STRUCTURED SURFACES AS OPTICAL METAMATERIALS

Optical metamaterials are an exciting new field in optical science. A rapidly developing class of these metamaterials allow the manipulation of volume and surface electromagnetic waves in desirable ways by suitably structuring the surfaces they interact with. They have applications in a variety of fields, such as materials science, photovoltaic technology, imaging and lensing, beam shaping, and lasing.

Describing techniques and applications, this book is ideal for researchers and professionals working in metamaterials and plasmonics, as well as for those just entering this exciting new field. It surveys different types of structured surfaces, their design and fabrication, their unusual optical properties, recent experimental observations, and their applications. Each chapter is written by an expert in that area, giving the reader an up-to-date overview of the subject. Both the experimental and theoretical aspects of each topic are presented.

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Preface

If a metamaterial can be defined as a deliberately structured material that possesses physical properties that are not possible in naturally occurring materials, then deliberately structured surfaces that possess desirable optical properties that planar surfaces do not posses can surely be considered to be optical metamaterials. The surface structures displaying these properties can be periodic, deterministic but not periodic, or random.

In recent years interest has arisen in optical science in the study of such surfaces and the optical phenomena to which they give rise. A wide variety of these phenomena have been predicted theoretically and observed experimentally. They can be divided roughly into those in which volume electromagnetic waves participate and those in which surface electromagnetic waves participate. Both types of optical phenomena and the surface structures that produce them are described in this volume.

The first several chapters are devoted to optical interactions of volume electromagnetic waves with structured surfaces. One of the earliest examples of a structured surface that acts as an optical metamaterial, and the one that today is perhaps the best known and most widely studied, is a metal film pierced by a two-dimensional periodic array of holes with subwavelength diameters. It was shown experimentally by Ebbesen *et al.* [1] that the transmission of p-polarized light through this structure can be extraordinarily high at the wavelengths of the surface plasmon polaritons supported by the film. "Extraordinarily high" in this context refers to the observation that more than twice as much light is transmitted as impinges on the holes. This paper stimulated a great deal of theoretical and experimental work directed at elucidating the mechanism(s) responsible for the extraordinarily high transmissivity, and at enhancing it even more. In the first chapter, E. Popov and N. Bonod describe the theoretical and experimental studies of this phenomenon, whose explanation at times has been the subject of some controversy.

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Not all optical enhancement effects occur in transmission through structured surfaces. In Chapter 2, T. V. Teperik discusses recent theoretical and experimental work on the diffraction of light from a two-dimensional periodic lattice of submicron voids (nanopores) situated beneath the surface of a metal in contact with vacuum. This kind of structure supports both dispersive surface plasmon polaritons at the vacuum–metal interface, and nondispersive void plasmons associated with each void. One of the interesting and important consequences of the existence of the latter type of excitation is the possibility of achieving omnidirectional total absorption of p- and s-polarized light of a specified wavelength incident on the structure when the voids are filled with a dielectric medium. Moreover, as a consequence of Kirchhoff's law, such a structured surface can also exhibit omnidirectional blackbody emission at a resonant frequency that can be varied by varying the radius of the dielectric-filled voids. Other interesting optical properties of nanoporous metal surfaces are also discussed in this chapter.

The reflection of an optical plane wave from, and its transmission through, yet another type of two-dimensional periodic planar structure is discussed by A. Alú and N. Engheta in Chapter 3. The structure considered is a dense planar array of nanoparticles, primarily metallic nanospheres whose diameter and periods are smaller than the wavelength of the illuminating electromagnetic field, that are treated in the dipolar approximation. The reflection and transmission spectra display features arising from the plasmonic resonances of the individual nanoparticles, and from the two-dimensional periodicity of the structure as a whole. It is shown that structures of this type offer the possibility of basing highly reflective and/or frequency-selective surfaces at optical frequencies on them, which can be used for filtering, absorption, and radiation purposes.

A planar metamaterial is a planar two-dimensional surface of zero thickness that is periodically structured on the sub-wavelength scale. In practice such a material is represented by a single periodically patterned metal or dielectric layer that is very thin compared to the wavelength of the light incident on it, and is often supported by a transparent substrate. In a comprehensive review in Chapter 4, E. Plum and N. Zheludev analyze polarization and propagation properties of these metamaterials on the basis of such general principles as symmetry, Lorentz reciprocity, and energy conservation. They show that suitably structured planar metamaterials can display circular birefringence and circular dichroism, linear birefringence and linear dichroism, as well as asymmetric transmission of circularly polarized light incident on them from opposite directions.

The ability to control the propagation of light is important for a variety of applications. In recent years a great interest has arisen in the negative refraction of light as it passes through the interface between two media. This interest is due to the fundamental importance of this effect, as well as to possible applications

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of it. For example, a perfect lens can be created on the basis of a medium that produces negative refraction, and sub-wavelength imaging can also be achieved by the use of such a medium. Negative refraction has been achieved in two types of materials. The first type is a metamaterial that possesses simultaneously a negative dielectric permittivity and a negative magnetic permeability within some frequency range [2]. Such a medium has a negative-index of refraction, and hence is often referred to as a negative-index material. The first material with these properties was fabricated by embedding arrays of split-ring resonators in a lattice of metal wires [3]. The second type of material is a nonmagnetic metamaterial with a positive dielectric permittivity. Such a material has a positive index of refraction, and is often referred to as a positive-index material. Photonic crystals formed from dielectric components can serve as positive-index materials that display negative refraction. One of the mechanisms responsible for negative refraction in such media is the presence in their photonic band structure of a surface of constant frequency with a negative group velocity in some frequency range [4]. In this case the Poynting vector of a wave packet is directed opposite to its wave vector, which leads to negative refraction [5]. The negative group velocity of circularly polarized electromagnetic waves of one handedness propagating in a gyrotropic medium also leads to negative refraction in certain frequency ranges [6].

The types of metamaterials just described are bulk materials. However, negative refraction of volume electromagnetic waves can also be achieved by the use of suitably structured surfaces. In a recent study, Lu *et al.* [7] showed that negative refraction can be achieved when light is incident from a dielectric medium with a real positive refractive index $n > 1$ on a periodically corrugated interface with air, at an angle of incidence θ_0 that is greater than the critical angle for total internal reflection, $\theta_0 > \theta_c = \sin^{-1}(1/n)$. In this situation the zeroth and all positive orders of the light refracted into the air are suppressed, and by a suitable choice of the period of the corrugation of the interface only the (-1)-order refracted beam is nonzero. This mechanism for negative refraction has been confirmed experimentally. These authors also show that by introducing the periodic surface not on a homogeneous semi-infinite dielectric medium but on a planar multilayered medium, the restriction $\theta_0 > \theta_c$ can be lifted. This prediction has also been verified experimentally. W. T. Lu and S. Sridhar review this work in Chapter 5, and present descriptions of several optical devices based on this approach to negative refraction.

A more general type of refraction is described by A. A. Maradudin *et al.* in Chapter 6, where it is shown how to design and fabricate a two-dimensional randomly rough surface that transforms a beam with a specified transverse intensity distribution into a beam with a different specified intensity distribution on its transmission through that surface. Such beam shaping is used in a variety of applications from laser surgery to optical scanning. In this chapter it is also shown

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how to design and fabricate a circularly symmetric but radially random surface that transforms a plane wave incident on it into a transmitted beam that does not spread over a finite distance along the symmetry axis of the structure from the surface – a pseudo-nondiffracting beam. Such beams can be used in precision alignment and in laser machining, for example.

The preceding examples of structured surfaces that act as optical metamaterials have all consisted of surfaces that are illuminated by volume electromagnetic waves. However, the propagation of surface electromagnetic waves, and even their existence, can be modified in specified desirable ways by structuring in suitable ways the surfaces on which they propagate. Similarly, novel applications of these waves can be realized by a suitable structuring of the surfaces supporting them.

For example, it has been known for some time that the planar surface of a semi-infinite perfect conductor does not support a surface electromagnetic wave. However, if a perfectly conducting surface is periodically corrugated, as in a classical grating, or is doubly periodically corrugated, as in a bigrating, it can support a surface electromagnetic wave. These theoretical predictions have recently been confirmed experimentally. The interesting properties of these surface waves, which owe their existence to the structuring of the surfaces on which they propagate, are described by A. I. Fernández-Domínguez *et al*. in Chapter 7.

As we have noted above, the negative refraction of volume electromagnetic waves has been studied theoretically and experimentally by many investigators, and several mechanisms for accomplishing such refraction have been explored, including the use of a periodically corrugated dielectric surface [7]. Recently, attention has been directed at the negative refraction of surface plasmon polaritons. Shin and Fan [8] proposed a metal–dielectric–metal structure that produces all-angle negative refraction of a surface plasmon polariton incident on it. The negative refraction they predicted is not due to the structure producing it possessing simultaneously a negative dielectric permittivity and a negative magnetic permeability in some frequency range. Instead it arises because each structure supports a surface plasmon polariton whose dispersion curve possesses a branch with an isotropic negative group velocity. It has been known for some time that the existence in a medium of an elementary excitation that possesses a negative group velocity within some frequency range is a sufficient condition for that medium to display in that frequency range the negative refraction of light incident on it with a frequency in that range [4, 5]. The theoretical and experimental aspects of the negative refraction of a surface plasmon polariton are presented in Chapter 8 by P. B. Catrysse *et al*.

There exists a commonly held belief that any randomness in a long one-dimensional conductor leads to an exponentially small transmission due to the Anderson localization of all of its eigenstates. However, the actual situation is

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subtler than this. It has been shown [9] that specific long-range correlations in a scattering potential give rise to perfect electron wave transmission within any given energy/frequency window. This result, which is known as selective transparency, was confirmed in experiments on a single-mode waveguide possessing this type of disorder. The experimental results clearly showed the mobility edges that separate regions of perfect transparency from those with localized transport. As F. M. Izrailev and N. M. Makarov point out in Chapter 9, these results suggested to them that similar results should be observed in single-mode or multimode planar waveguides with one of their surfaces randomly rough, when the rough surface profile function has long-range correlations of a specific type. These authors present results confirming their expectation for both single-mode and multimode waveguides.

A recently introduced class of metamaterials is one consisting of materials designed in such a way that an object embedded in one of them is cloaked from observation by electromagnetic waves propagating through the material. Perhaps the most commonly employed approach to the design of such cloaks is transformation optics [10, 11]. It predicts materials with dielectric permittivities and magnetic permeabilities that possess coordinate dependencies that deform the path of electromagnetic waves propagating in them to avoid spatial regions occupied by the objects to be cloaked. This approach to the cloaking of two- and three-dimensional objects, and other approaches that have been proposed, are reviewed by C. C. Davis and I. I. Smolyaninov in Chapter 10. They then show how the approach to the cloaking of two-dimensional objects in metamaterials designed by transformation optics can be extended to the design of surface structures that cloak surface defects from detection by surface plasmon polaritons, and produce the "trapped rainbow" effect for guided waves, in which a suitably designed plasmonic waveguide slows down and stops light of different wavelengths at different spatial points along the waveguide. Experimental results demonstrating both effects are presented.

In a planar waveguide consisting of a thin oxide layer sandwiched between an air superstrate and a metallic substrate the electric field intensity of the surface electromagnetic wave guided by this structure becomes a maximum at the interface between air and the oxide layer as the waveguide thickness is made extremely thin but finite. If the oxide layer is patterned with a periodic structure, e.g. by an array of holes, a standing electromagnetic surface wave can be formed. Such a standing wave enhances the interaction between a molecule placed on the air–oxide interface and the electromagnetic field of the surface wave. This enhanced interaction can be useful in surface-enhanced Raman spectroscopy, in the detection of molecules on a surface, and as a source for coherent radiation (lasers). These applications, and the physics underlying them, are described by H. Grebel in Chapter 11.

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The chapters constituting this book present an up-to-date survey of many aspects of optical effects produced by structured surfaces. Yet, the topics covered in it do not exhaust the optical phenomena to which suitably structured surfaces can give rise. Indeed, they are limited only by our imagination. Nevertheless they provide a good indication of the variety of these phenomena, and the kinds of surfaces required for their realization, and help to indicate why this emerging field in optical science will continue to generate more research activity and applications in the future.

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References

[1] T. W. Ebbesen, H. J Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, "Extraordinary optical transmission through sub-wavelength hole arrays," *Nature* **391**, 667–669 (1998).
[2] V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ϵ and μ," *Soviet Physics-Uspekhi* **10**, 509–514 (1968).
[3] R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," *Science* **292**, 77–79 (2001).
[4] N. Notomi, "Theory of light propagation in strongly modulated photonic crystals: refractionlike behavior in the vicinity of the photonic band gap," *Phys. Rev. B* **62**, 10696–10705 (2000).
[5] L. I. Mandel'shtam, "Group velocity in crystalline arrays," *Zh. Eksp. Teor. Fiz.* **15**, 475–478 (1945).
[6] V. M. Agranovich, Yu. N. Gartstein, and A. A. Zakhidov, "Negative refraction in gyrotropic media," *Phys. Rev. B* **73**, 045114 (1-12) (2006).
[7] W. T. Lu, Y. J. Huang, P. Vodo, R. K. Banyal, V. H. Perry, and S. Sridhar, "A new mechanism for negative refraction and focusing using selective diffraction from surface corrugation," *Opt. Express* **15**, 9166–9175 (2007).
[8] H. Shin and S. Fan, "All-angle negative refraction for surface plasmon waves using a metal-dielectric-metal structure," *Phys. Rev. Lett*. **96**, 073907 (1-4) (2006).
[9] F. A. B. F. de Moura and M. L. Lyra, "Delocalization in the 1D Anderson model with long-range correlated disorder," *Phys. Rev. Lett*. **81**, 3735–3738 (1998).
[10] U. Leonhardt, "Optical conformal mapping," *Science* **312**, 1777–1780 (2006).
[11] J. B. Pendry, D. Schurig, and D. R. Smith, "Controlling electromagnetic fields," *Science* **312**, 1780–1782 (2006).

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