REFLECTARRAY ANTENNAS

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IEEE Antennas and Propagation Society, *Sponsor*

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PREFACE

The concept of the reflectarray antenna was introduced in 1963 using waveguide elements, but the real interest in reflectarrays only came about in the late 1980s with the development of low-profile printed antennas. For this reason, the printed reflectarray can be considered as a fairly new type of antenna. A reflectarray is made up of an array of radiating elements that provide a preadjusted phasing to form a focused beam when it is illuminated by a feed, in a similar way to a parabolic antenna. Printed reflectarrays combine certain advantages of reflector antennas and phased arrays. They are manufactured on a planar substrate using printed circuit technology and offer the possibility of beam steering as phased arrays; on the other hand, the feeding mechanism (as in a reflector antenna) eliminates the complexity and losses of the feeding network used in planar arrays, thus providing a higher efficiency. Reflectarrays have demonstrated their capability to produce contoured beams, which are conventionally generated by using shaped reflectors or phased arrays. Recently, some potential applications of reflectarrays in space have been researched, such as contoured beam antennas for Direct Broadcast Satellites and very large inflatable antennas. However, there is one major shortcoming of the reflectarray, which is its narrow-bandwidth behavior, but the bandwidth has been significantly increased in recent developments.

The purpose of this book is to present a comprehensive overview of reflectarray antennas, including the operating principles, their advantages over other antennas, their development history, analysis techniques, practical design procedures, bandwidth issues, and wideband techniques, as well as their applications and recent developments. This book can be used as a reference book for graduate students, researchers, and antenna engineers. Furthermore, it will allow the reader to become more familiar with this relatively new type of antenna and will provide valuable support in designing these antennas.

The book is organized into seven chapters. Chapter 1 presents a general introduction to reflectarray antennas, including their operating principles, the most common implementations, their most significant features, and a description of the advantages and drawbacks with respect to other types of antenna. A detailed development history of the reflectarray since its invention is presented in Chapter 2. It will greatly enhance the ability of an engineer to understand the reflectarray system if he is familiar with the evolution of the reflectarray antenna. In the same chapter, performance comparisons with two similar technologies, array lens and Fresnel-Zone plate reflector, are also briefly discussed.

The reflectarray is a relatively complex antenna, and an accurate analysis technique is essential for precise predictions of the radiation features, such as efficiency, gain, co- and cross-polar radiation patterns, and bandwidth. Chapter 3 provides a detailed discussion of the different approaches used for the analysis of reflectarrays. A full-wave technique based on the Method of Moments in the Spectral Domain and Floquet modal expansions, under the assumption of local periodicity to account for mutual couplings, is described in detail. Although the method of analysis has already been described in journal papers, in this chapter the method is focused to the specific analysis of reflectarray antennas. The analysis technique is used to compute the phase response and losses of different types of reflectarray elements, such as printed patches with attached or aperture-coupled stubs and varying-sized patches in single- and multiple-layer configurations. Several results are presented to validate the analysis tool and to show the capabilities and limitations of each element type. Finally, the chapter describes a technique for the computation of co- and cross-polar radiation patterns, including the modeling of the feed-horn.

Chapter 4 is devoted to providing practical skills for the design of the reflectarray antenna. Apart from the analysis technique, there are some aspects that must be taken into account during the design of a reflectarray antenna, such as the selection criteria for the phasing elements, the appropriate spacing to provide enough phase-range and avoid the appearance of grating lobes, the geometrical definition of the antenna, etc. These aspects are essential to achieving a good efficiency and are discussed in Chapter 4.

The most severe drawback in reflectarray operation is its narrow frequency band, and much effort has been made in recent years to overcoming this limitation. Chapter 4 is devoted to bandwidth improvement in reflectarrays. The bandwidth in reflectarrrays is mainly limited by two different factors: the phase response of the radiating element and the different path lengths from the feed to the phase front. After discussing the two factors in detail, several solutions are presented in Chapter 5 to improve the bandwidth. Two different types of broadband reflectarray elements are analyzed: one based on stacked patches of varying size and the other using patches with aperture-coupled lines. A 16 percent bandwidth was achieved by using two stacked patches as reflectarray element. On the other hand, the effect of different path lengths is only significant in large reflectarrays as in the case of antennas for space applications. Several techniques are described to overcome the bandwidth limitation produced by the different path lengths and some results are given for large antennas. The first technique is based on the implementation of delay lines aperture-coupled to printed patches to compensate for the real phase delay in the whole range (several times 360°), the second one consists of compensating the spatial phase delay in a given frequency band with the phase of the reflection coefficient, and the last one, more suitable for very large apertures, uses a faceted configuration that approximates the shape of a parabolic surface.

Chapter 6 presents dual-band and multi-band techniques for a single reflectarray to handle multiple frequencies that are separated far apart.

Several important recent applications, as well as possible future applications, are presented in the final chapter. Examples such as inflatable reflectarray, contour-beam applications, multibeam reflectarrays, amplifying reflectarrays, a folded low-profile configuration, a Cassegrain offset configuration, very large aperture applications, and beam scanning reflectarrays are presented in some detail. Due to the multitude of capabilities, the development and application of reflectarrays are expected to carry on during the next decades.

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CHAPTER 1

Introduction to Reflectarray Antenna

For most radar and long distance communications, the need for high-gain antennas is unavoidable. Traditionally, high-gain applications have relied upon parabolic reflectors or arrays [1]. However, the parabolic reflector in many cases, due to its specifically curved surface, is difficult to manufacture, in particularly at higher microwave frequencies. It also lacks the ability to achieve wide-angle electronic beam scanning. On the other hand, the high-gain array antenna, when equipped with controllable phase shifters, can achieve wide-angle beam scanning electronically, but generally becomes very expensive due to its complicated beamformer and many high-cost amplifier modules. The amplifier modules must be used to alleviate the problem associated with the power inefficiency that occurs in the high-loss beamformer and phase shifters. As a result, a third type of antenna, namely the "reflectarray", has evolved to mitigate the disadvantages associated with either the parabolic reflector or the conventional array.

1.1 DESCRIPTION OF REFLECTARRAY

The reflectarray [2, 3] is an antenna consisting of either a flat or a slightly curved reflecting surface and an illuminating feed antenna as shown in Fig. 1.1. On the reflecting surface, there are many radiating elements (e.g., open-ended waveguides, printed microstrip patches, dipoles, or rings) without any power division transmission lines. The feed antenna spatially illuminates these reflectarray elements that are predesigned to reradiate and scatter the incident field with electrical phases that are required to form a planar phase front in the far-field distance. In other words, the predesigned phases of all elements are used to compensate for the different phases associated with the different path lengths (S_1, S_2, . . . , S_n in Fig. 1.1) from the illuminating feed. This operation is similar in concept to the use of a parabolic reflector that utilizes its unique curvature to reflect and form a planar phase front when a feed is placed at its focal point. Thus, the term "flat reflector" is sometimes used to describe the

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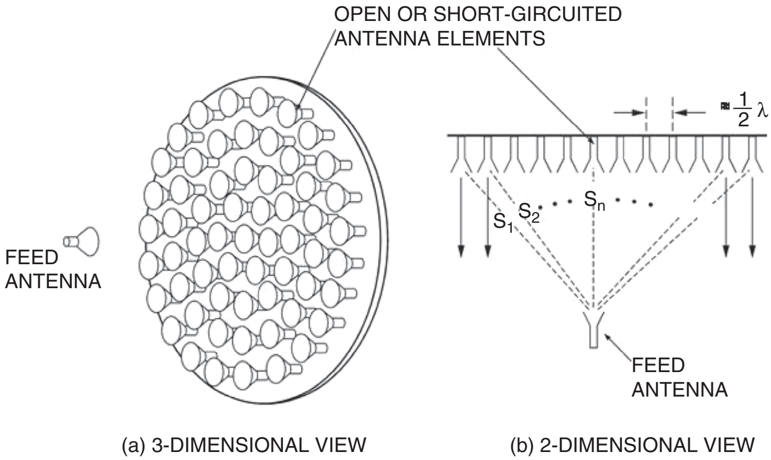

Figure 1.1. Configuration of a reflectarray antenna.

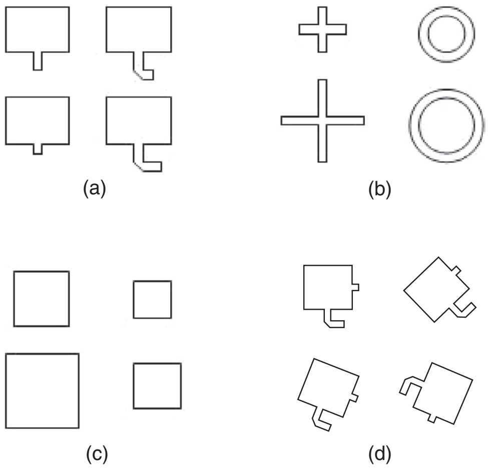

Figure 1.2. Various reflectarray elements, (a) identical patches with variable-length phase delay lines, (b) variable-size dipoles or loops, (c) variable-size patches, (d) variable angular rotations.

reflectarray, which utilizes both technologies of reflector and array. As shown in Fig. 1.2, there are several methods for reflectarray elements to achieve a planar phase front. One is to use identical microstrip patches with variable-length phase delay lines attached [4, 5] so that they can compensate for the phase delays over the different paths from the illuminating feed. Another is to use variable-size patches, dipoles, or rings [6–8] so that elements can have different scattering impedances and, thus, different phases to compensate for the different feed-path delays. With the third method, for circular polarization only, the reflectarray has all identical circularly polarized elements but with different angular rotations [9] to compensate for the feed path-length differences.

1.2 PRINTED REFLECTARRAY

Reflectarrays using printed microstrip elements have been developed to achieve low reflecting surface profile, small antenna mass, and low manufacturing cost. A configuration of a reflectarray using printed patch elements with variable-length delay lines is shown in Fig. 1.3. These printed reflectarrays combine some of the salient features of the traditional parabolic reflector antenna and the microstrip array technology. Its advantages, as well as disadvantages, when used as a large-aperture antenna are separately discussed below.

1.2.1 Advantages of Reflectarray

Similar to a parabolic reflector, the reflectarray can achieve very good efficiency (>50 percent) for a very large aperture since no power divider is needed and thus very little resistive insertion loss is encountered here. On the other hand, very similar to an array antenna, the reflectarray can have its main beam designed to tilt at a large angle (>50°) from its broadside direction. Low-loss electronic phase shifters can be incorporated into the elements for wide-angle

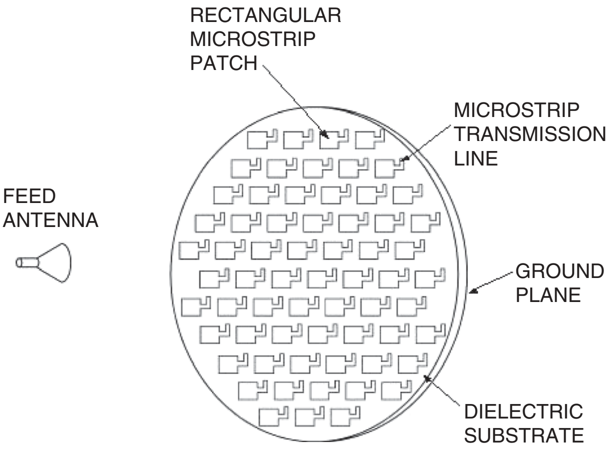

Figure 1.3. Reflectarray using printed patch elements with variable-length delay lines.

electronic beam scanning [10, 11]. With this beam scanning capability of the reflectarray, the complicated high-loss beamforming network and high-cost transmit/receive (T/R) amplifier modules of a conventional phased array are no longer needed.

One significant advantage of the printed reflectarray is that, when a large aperture (e.g., 10-m size) spacecraft antenna requires a deployment mechanism, the flat structure of the reflectarray allows a much simpler and reliable folding mechanism compared with that required for the doubly curved surface of a parabolic reflector. In addition, an inflation system augmented with a large, flat, thin membrane reflectarray aperture can be deployed using a rolling mechanism to form an inflatable antenna. The flat reflecting surface of the reflectarray also lends itself for flush mounting onto an existing flat structure without adding significant amount of mass and volume to the overall system structure. A reflectarray with hundreds or thousands of elements, being in the form of a printed microstrip antenna, can be fabricated with a simple and low-cost chemical etching process, especially when produced in large quantities.

Another major feature of this antenna is that, with a large number of elements in a reflectarray having elemental phase adjustment capability, it can achieve very accurate contour beam shape by using a phase synthesis technique [12, 13]. Similar to the parabolic reflector, multiple-beam capability can also be achieved by placing multiple feed elements at the focal area of the antenna. The reflectarray technology can be applied throughout the microwave spectrum, as well as at the millimeter-wave frequencies.

1.2.2 Disadvantage of Reflectarray

With all the above capabilities, there is one distinct disadvantage associated with the reflectarray antenna. This is its inherent characteristic of narrow bandwidth, which generally cannot exceed much beyond ten percent depending on its element design, aperture size, focal length, etc. The bandwidth performance of a reflectarray [14, 15] is no match to that of a parabolic reflector, where theoretically infinite bandwidth exists. For a printed microstrip reflectarray, its bandwidth is primarily limited by two factors. One is the narrow bandwidth of the microstrip patch elements on the reflectarray surface and the other is the differential spatial phase delay.

1.2.2.1 Bandwidth Limited by Element. The microstrip patch element generally has a bandwidth of about 3 to 5 percent. To achieve wider bandwidth for a conventional microstrip array, techniques such as using thick substrate for the patch, stacking multiple patches [16, 17], and using sequentially rotated subarray elements have been employed. More than 15 percent bandwidths have been reported.

1.2.2.2 Bandwidth Limited by Differential Spatial Phase Delay. The second reflectarray limiting factor, the differential spatial phase delay, can be

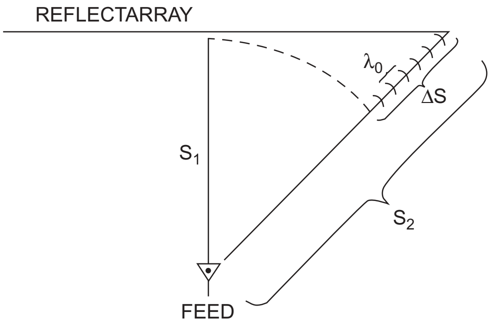

Figure 1.4. Differential spatial phase delay of reflectarray.

best explained by referring to Fig. 1.4 where the differential spatial phase delay, ΔS, is the phase difference between the two paths S1 and S2 from the feed to the reflectarray elements. This ΔS can be many multiples of the wavelength (λ) at the center operating frequency. It can be expressed as $\Delta S = (N + d)\lambda$ where N is an integer and d is a fractional number of a free-space wavelength λ. At each element location, d is compensated by an appropriate phase delay achieved by the reflectarray element design (achieved by variable patch size, variable phase delay line length, etc.). As the frequency changes, the factor $(N + d)\lambda$ becomes $(N + d)(\lambda + \Delta\lambda)$. Since the design and the compensating phase for each element are fixed for the center frequency, a frequency excursion error will occur in the reradiated phase front. The amount of phase change in each path when compared with a reference path, say S1, is $(N + d)\Delta\lambda$ which can be a significant portion of a wavelength or 360°.

To reduce the amount of frequency excursion error, the integer number N must be reduced. There are several methods to reduce N. One is to design the reflectarray with a larger focal-length-to-diameter (f/D) ratio and hence to minimize the difference between paths S1 and S2. The second way is simply to avoid the use of a reflectarray with a large electrical diameter. The third method to reduce frequency excursion error is to use time delay lines or partial time delay lines instead of the phase delays. In other words, when using the phase delay line technique (not the variable patch size technique), instead of using $d\Delta\lambda$ for the delay line length, $(N + d)\Delta\lambda$ could be used for the delay line. Certainly, additional line insertion loss and needed real estate for the lines are issues to be encountered.

Another method to increase the bandwidth is to use, instead of a complete flat reflectarray surface, a concavely curved reflectarray with piecewise flat surfaces. This piecewise flat reflectarray has advantages over a curved parabolic reflector: its beam is able to be scanned to large angles with phase shifter inserted into each element, and, for a space deployable antenna, the piecewise flat surfaces in some cases are more easily folded into a smaller stowed volume.

The narrow bandwidth behavior of the reflectarray will be discussed further in Chapter 5. Techniques to expand the bandwidth will also be presented. Although the reflectarray has bandwidth limitation, due to its multitude of capabilities, the development, research, and application of the printed reflectarray antenna would remain to be boundless in the future.

This book is divided into seven chapters covering different aspects of the reflectarray. Chapter 2 gives a detailed development history of the reflectarray since its invention. It would greatly enhance the ability of an engineer in understanding the reflectarray system if he or she is familiar with the evolution of the reflectarray antenna. In this same chapter, performance comparisons with two similar technologies, array lens and Fresnel-Zone plate reflector, are also briefly discussed. Reflectarray is a relatively complex antenna. Its radiation efficiency is highly dependent on the accuracy of the analysis technique and design knowledge. Chapter 3 provides a detailed discussion on several viable analysis techniques, while Chapter 4 gives practical design points for the element and antenna geometry designs. Since the major drawback of the reflectarray is its relatively narrow bandwidth, several researchers have developed techniques to broaden its bandwidth from a few percent to more than ten percent. Chapter 5 discusses the bandwidth limitation of a reflectarray and its broadband techniques. Chapter 6 presents dual-band and multi-band techniques for a single reflectarray aperture to handle multiple frequencies that are widely separated. Although the reflectarray was invented more than 40 years ago, its application has not been diversified until recently due to the development of the printable microstrip reflectarrays. Several important recent applications, as well as possible future applications, are presented in the final Chapter 7. Examples such as inflatable reflectarray, contour-beam application, multibeam reflectarray, amplifying reflectarray, folded low-profile configuration, Cassegrain offset configuration, very large aperture application, and beam scanning reflectarray are presented with some details. Due to the multitude of capabilities, the development and application of reflectarrays are expected to continue well into the future.

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