgap structures and more generally for frequency selective volumes.

Section 3 of this paper considers novel optimization methods for the design of broadband antennas. Starting from periodic PBG substrates, optimal values for the length/width of the circular/rectangular perforations can be achieved by employing size optimization [6]. Performance enhancement can further be achieved by applying topology optimization methods such as the density and homogenization design methods in conjunction with antenna simulators based on the finite element. These methods could be combined to find the size and shape of holes and/or the material distribution of the hole region for optimal performance. Theoretically, there is no restriction on the topology of the substrate, and these holes might be of arbitrary shape and with any possible periodicity or topology.

2. Multilayered FSS Design

FSS can be modeled as either infinite or finite arrays of identical unit cells, whose shape can typically be one of those as in Figure 1. They exhibit total reflection (patches) or transmission (apertures) in the neighborhood of the element resonance. FSS characteristics depend on the element shape and dimensions, as well as on the thicknesses and permittivities of the dielectric layers.

To synthesize a filter with desired frequency response, one typically searches in the knowledge base through a trial-and-error procedure which could be very tedious. Therefore, optimization techniques are necessary to design an FSS having a desired response. There are mainly two ways to do this. One is to search for the optimal design by optimizing the dimensions and dielectric layers of a given element shape [3]. The other is to obtain the optimal design by cascading elementary building blocks of predefined element shapes and dielectric layers [4]. There have been efforts to design FSS using optimization techniques, such as neural networks [3] and genetic algorithms [4]. In this paper, we will allow for a much greater material and geometrical flexibility in achieving prespecified design criteria for antenna performance. Gradient-based techniques such as sequential programming method (SQP) along with density or homogenization methods offer such possibilities.



(a) (b)

Figure 1. Multilayered FSS: (a) side view; (b) top view with dipole elements.

The problem model could be written as follows:

$$\text{Find: } l, w, \alpha, h_1, h_2$$

$$\text{Such that: } \Gamma = 1 \text{ for } f = f_1 \text{ to } f_2 \text{ GHz and } \Gamma = 0 \text{ for } f = f_3 \text{ to } f_4 \text{ GHz}$$

where l and w are dipole length and width, α is skew angle (see Figure 1), and h_i ($i = 1, 2$) are thicknesses of the dielectric substrate layers. Γ denotes the power reflection coefficient and f is the frequency.

For the above problem the goal is to find the optimal design for an FSS consisting of infinite dipole array so that $[f_1, f_2]$ is the stopband and $[f_3, f_4]$ is the passband. The frequency responses are continuous in these bands and some sampled frequency points must be used in the design to check the responses at a number of discrete points. The problem objective is then to minimize the mean square error between the realized and desired power reflection at these sample points. Therefore, the objective function can be refined as follows:

$$\text{Minimize } \sum_{i=0}^{M} \left|\Gamma_{f_1 + i/2} - 1\right|^2 + \sum_{j=0}^{N} \left|\Gamma_{f_3 + j/2} - 0\right|^2$$

where Γ_f is the power reflection coefficient at some frequency f. Here the stopband and passband are sampled using a total of $M+N+2$ sample frequency points.

3. Bandwidth Enhancement Design on Aperiodic Structures

Microstrip antennas on high dielectric-constant substrates can have smaller antenna sizes than those on low dielectric-constant substrates, but there is a sacrifice of low efficiency and narrow bandwidth. Several methods have been proposed to solve this problem, one of which is to use closely spaced holes underneath and around the microstrip antenna, thus lowering the effective dielectric constant. Several patch antennas have been fabricated based on micromaching techniques and bandwidth improvement for these antennas has been observed [7].

In our research, a finite element boundary-integral (FE-BI) method is used to model a cavity backed patch antenna with periodically perforated substrate. As a first step, we started from the periodic PBG substrate where all holes are of the same size. The uniform effective dielectric constant was computed based on a volumetric average of the substrate permittivity and free space for the hole. Optimal values for the length/width of the circular/rectangular perforations were achieved by employing size optimization [6]. In this paper, performance enhancement is further achieved by applying topology optimization methods such as the density and homogenization design methods in conjunction with antenna simulators based on the finite element.

Topology optimization techniques are used to compute the material distribution of the dielectric substrate. They allow for completely arbitrary and novel designs, and have been very successful in structural optimization problems in automotive and magnetostatics designs [8] [9]. The design domain is discretized into finite elements and each finite element is viewed as one or more microstructures as shown in Figure 2. A microstructure can be expressed as void, porous, or solid depending on the hole size of the microstructure. On the basis of the homogenization design method (HDM), the homogenized value of the material constant for each finite element is first computed on the basis of its microstructures in each iteration. In contrast, when employing the density method, the material constants of the microstructures need not be homogenized. In this paper, we assume that each finite element consists of only one microstructure with a rectangular hole. For the N finite elements in the entire domain, each has a hole size of a_j by b_j ($j = 1, ..., N$). All these a's and b's are taken as design variables and are employed to compute the effective dielectric constant ε_{rj} of each finite element. The final configuration of the substrate could be obtained from the optimized values of the hole dimensions.

Numerical results illustrating the designs of section 2 and section 3 will be provided at the presentation.

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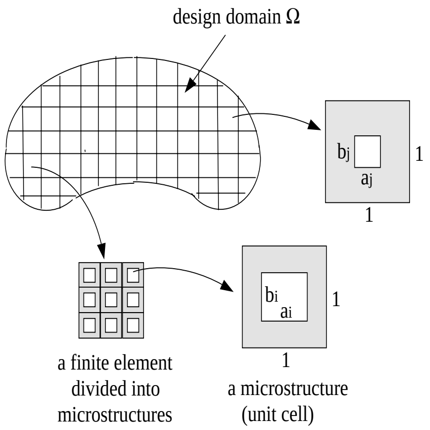

Figure 2. Microstructures in a design domain.