

## 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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# STRUCTURED SURFACES AS OPTICAL METAMATERIALS

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Contents

<i>List of contributors</i>	page xiii
<i>Preface</i>	xvii
1 Physics of extraordinary transmission through subwavelength hole arrays	1
EVGENY POPOV AND NICOLAS BONOD	
1.1 A brief reminder of the history of grating anomalies and plasmon surface waves	1
1.2 Generalities of the surface waves on a single interface	2
1.3 Extraordinary transmission and its first explanations	5
1.4 The role of the evanescent mode	10
1.5 Enhanced Fabry–Perot resonances through evanescent modes	16
1.6 What resonance predominates?	16
1.7 Nonplasmonic contributions	20
1.8 Conclusions	24
References	25
2 Resonant optical properties of nanoporous metal surfaces	28
TATIANA V. TEPERIK	
2.1 Introduction	28
2.2 Resonant optical properties of metal surfaces with spherical pores	30
2.3 Self-consistent electromagnetic model: scattering-matrix layer-KKR approach	33
2.4 Optical spectra of nanoporous metal surfaces	36
2.5 Total light absorption in nanostructured metal surfaces	43
2.5.1 Equivalent resonant <i>RLC</i> circuit model	44
2.5.2 General conditions for total light absorption	48
	v

2.5.3	Omnidirectional absorption by a nanoporous metal surface	50
	Acknowledgments	54
	References	54
3	Optical wave interaction with two-dimensional arrays of plasmonic nanoparticles	58
	ANDREA ALÚ AND NADER ENGHETA	
3.1	Introduction	58
3.2	Plane wave excitation of two-dimensional arrays of nanoparticles: theoretical analysis	59
3.2.1	TE excitation	61
3.2.2	TM excitation	69
3.3	Numerical results and design principles	75
3.3.1	TE polarization: lossless nanoparticles	75
3.3.2	TE polarization: realistic levels of absorption	84
3.3.3	TM polarization: realistic levels of absorption	87
3.4	Conclusions	91
	Acknowledgments	91
	References	91
4	Chirality and anisotropy of planar metamaterials	94
	ERIC PLUM AND NIKOLAY I. ZHELUDEV	
4.1	Introduction	94
4.2	General planar metamaterials	95
4.2.1	Lossless complementary planar metamaterials	101
4.2.2	Two-dimensional (2D) achiral planar metamaterials	101
4.2.3	Normal incidence onto achiral planar metamaterials	103
4.2.4	Two-fold rotational symmetry or normal incidence	104
4.3	Definitions	105
4.3.1	Alternative variables for the elements of scattering and transmission matrices	105
4.3.2	Polarization states	106
4.4	Polarization effects	107
4.4.1	Optical activity at oblique incidence ( $a \neq d$ )	107
4.4.2	Circular conversion dichroism ( $ b  \neq  c $ )	112
4.4.3	Linear conversion dichroism	116
4.4.4	Linear birefringence and linear dichroism	118
4.5	Eigenstates	120
4.5.1	Eigenstates for pure optical activity ( $b = c = 0$ )	123
4.5.2	Eigenstates in the absence of optical activity ( $a = d$ )	123

<i>Contents</i>	vii
4.6 Energy conservation	127
4.6.1 Lossless planar metamaterials	129
4.6.2 Lossless planar metamaterials without linear birefringence/dichroism ( $L = 0, b = c = 0$ )	133
4.7 Applications and limitations	135
4.7.1 Attenuators, beam splitters, mirrors, and empty space	135
4.7.2 Linear polarizer	136
4.7.3 Wave plates	138
4.7.4 Polarization rotators	141
4.7.5 Circular polarizers	146
4.8 Normal incidence	147
4.8.1 Achiral planar metamaterials at normal incidence	148
4.8.2 Isotropic planar metamaterials at normal incidence	151
4.8.3 Lossless planar metamaterials: normal incidence or two-fold rotational symmetry	151
4.9 Summary	153
References	155
5 Novel optical devices using negative refraction of light by periodically corrugated surfaces	158
WENTAO TRENT LU AND SRINIVAS SRIDHAR	
5.1 Introduction	158
5.2 Negative refraction with visible light and microwaves by selective diffraction	159
5.3 Focusing microwaves by a plano-concave grating lens	163
5.4 Realization of a plano-concave grating lens in optics	165
5.5 AANR and a negative lateral shift through a multilayered structure with surface gratings	169
5.6 Surface corrugation approach to AANR in 2D photonic crystals	171
5.7 Flat lens imaging with large $\sigma$	176
5.8 Discussions and conclusions	179
Acknowledgments	180
References	181
6 Transformation of optical fields by structured surfaces	185
A. A. MARADUDIN, E. R. MÉNDEZ, AND T. A. LESKOVA	
6.1 Introduction	185
6.2 Beam shaping	188
6.2.1 The transmitted field	188
6.2.2 The inverse problem	193

6.2.3	Beam shaping	197
6.2.4	Example	198
6.2.5	Fabrication of surfaces formed from triangular facets	199
6.2.6	Replacement of ensemble averaging by frequency averaging	204
6.3	Pseudo-nondiffracting beams	209
6.3.1	The transmitted field	209
6.3.2	The inverse problem	212
6.3.3	Three-dimensional distribution of the mean intensity in the radial direction from the optical axis	215
6.3.4	Pseudo-nondiffracting beam	217
6.3.5	Fabrication of circularly symmetric radially random surfaces	219
6.3.6	Replacement of ensemble averaging by frequency averaging	222
6.4	Discussion and conclusions	224
	Acknowledgments	225
	Appendix	225
	References	226
7	Surface electromagnetic waves on structured perfectly conducting surfaces	232
	A. I. FERNÁNDEZ-DOMÍNGUEZ, F. GARCÍA-VIDAL, AND L. MARTÍN-MORENO	
7.1	Introduction	232
7.2	Theoretical formalism: coupled mode method	234
7.3	Planar geometries	240
7.3.1	Textured surfaces	240
7.3.2	Perforated slabs	243
7.4	Cylindrical geometries	247
7.5	Terahertz waveguides based on spoof SPPs	251
7.5.1	Milled wires	251
7.5.2	Helically grooved wires	253
7.5.3	Corrugated channels	257
7.5.4	Corrugated wedges	259
7.5.5	Domino structures	262
7.6	Conclusions	264
	References	265

<i>Contents</i>		ix
8	Negative refraction using plasmonic structures that are atomically flat	269
	PETER B. CATRYSSÉ, HOCHEOL SHIN, AND SHANHUI FAN	
8.1	Introduction	269
8.2	Physics	270
8.3	All-angle negative refraction for surface plasmon waves	273
8.4	All-angle negative refraction and evanescent wave amplification	278
8.5	Related work	282
	References	284
9	Anomalous transmission in waveguides with correlated disorder in surface profiles	287
	F. M. IZRAILEV AND N. M. MAKAROV	
9.1	Introduction	287
9.2	Surface-corrugated waveguide	289
9.3	Single-mode structure	292
9.4	Design of a random surface profile with predefined correlations: convolution method	296
9.5	Gaussian correlations	297
9.6	Two complementary examples of selective transparency	299
9.6.1	Example 1	299
9.6.2	Example 2	300
9.7	Random narrow-band reflector	302
9.8	Multi-mode waveguide	304
	Acknowledgments	310
	References	310
10	Cloaking	316
	CHRISTOPHER C. DAVIS AND IGOR I. SMOLYANINOV	
10.1	Introduction, general background, and history	316
10.2	The difference between “cloaking,” “blackness,” and “camouflage”	318
10.2.1	Impedance matching	319
10.2.2	Highly absorbing and nonreflective surfaces	320
10.2.3	Camouflage	321
10.3	Transformational optics and optical metamaterials	322
10.4	Dielectric constants, relative permeabilities, and refractive indices	322
10.5	Negative refractive index materials	324



10.6	Generalized transmission lines and backward wave systems	325
10.7	Transformation optics and the ray optics of cloaks	328
10.7.1	Spherical cloak	333
10.7.2	Cylindrical cloak	336
10.7.3	Homogeneous isotropic cloak	337
10.7.4	Cloaks of arbitrary shape	337
10.7.5	Cloak boundary conditions	338
10.7.6	Ray dynamics in cloaks	339
10.7.7	The Hamiltonian optics of rays	340
10.7.8	Ray and wave paths in inhomogeneous and anisotropic materials	343
10.7.9	Nonmagnetic cloak for visible light	345
10.8	Conformal mapping for cloaking	348
10.9	Ray dynamics entering a dielectric cloak	356
10.10	Practical cloaking experiments	356
10.10.1	Microwave cloak	356
10.10.2	Visible light cloak	359
10.11	“Cloaking” by scattering compensation (plasmonic cloaks)	364
10.12	Carpet cloaks	366
10.13	Metamaterial emulation using tapered waveguides	368
10.14	Trapped rainbow	376
10.15	The limitations of real cloaks	378
10.16	Prospects for the future	380
	Acknowledgments	381
	References	381
11	Linear and nonlinear phenomena with resonating surface polariton waves and their applications	386
	HAIM GREBEL	
11.1	Introduction	386
11.2	Two-dimensional surface polariton modes (a straightforward analysis)	389
11.2.1	Homogeneous waveguides and interfaces	389
11.2.2	Goos–Hänchen shift in optical waveguides (ray optics approach)	394
11.2.3	Surface modes	395
11.2.4	Periodically patterned interfaces	398
11.2.5	Suspended periodic metallic structures	400
11.2.6	Energy considerations, dispersion, and loss	402
11.3	Raman spectroscopy with metamaterials	406

<i>Contents</i>	xi
11.3.1 Fields and resonance effects (colloids and structured surfaces)	406
11.3.2 Examples (sensors, etc.)	411
11.4 Gain and feedback with structured metallo-dielectric surfaces	412
11.4.1 From local to extended feedback mechanisms	413
11.4.2 Electric field distribution	418
11.4.3 Examples (enhanced fluorescence and SP lasers)	419
11.5 Concluding remarks	422
References	423
<i>Index</i>	427

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xv

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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 possess 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.

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 sub-micron 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 black-body 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

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  $\theta_0$  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



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

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.

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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