

Introduction to Reflectarray Antennas

1.1 Reflectarray Concept

Communicating over long distances had long been a dream for mankind until 1901 when Marconi demonstrated the first cross Atlantic wireless signal transmission. Since then, long distance communications have evolved to a degree where mankind can communicate wirelessly across the Solar System and beyond. Long distance communication requires large antennas in order to establish the wireless link between the transmitter and receiver. One of the most practical types of electrically large antennas are reflectors. While reflectors were originally built as optical devices [1], the discovery of electromagnetic waves by Maxwell, began a new era for communication with these antennas. The first experimental demonstration of wireless communication by Hertz in 1887, used a dipole-fed cylindrical parabolic antenna, which is believed to be the first reflector antenna operating at non-optical frequencies. Since then, reflectors have become the most widely used high-gain antenna in communications, radio astronomy, remote sensing, and radar [2].

An alternative approach to realization of a large antenna is by using several smaller antennas in the form of an array [3]. The first antenna array was built over 100 years ago [4]. In order to increase the directivity of a single monopole, Brown used two vertical antennas separated by half a wavelength and fed them out of phase [5]. He and several other notable scientists such as Marconi, Braun, and Adcock explored the unique characteristics of antenna array over the years [6]–[8]. Antenna array engineering evolved rapidly thereafter, particularly during the Second World War; however, it was the development of semiconductor technology in the 1960s and the printed circuit board technology in the 1970s that had the largest impact on their development. In particular the microstrip patch antenna proposed by Deschamps in 1953 [9] and later made practical by Munson in 1972 [10], revolutionized array engineering. Microstrip antenna arrays have since then played an important role in modern phased array systems.

While reflectors and arrays still compete for large aperture jobs in many types of systems, in the recent years, a new generation of high-gain antennas has emerged, which have attracted increasing interest from the antenna/electromagnetic community because of their low-profile, low-mass, and in many cases, low-cost features. This antenna is known as the reflectarray antenna [11]–[13]. The reflectarray antenna is a hybrid design, which combines many favorable features of reflectors and printed arrays, and as



Figure 1.1 The geometry of an offset-fed reflectarray antenna.

such can provide advantages over these two conventional antennas. The parabolic reflector is difficult to manufacture in many cases due to its curved surface that requires expensive custom molds and also become more difficult to manufacture at higher microwave frequencies. On the other hand, while antenna arrays offer the advantages of flexible design freedoms and versatile radiation performance, its feeding network suffers from the energy loss and design complexity, and the cost of the T/R modules [14] in active phased arrays becomes prohibitively high for many applications. As such, the reflectarray has fast been gaining attention as an alternative to these more mature technologies as it is able to mitigate the disadvantages associated with both of these high-gain antennas.

The reflectarray is an antenna with a flat reflecting surface consisting of hundreds of elements on its aperture and an illuminating feed antenna, as shown in Figure 1.1.

The feed antenna spatially illuminates the aperture where the elements are designed to reflect the incident field with certain phase shifts in order to collimate the beam of the antenna in the desired direction and with the preferred shape. Its operation principle is similar in concept to reflector antennas with respect to the spatial illumination, and again similar in concept to antenna arrays with respect to phase synthesis and beam collimation.

1.2 Reflectarray Developments

The concept of reflectarray antennas was initially introduced in the early 1960s using short-ended waveguide elements with variable lengths [11]. The feed antenna illuminated the waveguides where the lengths of the shorted waveguides were designed such that the phase of the reradiated signals would form a collimated beam in the desired far-field direction. While the concept was very interesting, the bulky and heavy

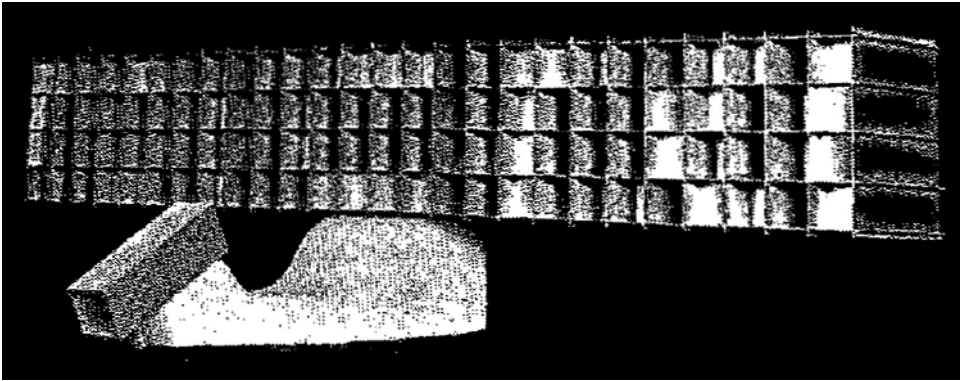


Figure 1.2 The first reflectarray antenna using waveguide technology. Source: Berry 1963 [11]. Reproduced with permission from IEEE.

waveguide structure of this first reflectarray antenna was a major drawback. The experimental model of the waveguide reflectarray is shown in Figure 1.2.

Although some work on spiralphase reflectarrays was reported by Phelan in the mid-1970s [15], the reflectarray antenna did not receive much attention after that until the revolutionary breakthrough of printed microstrip antenna technology in the 1980s. Since then, research on reflectarray antennas has been on the rise, and several diversified applications such as multi-beam antennas for point-to-point communication, beam-scanning antennas for radar applications, and spatial power combining reflectarray systems have been demonstrated. In particular, over the past 10 years, an increased interest in reflectarray antenna research has been observed in both academic and industrial sectors of the antenna community, which is also propelled by advances in fabrication technologies as well as computational resources.

Since 2006, the *IEEE Antennas and Propagation International Symposium* (APS) has included sessions dedicated to reflectarray antennas in the general conference proceedings, and several sessions and special sessions have been held since then. Most notably a full-day special session on reflectarray antennas was held at the 2011 APS. Several hundred papers have been presented in these sessions, and many researchers are now interested in joining this active research area. In 2012, the *International Journal of Antennas and Propagation* published a special issue on Reflectarray Antennas: Analysis and Synthesis Techniques, which further stimulated the research interest in this area. A literature search on IEEE Xplore using the keyword “reflectarray” showed more than 1200 articles have been published in IEEE in this area, as shown in Figure 1.3. The majority of the articles, however, have been published in the recent years, and in particular, there has a notable increase in the number of papers over the last 10 years.

The reflectarray antenna offers a multitude of capabilities that has encouraged continuous development and exciting applications in recent years. The elements of the reflectarray are designed to reflect the electromagnetic wave with a certain phase to compensate for the phase delay caused by the spatial feed. The phase shift of the elements is realized using various methods such as variable size elements, phase-delay lines, and element rotation techniques. The infinite array approach is used to calibrate the element phase versus element change [12]. Due to the very large number of elements

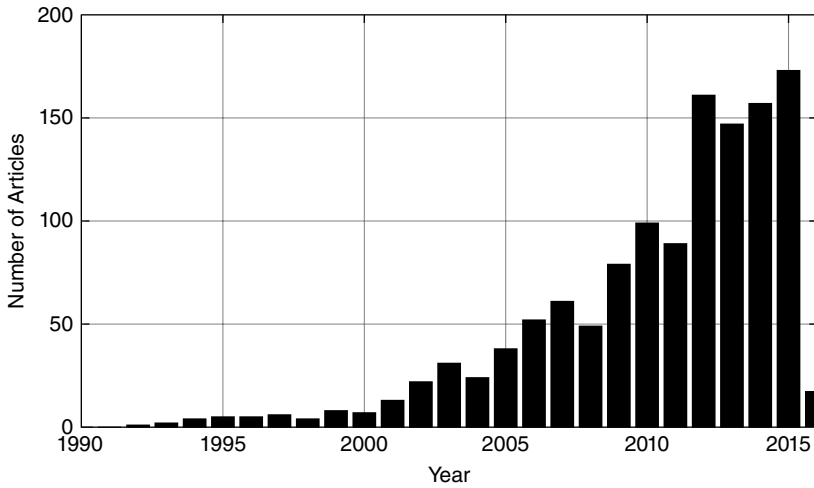


Figure 1.3 The number of articles on reflectarray antennas published in IEEE. Data obtained from IEEE Xplore on April 1, 2016.

involved in a reflectarray, full-wave simulation of the entire reflectarray antenna is still challenging. On the other hand, different theoretical models have been developed for the analysis of reflectarrays, such as the array theory formulation and the aperture field analysis technique, which show a good agreement with measured results. Moreover, implementing the spectral transform in these calculations allows for fast calculation of the radiation characteristics of the antenna, which is a considerable advantage for synthesis design problems using iterative procedures.

Single and multilayer reflectarrays have been designed to achieve broadband and multiband performance from microwave frequencies up to the THz range [16], [17]. Considerable improvements have been made to these designs over the years, and many practical designs have been demonstrated. One of the main challenges in reflectarray designs is improving the bandwidth of the antenna, which is the major drawback of printed resonator-type structures [18]. Different bandwidth improvement techniques such as using multilayer designs [19], [20], true time-delay lines [21], and sub-wavelength elements [22] have been studied and bandwidths of more than 20% have been reported.

Meanwhile, the direct control of the phase of every element in the array allows multi-beam performance with single or multiple feeds. The design of contoured beam reflectarrays is also a challenging field [23]. A phase-only synthesis process is used to obtain the required element phase shift from any given mask. Multi-feed multi-beam contoured beam designs have been demonstrated [24]; however, the performances of these designs are slightly inferior to the shaped-beam parabolic reflectors. Another advantage of reflectarrays is the ability of the antenna to scan the main beam to large angles off broadside. Beam-scanning reflectarrays are designed by using low-loss phase shifters integrated in every element of the array [25]. These beam-scanning reflectarrays require a switch board to control the main beam direction and are well suited for radar applications, and some models have been demonstrated; however, considerable challenges lie in improving the performance of these beam-scanning antennas.

In addition to the numerous capabilities and potentials that reflectarray antennas have demonstrated, a great deal of interest is now in the practical implementation of reflectarray antennas for space applications. Since the common considerations for space antennas are size, weight, and power (SWaP), because of limitations imposed by the satellite launch capabilities [26], the reflectarray antenna shows significant advantages over conventional high-gain space antennas, which are typically reflectors/lenses and arrays. These momentous promises make the reflectarray antenna a suitable low-cost choice for the new generation of space antennas.

The advantages of reflectarrays, such as low-profile, lightweight, and conformal geometry, make it desirable for various communication systems, especially for those mobile platforms. Its applications in space exploration, satellite communications, remote sensing, and radar systems are rising up within the last decade, and will continue to increase in the future. In addition, the current printed circuit board (PCB) fabrication technology and available low-cost commercial laminates, allows for low-cost rapid prototype fabrication. This is also leading to commercial implementation and large-scale fabrication of reflectarray antennas for commercial applications.

Terahertz and optical applications are also a very promising future of reflectarrays. With advances in fabrication technologies such as 3D printing devices and nanotechnology, the practical implementation of THz and optical reflectarray designs at a competitive cost is not far away. The full potential of reflectarray capabilities has not yet been fully exploited. Researchers in this field are constantly presenting new ideas and designs ranging from advanced materials to multifunctional system designs. As such it is expected that this field will remain an active area of research in the next decade, and there is no doubt that reflectarrays will become an important member in the antenna family.

1.3 Overview of this Book

The aim of the book is to provide scientists and engineers in the fields of antenna, microwave, and electromagnetic, with an up-to-date knowledge of reflectarray antenna theories as well as the design and analysis techniques. This book will provide the reader with:

- An overview of the reflectarray antenna research history, including various implementations and state-of-the-art.
- A good knowledge of the basic theories for design and analysis of reflectarray antennas, which will help to build up the fundamental capabilities for reflectarray research. In addition, a wealth of design examples along with numerical and experimental results are presented, which serves as a reference for researchers to verify their own developed programs.
- Detailed design procedures for a wide range of diversified applications, such as broadband designs, multiband operation, multi-beam performance, contour-beams, beam-scanning systems, and conformal reflectarray antennas, along with illustrative examples for each design.

The prerequisite for this book is that the readers should be familiar with the basics of antenna engineering. An introductory course to antenna engineering is typically offered as a senior level course for a bachelor student in the field of electrical engineering.

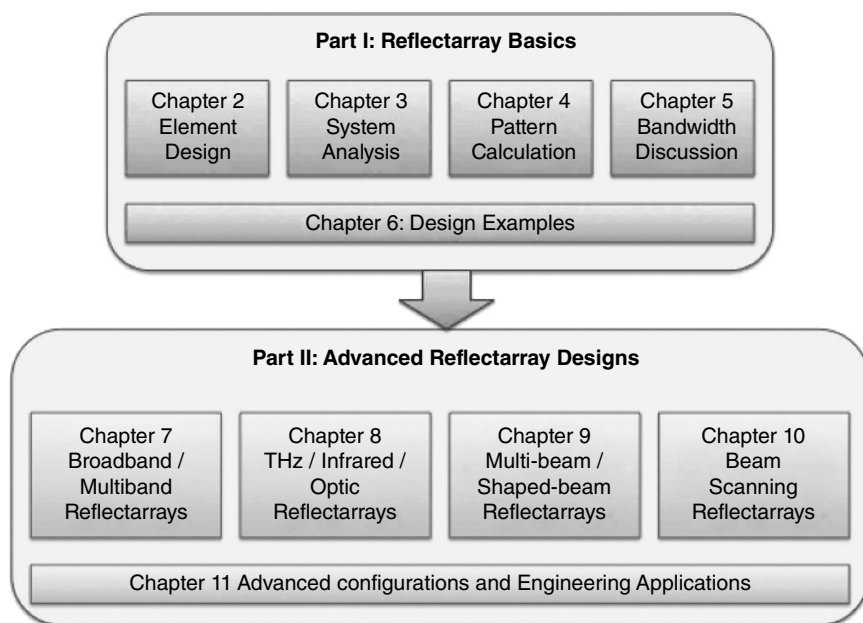


Figure 1.4 Organization of this reflectarray book.

As such any student in this field will be able to benefit from this book. However, this book is intended for both beginners and specialists in the field of electrical engineering. This is achieved by organizing and preparing this book in two parts and in 11 chapters, as illustrated in Figure 1.4.

The first part, which includes the fundamental theories of reflectarrays, is intended for engineers that know the basics of antenna theory and are starting to become familiar with this new generation of high-gain antennas. The second part of the book is intended for researchers and specialists that have a good knowledge of the basic theories in reflectarray, and aim at designing reflectarray antennas for specific applications/operations.

The first part includes the basic theories for analysis and design of reflectarray antennas. This section of the book builds the fundamental knowledge one needs to have in order to understand the governing dynamics of a reflectarray antenna system, and efficiently design and analyze reflectarray antennas. Chapter 2 is devoted to analysis and design of reflectarray phasing elements, and provides a comprehensive coverage of aperture phase requirements in reflectarray systems, phasing element design methodologies, element analysis techniques, as well as design examples. The reflectarray system design is introduced in Chapter 3, where the readers will learn the basics of the reflectarray systems and efficiency analysis for practical designs. A detailed coverage of the various methods to compute the radiation characteristics of reflectarray antennas is presented in Chapter 4. The bandwidth characteristics of reflectarray antennas is studied in detail in Chapter 5. The last chapter of the first part of this book is devoted to design examples, where a variety of reflectarray designs are presented that can serve as a useful reference for interested readers.

The second part of the book is intended for researchers that have a good knowledge of the basic theories in reflectarray, and aim at designing reflectarray antennas for specific applications/operations. This part starts with a comprehensive chapter on broadband and multiband reflectarray antennas in Chapter 7. Reflectarrays operating above microwave frequencies such as in the terahertz, infrared, and optical spectrums are introduced in Chapter 8. After discussion of the frequency behaviors of reflectarrays, advanced designs on the radiation patterns are followed. A detailed coverage of multi-beam and shaped-beam reflectarrays is presented in Chapter 9. Chapter 10 is devoted to beam-scanning reflectarray antennas, where the extensive research on these types of reflectarrays are summarized and analyzed in a comprehensive fashion. The final chapter of this book is devoted to advanced configurations of reflectarray antennas, such as conformal geometries and dual-reflector configurations, and applications such as satellite communications and spatial power combining.

References

- 1 A. Dodd, "An acre of glass – The history of the telescope," [Online]. Available: <http://ezinearticles.com/?An-Acre-of-Glass-The-History-of-the-Telescope&id=2601009> (accessed July 1, 2017).
- 2 Y. Rahmat-Samii and R. L. Haupt, "Reflector antenna developments: A perspective on the past, present and future," *IEEE AP-S Mag*, Vol. 57, No. 2, Apr 2015.
- 3 R. L. Haupt and Y. Rahmat-Samii, "Antenna array developments: A perspective on the past, present and future," *IEEE AP-S Mag*, Vol. 57, No. 1, Feb 2015.
- 4 J. A. Fleming, *The Principles of Electric Wave Telegraphy and Telephony*, 3rd Edn, New York: Longmans, Green, and Co., 1916.
- 5 S. G. Brown, Brit. Patent No. 14,449, 1899.
- 6 G. Marconi, "On methods whereby the radiation of electric waves may be mainly confined to certain directions, and whereby the receptivity of a receiver may be restricted to electric waves emanating from certain directions," *Proc. Roy. Soc. Lond., Ser. A.*, Vol. 77, p. 413, 1906.
- 7 F. Braun, "Electrical oscillations and wireless telegraphy," Nobel Lecture, Dec. 11, 1909.
- 8 F. Adcock, Improvement in means for determining the direction of a distant source of electro-magnetic radiation, UK Patent 130,490, Aug. 7, 1919.
- 9 G. A. Deschamps, "Microstrip microwave antennas," presented at the *3rd USAF Symp. on Antennas*, 1953.
- 10 R. E. Munson, "Microstrip phased array antennas," *Proc. of 22nd Symp. on USAF Antenna Research and Development Program*, Oct 1972.
- 11 D. G. Berry, R. G. Malech, and W. A. Kennedy, "The reflectarray antenna," *IEEE Trans. Antennas Propagat.*, Vol. AP - 11, Nov. 1963, pp. 645–651.
- 12 D. M. Pozar, S. D. Targonski, and H. D. Syrigos, "Design of millimeter wave microstrip reflectarrays," *Proc. IEEE Trans. Antennas Propagat.*, Vol. 45, pp. 287–295, Feb. 1997.
- 13 J. Huang and J. A. Encinar, *Reflectarray Antennas*. New York, NY, USA: Wiley-IEEE, 2008.
- 14 R. C. Hansen, *Phased Array Antennas*, 2nd Edn, Chichester, UK: John Wiley & Sons, Ltd, 2009.
- 15 H. R. Phelan, "Spiralphase reflectarray for multitarget radar," *Microwave Journal*, Vol. 20, July 1977, pp. 67–73.

- 16 A. Yu, "Microstrip reflectarray antennas: Modeling, design and measurement," Ph.D. dissertation, Dept. Elect. Eng., University of Mississippi, Oxford, MS, 2010.
- 17 P. Nayeri "Advanced design methodologies and novel applications of reflectarray antennas," Ph.D. dissertation, Department of Electrical Engineering, University of Mississippi, MS, 2012.
- 18 D. M. Pozar, "Bandwidth of reflectarrays," *Electronics Letters*, Vol. 39, No. 21, Oct. 2003.
- 19 J. A. Encinar, "Design of two-layer printed reflectarrays using patches of variable size," *IEEE Trans. Antennas Propag.*, Vol. 49, No. 10, pp. 1403–1410, Oct. 2001.
- 20 J. A. Encinar and J. A. Zornoza, "Three-layer printed reflectarrays for contoured beam space applications," *IEEE Trans. Antennas Propag.*, Vol. 52, No. 5, pp. 1138–1148, May 2004.
- 21 E. Carrasco, J. A. Encinar, and M. Barba, "Bandwidth improvement in large reflectarrays by using true-time delay," *IEEE Trans. Antennas Propag.*, Vol. 56, No. 8, pp. 2496–2503, Aug. 2008.
- 22 P. Nayeri, F. Yang, and A. Z. Elsherbeni, "A broadband reflectarray using sub-wavelength patch elements," *IEEE Antennas and Propagation Society International Symposium*, South Carolina, U.S., 2009.
- 23 D. M. Pozar, S. D. Targonski, and R. Pokuls, "A shaped-beam microstrip patch reflectarray," *IEEE Trans. Antennas Propag.*, Vol. 47, pp. 1167–1173, July 1999.
- 24 M. Arrebola, J. A. Encinar, and M. Barba, "Multifid printed reflectarray with three simultaneous shaped beams for LMDS central station antenna," *IEEE Trans. Antennas Propag.*, Vol. 56, No. 6, pp. 1518–1527, June 2008.
- 25 S. V. Hum, M. Okoniewski, and R. J. Davies, "Modeling and design of electronically tunable reflectarrays," *IEEE Trans. Antennas Propag.*, Vol. 55, No. 8, pp. 2200–2210, Aug. 2007.
- 26 R. B. Dybdal, "Satellite antennas," in *Antenna Engineering Handbook*, J. Volakis (ed.), McGraw-Hill, 2007.