1 Introduction to Surface Electromagnetics

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1.1 What Is Surface Electromagnetics?

The essence of a thing is hidden in its interior, while the (misleading) sensate qualities are caused by the surface.

Democritus, 460–365 BC

Most of the time, people start to comprehend the essence of a material from its outside appearance, i.e., the surface features. Surfaces, surface phenomena, and surface processes widely exist in nature and our daily lives. In general, surface science and surface engineering explore these phenomena and processes and utilize the acquired knowledge to improve the lives of human beings [1–3]. For example, when people discovered the surface tension effect from water beading on a leaf, waterproof cloth was invented accordingly.

In chemistry, it is critical to understand chemical reactions on surfaces, either for desirable reactions, such as in heterogeneous catalysis, or undesirable ones, such as in corrosion chemistry. In modern physics, scientists study the specific arrangement of atoms on the surface layer of matter through advanced experimental equipment such as X-ray photoelectron spectroscopy and scanning tunneling microscopy, which help us to see and to change the micro-world. Novel surface-type materials, such as graphene [4], have been invented recently and have attracted growing interest in science and engineering communities. In brief, surface science and engineering have broad impacts on modern industries such as oil, metallurgy, microelectronics, lubrication, and adhesion. They are also closely related to human health because of their impacts on biology and pharmaceuticals.

This book focuses on "surface electromagnetics" (SEM), a subdiscipline in electromagnetics with an abundance of specialized and exciting knowledge yet to be explored. As we know, electromagnetics is a fundamental science discipline that describes the temporal and spatial behaviors of electric and magnetic fields [5]. From the temporal viewpoint, electromagnetics is usually classified into different categories according to the field's oscillation frequency, such as direct current (DC), radio frequency (RF), microwaves, terahertz (THz), optics, X-rays, and beyond. This begs the question of how we categorize electromagnetics from the spatial viewpoint. To answer this, serious and in-depth contemplation is required.

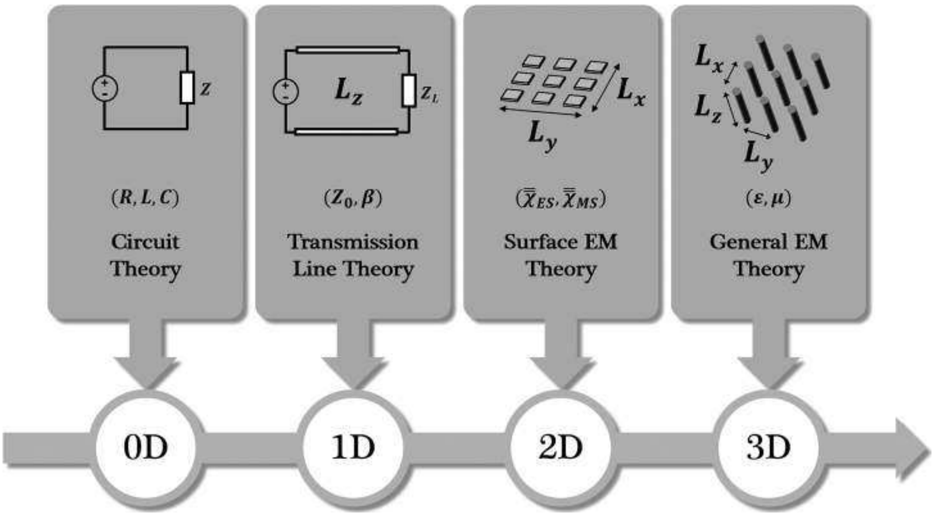

Figure 1.1 Classifications of electromagnetic phenomena in space domain based on the three-dimensional electric sizes. A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

Figure 1.1 illustrates our preliminary contemplation on this question. As a unified and fundamental theorem, Maxwell's equations are used to describe all macroscopic electromagnetic phenomena, where three-dimensional spatial variations are considered. Thus, the spatial dimensions of the field oscillation can be used as a measure to categorize different electromagnetic (EM) phenomena. For each group of electromagnetic phenomena, corresponding theorems have been developed based on Maxwell's equations.

- **General 3-D EM phenomena.** When field variations are comparable to wavelength in all three dimensions (L_x, L_y, $L_z \sim \lambda$), it belongs to the three dimensional (3-D) phenomena. General electromagnetic theory has experienced a long time of development to deal with these 3-D phenomena. Due to the complexity, analytical solutions exist only for several canonical geometries. Recently, with the progress of computing capability, people are able to solve Maxwell's equations numerically [6] in complex media with certain (ε, μ), general shapes, and various boundary conditions. Of course, computing time and memory usage are still limiting factors.
- **0-D EM phenomena.** When the spacial variations of a device or an EM phenomenon are much smaller than wavelength in all three dimensions (L_x, L_y, $L_z \ll \lambda$), it belongs to the zero-dimensional (0-D) phenomena. Circuit theory is proved to be an accurate and efficient approach for 0-D problems, which is a good simplification of Maxwell's equations. Resistor (R), inductor (L), and capacitor (C) are typical components in electronic circuits with lumped voltage and current sources [7].
- **1-D EM phenomena.** In microwave circuits and optical waveguides, their transverse dimensions are much smaller than wavelength, but the longitudinal

dimension is comparable to wavelength (L_x, $L_y \ll \lambda$, $L_z \sim \lambda$). Thus they are categorized as one-dimensional (1-D) phenomena. Circuit theory is no longer valid, while general EM theory is relatively complex for the analysis. Hence, transmission line theory, which has become a fundamental pillar stone of microwave engineering, was developed [8]. The characteristic impedance (Z_0) and the propagation constant (β) are critical parameters to describe these one-dimensional (1-D) EM phenomena.

- **2-D EM phenomena.** Reviewing Figure 1.1, it is interesting to note that surface electromagnetic theory, which deals with two-dimensional (2-D) EM phenomena (L_x, $L_y \sim \lambda$, $L_z \ll \lambda$), has not been fully developed yet. The eigen-parameters of general surfaces need to be defined, and the simplified theorems from Maxwell's equations need to be derived. Furthermore, application of appropriate SEM theorems to analyze and design advanced EM surfaces is still challenging.

By focusing on the 2-D EM phenomena, this book provides a comprehensive presentation of surface electromagnetics by editing the most state-of-the-art concepts, physics, engineering designs, and exciting applications. It covers the fundamental theorems of SEM, including the analytical surface models, general sheet transmission condition (GSTC), and efficient numerical algorithms. A plethora of applications are presented in this book to demonstrate the broad impact of SEM, including gap waveguides, leaky wave antennas, transmitarrays, orbital angular momentum (OAM) beam generation, and mantle cloaking. These SEM-based applications span widely from microwave to terahertz to optical spectrums.

1.2 Development of Electromagnetic Surfaces

Surface electromagnetics is not a completely new topic. Instead, it has a rich history of fascinating discoveries. For example, light bends at the interface between air and water, and light focused by a parabolic reflector can ignite a paper [9]. On the other hand, surface electromagnetics is also an exciting frontier full of new breakthroughs. Anomalous reflection and refraction have been recently discovered [10], and meta-lenses of nano-thickness have been successfully designed [11], which opens up a whole new way to design optical devices.

This section provides a historical review on the development of electromagnetic surfaces and interesting phenomena associated with them. It is expected that this history will stimulate and inspire new ideas in the future.

1.2.1 Classical Uniform EM Surfaces

It might be argued that the earliest electromagnetic surfaces people encountered were the natural surfaces that resided between two different media, for example, the surface of earth, an interface between air and water. Reflection occurs on these surfaces, and refraction also occurs when the second medium is a dielectric. Usually, the reflection

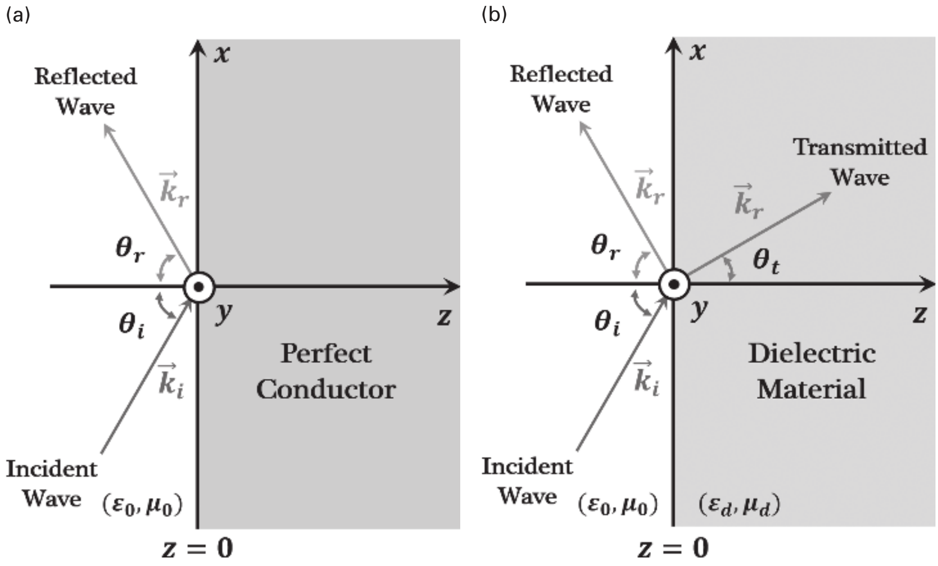

Figure 1.2 Reflection and refraction on a uniform surface: (a) an interface between air and a conductor; (b) an interface between air and a dielectric.

angle equals to the incident angle, which agrees with people's intuition. Meanwhile, the refraction angle is different from the incident angle (Figure 1.2b), which has fascinated and puzzled people for years.

In 1621, Dutch astronomer Willebrord Snellius (Snell) derived a mathematical formula for the incident, reflection, and refraction angles [12]:

$$\sqrt{\epsilon_0\mu_0}\sin\theta_i = \sqrt{\epsilon_0\mu_0}\sin\theta_r = \sqrt{\epsilon_d\mu_d}\sin\theta_t \tag{1.1}$$

This equation is well known as Snell's law, which provides a quantitative relationship of the three angles. It agrees well with measurement results and has been widely used to design electromagnetic devices or to measure the properties of an unknown medium. Based on this equation, many interesting phenomena have been discovered, such as the critical angle for total reflection and Brewster's angle for total transmission. Optical fiber, a fundamental device in the modern communication world, is designed based on the total reflection phenomenon.

It is important to point out that these natural surfaces are uniform surfaces. Along the normal direction (n), medium properties change. Along the tangential directions (t_1, t_2), the surface property does not change. Hence, the following relation exists:

$$\frac{\partial}{\partial n} \neq 0, \frac{\partial}{\partial t_1} = 0, \frac{\partial}{\partial t_2} = 0 \tag{1.2}$$

Besides planar surfaces, curved surfaces have also been studied. Cylindrical surfaces, spherical surfaces, and many other canonical surfaces have been studied comprehensively. They have been broadly used to design electromagnetic devices. For example, a parabolic metallic surface has been used to design reflector antennas, both for ground and space applications. A lens antenna is designed using a certain dielectric material with a combination of two curved surfaces.

Furthermore, coating metallic ground with a layer of dielectric substrate is a popular technique in the electromagnetic community. Impedance boundary conditions (IBC) have been proposed to characterize these hybrid surfaces. Various analytical and numerical methods have been developed to analyze these surfaces [13]. Although the surfaces are uniform, this research area is enriched tremendously when considering surface curvatures, surface combinations, dielectric properties, frequency responses, incident angles, and incident polarizations.

1.2.2 Periodic EM Surfaces: Frequency Selective Surface

A giant step in surface electromagnetics was the invention of frequency selective surface (FSS) [14]. In the optics community, it is also known as optical grating. The demand for FSS originated in the early 1950s with the development of radar technology, which was to find a radar absorbing material with a narrow-band frequency window for antennas to operate. This demand has propelled the FSS field of study, resulting in many interesting artificial surfaces. In contrast to conventional uniform surfaces, these artificial surfaces now have variations along the tangential directions,

$$\frac{\partial}{\partial n} \neq 0, \left(\frac{\partial}{\partial t_1}, \frac{\partial}{\partial t_2}\right) \neq 0 \tag{1.3}$$

In particular, these variations are periodic, either one-dimensional or two-dimensional.

Figure 1.3 shows two typical geometries of frequency selective surfaces. Basically, an FSS consists of an array of identical unit cells arranged in a periodic lattice. Various scatterers have been used as the unit cells, and they can be classified into two main categories: dipole-type FSS and slot-type FSS. In the former group, conductive scatterers are arranged in a plane, and they are not connected with each other. In the latter group, periodic slots are perforated on a conductive sheet.

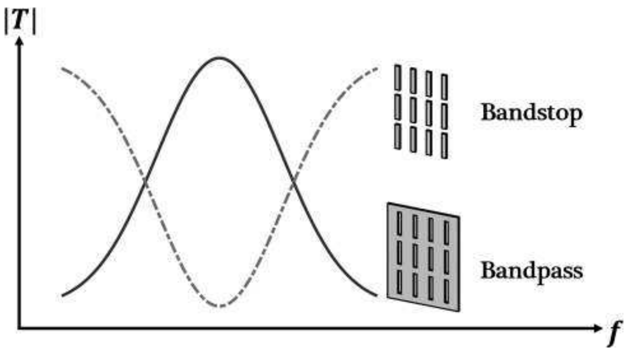

Figure 1.3 Frequency selective surfaces (FSS) and the band pass / band stop features.

The basic function of the FSS, as its name suggests, is to provide a certain frequency response for a plane wave to transmit through the surface. To be specific, the wave can pass through the surface in a certain frequency band and is rejected at other frequencies, or vice versa. As shown in Figure 1.3, a dipole-type FSS usually provides a band stop feature, while a slot-type FSS gives a band pass feature. Therefore, an FSS is also known as a spatial filter.

The FSS properties can be studied from both the circuit viewpoint and the field viewpoint. From the circuit viewpoint, it is analogous to an LC filter, and the resonant curve is of particular interest. The resonant frequency and the operation bandwidth are the most important features. Furthermore, wideband and multiband operations are always demanded. Meanwhile, unlike an LC filter that deals with a voltage or a current, an FSS deals with a plane wave. Hence, the field viewpoint is also critical. For example, angular stability and polarization stability are important considerations for FSS designs, as well as the cross-polarization levels.

Various FSSs have been developed to fulfill diversified design requirements. Different shapes have been studied, from simple cross dipoles, loops, and circular disks to advanced Jerusalem crosses and slotted patches and to their combinations. Dielectric loading is also found to be an effective approach, not only to provide mechanical support for scatterers but also to minimize their sizes. Multilayer FSSs are popularly designed, because they can cascade transmission zeroes and poles to shape the resonant curves, such as a flat top or a fast roll off. Furthermore, active FSSs have also been developed for reconfigurable frequency, beam control, grid oscillation and mixers, and spatial power combination [15].

To characterize the performance of these FSSs, various analysis methods and measurement techniques have been developed. For the analysis methods, the equivalent circuit approach provides a simple and straightforward understanding of the FSS's operating mechanism, while the mode-matching approach based on the Floquet theory provides an accurate result [16]. More recently, full-wave numerical techniques, such as the periodic method of moments (MoM) [17], the finite difference time domain (FDTD) method with periodic boundary conditions (PBC) [18], and the finite element method (FEM) [19], have also been used for FSS analysis with general applicability and high accuracy.

Nowadays, frequency-selective surfaces have been widely used in many civilian and defense applications. For example, it is used to design the door of a microwave oven, where the microwave cannot penetrate through but light can pass through. In contrast, the reverse function of the FSS is used to design a sun shield in a spacecraft, where a microwave signal can pass through for communication purpose, but light is reflected back to avoid overheating. FSSs are also used in a radome design for airplanes or a subreflector design for radio telescopes. In optics, it is a critical component in a laser source.

As a summary of this FSS section, it is worthwhile to emphasize that electromagnetic surfaces have evolved from a uniform surface to a periodic surface. An interesting analog is the evolution in circuit theory: from a direct current (DC) circuit to an alternating current (AC) circuit, which had a profound impact in circuits. The switch from DC to

AC is an evolution in the time domain, while the switch from a uniform surface to a periodic surface is an evolution in the space domain. This switch also has a profound impact in surface electromagnetics.

1.2.3 Periodic EM Surfaces: Soft/Hard Surface and EBG Surface

It is an important milestone in surface electromagnetics that a surface evolves from uniform to periodic. Besides the FSS designs, periodic surfaces have been used to design other functional surfaces, and many exciting phenomena have been discovered. This section will review some representative progress in this aspect.

As discussed before, periodic surfaces can be studied from both the circuit viewpoint and the field viewpoint. From the circuit viewpoint, FSS research mainly focuses on the resonant curve of the transmission magnitude. The transmission coefficient is usually a complex number with both the magnitude and the phase. When people explore the phase curve of a surface, interesting observations can be made such as an artificial magnetic conductor (AMC). From the field viewpoint, FSS research is limited within the plane wave incidence. When the incident wave is a surface wave propagating along the surface, novel surfaces and the corresponding features are discovered. Here, the soft/hard surfaces and high impedance surfaces are most prominent examples.

Figure 1.4a shows the geometry of a typical soft/hard surface. Basically, it is a corrugated surface with periodic metal walls on a ground plane [19,20]. The height of the corrugation wall is usually around quarter wavelength. When a surface wave propagates along the x direction, a low TE surface impedance and a high TM surface impedance are obtained, which represents a soft operation that stops the wave propagation. When a surface wave propagates along the y direction, a high TE surface impedance and a low TM surface impedance are obtained, which indicates a hard operation that allows the wave to propagate.

The above corrugated surface is periodic along the x direction but uniform along the y direction. Later on, a mushroom-like surface was proposed in [21], which is periodic in both x and y directions. It provides a high surface impedance for both x- and y-directed TM surface waves, which are usually the fundamental and lowest surface wave mode on a ground. Hence, it is also called a high impedance surface that stops the surface wave propagation. A dispersion diagram of surface wave modes is plotted in Figure 1.5a. It is observed that a distinct band gap exists where no surface wave can propagate on the surface regardless of its direction. Therefore, this type of surface is named an *electromagnetic band gap* surface [22], which resembles the energy band gap in semiconductors.

The EBG surface exhibits many interesting and unconventional features that do not occur or may not be readily available in nature. Thus, together with double-negative composites, it was put under the broad terminology of “metamaterials” [23]. No matter what we call them, we are more interested in their features. Besides the surface wave band gap, another exciting feature of the EBG surface is the in-phase reflection property. This time, we look back at the plane wave response of the EBG surface. However, instead of the magnitude curve in FSS, now we focus on the phase response of the

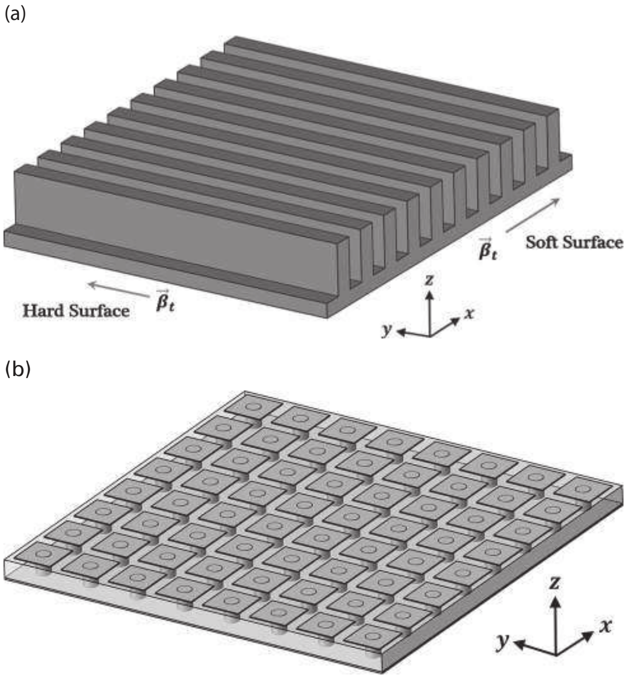

Figure 1.4 Geometries of (a) a soft and hard surface and (b) an electromagnetic band gap (EBG) surface.

surface. Figure 1.5b shows the reflection phase variation of an EBG surface versus frequency. At low frequency and high frequency, the reflection phase of the EBG surface is similar to a perfect electric conductor (PEC). At the center frequency, the reflection phase of the EBG surface is 0 degrees, which is the same as for a perfect magnetic conductor (PMC) that does not exist in nature. Since the EBG surface can mimic a nonexistent PMC surface, it is also called an *artificial magnetic conductor* (AMC) in some applications.

There is an abundance of exciting research going on when the surface evolves from uniform to periodic. There are multitude dimensions that the research can dig into. For example, besides the magnitude and phase, polarization is another important measure of an electromagnetic wave. A lot of interesting surfaces have been designed to control the wave polarization, such as from horizontal polarization to vertical polarization or from linear polarization to circular polarization [22]. A common feature of these designs is the thinness, which is usually much smaller than the wavelength.

This active surface research has led to many new device and system designs. For example, the soft/hard surfaces have been used in waveguide designs to support TEM wave propagation. They are also used in horn antennas to obtain a symmetric beam in E- and H-planes. The EBG surfaces have been used to reduce mutual coupling between array elements and in the IC packaging. They have also been used as ground planes of wire antennas to achieve a low profile configuration. Polarizer grids are also widely

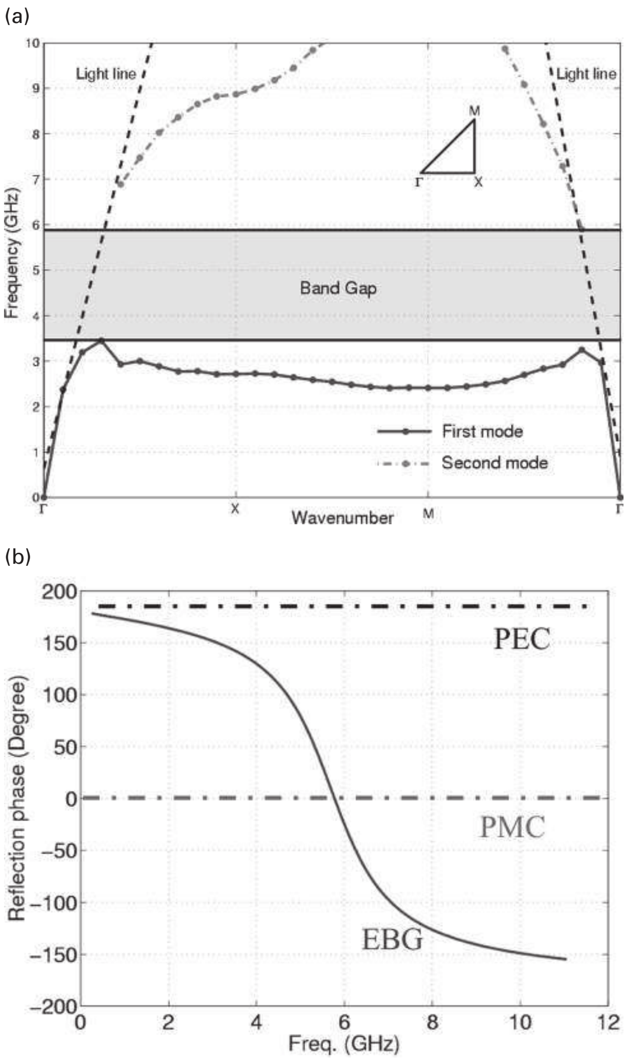

Figure 1.5 Properties of an EBG surface: (a) a frequency band gap for surface waves; (b) reflection phase varies with frequency.

used in microwave and optic systems to enhance the polarization purity. In summary, periodic surfaces are active and exciting research topics with broad impacts.

1.2.4 Recent Progress on Quasi-periodic EM Surfaces

When people are excited in exploring the realm of periodic surfaces and discovering interesting new phenomena, an even larger research tide is coming in. The core concept of this huge tide is quasi-periodic surfaces, which demonstrate more versatile and exceptional capabilities to manipulate electromagnetic waves. A broader area has opened to the scientists and engineers in the electromagnetic community! A similar breakthrough occurred in materials science, where Dan Shechtman observed unusual diffractograms from certain aluminum-manganese alloys in 1982. In contrast to the conventional periodic crystals, these types of materials are called quasi-periodic crystals or quasi-crystals, for which Shechtman was awarded the Nobel Prize in Chemistry in 2011 [24].

In a quasi-periodic surface, unit cells are arranged in a periodic lattice, and each cell differs from the others with some geometrical variations, such as scatterer size or orientation angle. Figure 1.6 shows two representative quasi-periodic surfaces developed by Prof. Fan Yang's group: one in the microwave band and the other in the optic region. Although the frequencies are vastly different, the operation principle behind them is identical. Figure 1.6a shows a reflectarray surface operating at 32 GHz, which consists of 9,636 square patches of varying sizes. The reflection phase changes with the patch size, similar to that in Figure 1.5b. When the patches are arranged to realize a Fresnel zone–type phase distribution, the surface can effectively focus the energy from a feed horn to generate a radiation beam with 43 dB high gain. Figure 1.6b illustrates an ultrathin (240-nm thickness) beam splitter operating at red light (632 nm), which consists of 640,000 circular disks of two diameters: 110 nm and 200 nm, respectively. Two columns of each type of disk are alternatively arranged, forming a phase distribution with a 180° phase variation. As a result, an incident red light will be split into two red lights upon the reflection from this ultrathin quasi-periodic surface.

From these examples, we can briefly summarize the operation principle of the quasi-periodic surfaces. First, each cell manipulates the incident wave locally and individually. The wave control and design method are similar to those in periodic surfaces discussed in the previous two sections. Next, the spatial distributions of these wave manipulations work together to change the wavefront of the incident wave, leading to extraordinary electromagnetic responses.

The above operation principle of quasi-periodic surfaces has enabled fascinating phenomena and designs that cannot be achieved conventionally, both in optics and in microwaves. An important breakthrough in optics is the generalized law of reflection and refraction [10]. By adding a gradient phase distribution of the surface into the conventional Snell's law, electromagnetic waves can now be reflected and refracted to any anomalous angle. Further research on the engineered phase gradient on the surface has allowed a negative-angle refraction in a broad wavelength range [25]. When this phase gradient is anisotropic, polarization conversion is observed together with the anomalous refraction at a subwavelength thickness [26]. Furthermore, if the phase gradient value is large enough, the surface can act as a bridge linking a plane wave with a surface wave [27]. Moreover, with careful design of surface phase distribution, various planar optical lenses for focusing and waveplates have been successfully designed [28,29], as have high-resolution holograms [30–34] and vortex beams [35,36]. By manipulating the phase of a propagating wave locally, metasurfaces were elaborately designed to function as an ultrathin invisibility skin cloak for visible light [37,38].

In the microwave region, quasi-periodic surfaces progress even further, since there are vigorous demands from communications and radars, and the fabrication technique is also readily available, which has led to practical devices and systems. The most prominent examples are reflectarray antennas (RA) [39] and transmitarray antennas