Direct Optimization of Quasi-Periodic Surfaces in Multi-Reflector Systems

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***Abstract*—In recent years, there has been an increasing interest in replacing traditional periodic surfaces, e.g., frequency selective surfaces, with quasi-periodic surfaces (non-identical elements) in multi-reflector systems for satellite applications. Quasi-periodic surfaces can be used to improve existing antenna solutions or to provide innovative concepts not possible with periodic surfaces. In many scenarios, the periodic/quasi-periodic surface is used in a multi-reflector configuration, e.g., as a subreflector, where the design specifications are on the radiation pattern from the main reflector. For these applications, the design of the surface is usually carried out using an in-direct optimization approach which may provide sub-optimal designs. In this paper, we demonstrate the direct optimization of quasi-periodic surfaces for the final pattern performance. This means that all array elements in the quasi-periodic surface are optimized simultaneously to directly fulfill the goal specifications on the final pattern from the main aperture.**

***Index Terms*—antenna, quasi-periodic surfaces, optimization, satellite applications, FSS, reflectarrays**

I. INTRODUCTION

Periodic surfaces (PS), e.g., frequency selective surfaces (FSS), circular polarization selective surfaces (CPSS), etc., that can either reflect or transmit electromagnetic fields when illuminated by an external source have existed for several decades. These surfaces are usually designed at the unit-cell level and optimized for a single or a few incidence angles. This approach may result in suboptimal design, particularly when the surface is exposed to a large range af incidence angles which is often the case in practical designs. Consequently, an interest in replacing PS using quasi-periodic surfaces (QPS) has emerged [1]. The idea is to design the surface using an approach similar to that used for reflectarrays where each array element is optimized for a certain incidence angle to maintain good angular performance.

The design of traditional QPS is often done using a phase-only synthesis approach: first the required phase distribution over the surface is determined, and second, the elements are optimized, element by element, to match the required phase distribution. This method is an in-direct optimization approach where the direct relation between the optimization variables (geometry) and the optimization goals (radiation pattern) is not maintained. As a result, it may provide sub-optimal designs.

Using a direct optimization technique where all array elements are optimized simultaneously to fulfill the pattern specifications, enhanced performance can be obtained [2]. The reason is that when all elements are optimized simultaneously in a direct manner, a local mismatch between the desired and actual element response can be compensated by other elements. This is not possible when the design is done element by element as it is often the case in the literature on QPS.

In case of traditional QPS such as reflectarrays and transmitarrays, the design goal is often specified for the radiation from the surface itself, e.g., radiation from a reflectarray. For such cases, the direct optimization has been presented in the literature [2]. However, for many practical applications, the PS/QPS is used in a multi-reflector system where the design specifications are on the radiation from the main reflector. An example is a dual-band dual-reflector system with an FSS subreflector that separates the two bands [3]. In this way, the main reflector can be used as a shared aperture operating in both bands. Another example could be the use of CPSS for dual-optics circular polarized offset reflectors [4]. The CPSS is used as subreflector and separates the two orthogonal polarizations. For these applications, all PS/QPS designs are currently carried out using an in-direct optimization approach due to limited design capabilities.

In this paper, we demonstrate the direct optimization of QPS in multi-reflector systems where the QPS is optimized directly for the performance of the final pattern.

II. DIRECT OPTIMIZATION OF QUASI-PERIODIC SURFACES

The direct optimization technique (DOT) used in this work takes outset in the work presented in [2]. The analysis method is based on a spectral domain method of moments assuming local periodicity, and the optimization algorithm is a gradient-based large-scale non-linear minmax optimization algorithm.

In [2], the DOT was applied to optimize the pattern from the QPS itself. In this work, the DOT has been extended such that it can be applied to optimize directly on the final pattern performance.

III. APPLICATION EXAMPLE

To demonstrate the direct optimization, we consider the configuration shown in Fig. 1. It consists of an offset reflector illuminated by a feed at 20 GHz. The feed is a conical horn with an aperture radius of 15 mm and operates in linear polarization. For the configuration under consideration, the dimensions of the feed aperture is too small to provide the optimal illumination over the reflector due to high spill-over. To compensate this, a circular array lens is positioned in front of the feed. The function of the array is to improve the peak gain of the main reflector. The array lens is tilted 45° wrt. to the feed aperture to minimize reflections into the feed.

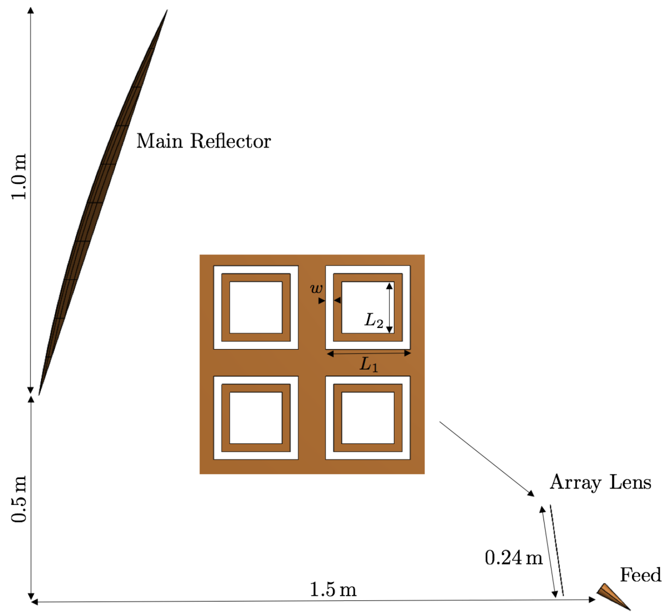

Fig. 1. Offset reflector configuration.

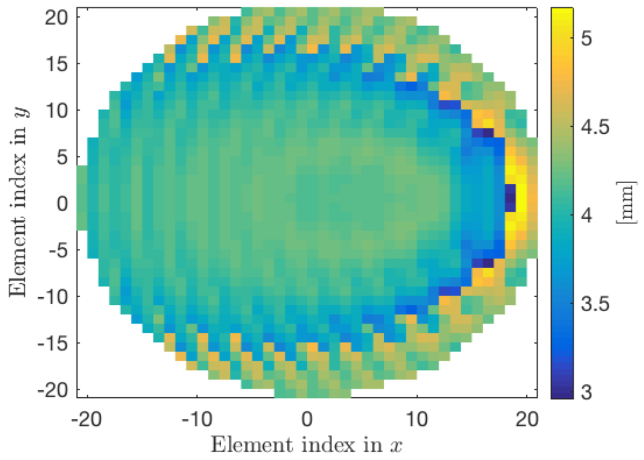

Fig. 2. The variation of L_1 over the array lens

Furthermore, the array lens is slightly displaced to ensure proper illumination from the feed.

As array element, we consider a single metal layer with a square loop-slot/aperture. The elements are printed on a 0.076 mm Kapton layer ($\epsilon_r = 2.8$, tan$\delta = 0.005$) bounded to a 3.175 mm honeycomb core ($\epsilon_r = 1.05$, tan$\delta = 0.0004$). The array elements are positioned in a regular grid with a separation of 5.5 mm in both x and y.

The goal is to optimize the array lens to enhance the peak gain of the main reflector. During each optimization iteration, the array lens is first analyzed with the feed as source, and subsequently, the combined response from the feed and the array lens is used to illuminate the main reflector. Finally, PO/PTD is used to obtain the final pattern from the main reflector.

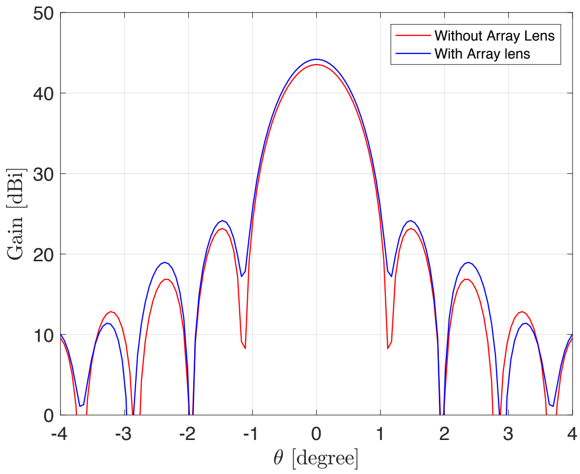

Fig. 3. Radiation pattern of the reflector with and without the array lens.

For the optimization of the array lens, a periodic design ($L_1 = 4.2$ mm, $L_2 = 2.6$ mm, $w = 0.4$ mm), which is optimized to be transparent at 20 GHz, is used as the starting point of the optimization. Using the DOT with L_1 and L_2 as optimization variables, all array elements are optimized simultaneously to increase the peak gain of the main reflector. The resulting variation of L_1 over the array lens is shown in Fig. 2.

In Fig. 3, the radiation pattern of the reflector is shown with and without the presence of the array lens. It is seen that the peak gain has been improved with approximately 0.8 dB with a peak of 44.2 dBi compared to 43.5 dBi without the array lens. In this design, the array lens consists of a single metallization layer. It is expected that further enhancements can be obtained using additional metallization layers in the design.

In the example shown here, the array lens is optimized only for peak gain goal specifications. One could also optimize the array lens for other goal specifications, e.g., cross-polarization level, beam scanning, shaped beam, detailed pattern templates, etc., or a combination of these. Furthermore, the proposed approach can also be applied on other multi-reflector systems involving QPS, e.g., dual-reflector systems with an FSS sub-reflector, thus providing advanced capabilities otherwise not possible.

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