APPLIED DIGITAL OPTICS

FROM MICRO-OPTICS TO NANOPHOTONICS

Bernard C. Kress

Photonics Systems Laboratory, Université de Strasbourg, France

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To my lovely wife Mei-Mei, whose unconditional love and support made this book possible. I even learned to appreciate her constant nagging, which drove me up the wall but helped me finish this project.

Bernard

I would like to dedicate this book to all my university colleagues, students, Photonics Systems Laboratory staff, my assistant Anne and members of institutions and companies all over the world that allowed us, by contributing to or supporting our microphotonics and nanophotonics activities in research and education, to gather the information that made this book possible.

Patrick

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About the Authors

Bernard Kress has been involved in the field of digital optics since the late 1980s. He is an associate professor at the University of Strasbourg, France, teaching digital optics. For the last 15 years Dr Kress has been developing technologies and products related to digital optics. He has been working with established industries around the world and with start-ups in the Silicon Valley, California, with applications ranging from optical data storage, optical telecom, military and homeland security applications, LED and laser displays, industrial and medical sensors, biotechnology systems, optical security devices, high power laser material processing, to consumer electronics. He is on the advisory boards of various photonics companies in the US and has also been advising venture capital firms in the Silicon Valley for *due diligence* reviews in photonics, especially in micro- and nano-optics.

He holds more than 25 patents based on digital optics technology and applications, and is the author of more than 100 papers on this subject. He has taught several short courses given at SPIE conferences. His first book on digital optics, *Digital Diffractive Optics* (2000), was published by John Wiley & Sons, Ltd and has been translated into Japanese in 2005 (published by Wiley-Maruzen). He is also the author of a chapter in the best seller *Optical System Design* (2007), edited by R. Fisher and published by McGraw-Hill. Bernard Kress can be contacted at bernard@applieddigitaloptics.com.

Patrick Meyrueis is full professor at the University of Strasbourg since 1986 (formerly Louis Pasteur University). He is the founder of the Photonics Systems Laboratory which is now one of the most advanced labs in the field of planar digital optics. He is the author of more than 200 publications and was the chairman of more than 20 international conferences in photonics. He was the representative of the Rhenaphotonics cluster and one of the founders of the CNOP in 2001 (national French committee of optics and photonics). He is now acting as the scientific director of the Photonics Systems Lab and the head of the PhD and undergraduate program in the ENSPS National School of Physics in Strasbourg.

Foreword by Professor Joseph Goodman

The field of digital optics is relatively new, especially when compared with the centuries-long life of the more general field of optics. While it would perhaps have been possible to imagine this field a century or more ago, the concept would not have been of great interest, due to the lack of suitable sources, computing power and fabrication tools. But digital optics has now come of age, aided by the extraordinary advances in lasers, processor speed and the remarkable development of tools for fabricating such optics, driven in part by the tools of the semiconductor industry.

It was perhaps in the seminal work of Lohmann on computer-generated holograms that interest in the field of digital optics was launched. Lohmann based his experimental work on the use of binary plotters and photo-reduction, but today the plotting tools have reached a level of sophistication not even imagined at the time of Lohmann's invention, allowing elements with even sub-wavelength structure to be directly fabricated on a broad range of materials.

Applied Digital Optics is a remarkable compendium of concepts, techniques and applications of digital optics. The book includes in-depth discussions of guided-wave optics, refractive optics, diffractive optics and hybrid (diffractive/refractive) optics. Also included is the important area of 'dynamic optics', which covers devices with diffractive properties that can be changed at will. The optics of sub-wavelength structures is also covered, adding an especially timely subject to the book.

Most interesting to me is the extremely detailed discussion of fabrication and replication techniques, which are of great importance in bringing diffractive optics to the commercial marketplace. Finally, the wide-ranging discussion of applications of digital optics is almost breathtaking in its range and coverage.

Professors Kress and Meyrueis provide therefore a comprehensive overview of the current state of research in the field of digital optics, as well as an excellent analysis of how this technology is implemented today in industry, and how it might evolve in the next decade, especially in consumer electronics applications.

In summary, this book will surely set the standard for a complete treatment of the subject of digital optics, and will hopefully inspire even more innovation and progress in this important field.

Professor Joseph W. Goodman
William Ayer Professor, Emeritus
Department of Electrical Engineering, Stanford University
Stanford, CA, USA

Foreword by Professor Trevor Hall

It was my privilege to host Bernard Kress at an early stage in his career. I was very impressed by his creativity, determination and tireless energy. I knew then that he would become a champion in his field of diffractive optics.

Applied Digital Optics is the second book written by Bernard and Professor Patrick Meyrueis from the Photonics Systems Laboratory (LSP) at Université de Strasbourg (UdS) in France. While their first book, *Digital Diffractive Optics*, was solely dedicated to diffractive optics, this one covers a much wider range of fields associated with digital optics, namely: waveguide optics, refractive micro-optics, hybrid optics, optical MEMS and switchable optics, holographic and diffractive optics, photonic crystals, plasmonics and metamaterials. Thus, the book's subtitle, *From Micro-optics to Nanophotonics*, is indeed a faithful description of its broad contents. After reviewing these optical elements throughout the first chapters, emphasis is set on the numerical modeling techniques used in industry and research to design and model such elements. The last chapters describe in detail the state of the art in micro-fabrication techniques and technologies, and review an impressive list of applications using such optics in industry today.

Professors Kress and Meyrueis have been investigating the field of digital optics at LSP since the late 1980s, when photonics was still struggling to become a fully recognized field, like electronics or mechanics. The LSP has been very active since its creation, not only by promoting education in photonics but also by promoting national and international university/industry relations, which has yielded a number of impressive results: publications, patents, books, industrial applications and products as well as university spin-offs both in Europe and the USA. This experience fueled also several European projects, such as the Eureka FOTA project (Flat Optical Technologies and Applications), which coordinated 27 industrial and academic partners, or more recently the European NEMO network (Network in Excellence in Micro-Optics).

The LSP has thus become today one of the premier laboratories in photonics and digital optics, through education, research and product development, and this book serves as a testimonial to this continuous endeavor.

Professor Trevor Hall
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Acronyms

Optical Design Acronyms

BPM	Beam Propagation Method
CGH	Computer-Generated Hologram
DBS	Direct Binary Search
DFT	Discrete Fourier Transform
DOE	Diffractive Optical Element
DOF	Depth Of Focus
EMT	Effective Medium Theory
FDTD	Finite Difference Time Domain
FFT	Fast Fourier Transform
FZP	Fresnel Zone Plate
HOE	Holographic Optical Element
IFTA	Iterative Fourier Transform Algorithm
M-DOE	Moiré DOE
MTF	Modulation Transfer Function
NA	Numeric Aperture
PSF	Point Spread Function
RCWA	Rigorous Coupled Wave Analysis
SBWP	Space Bandwidth Product

Computer Design Acronyms

CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
CIF	Caltech Intermediate Format
DFM	Design For Manufacturing
DRC	Design Rule Check
EDA	Electronic Design Automation
EPE	E-beam Proximity Effect
GDSII	Graphical Data Structure Interface
OPC	Optical Proximity Correction
OPE	Optical Proximity Effect
RET	Reticle Enhancement Techniques

Fabrication-related Acronyms

AFM	Atomic Force Microscope
AOM	Acousto-Optical Modulator
ARS	Anti-Reflection Surface
CAIBE	Chemically Aided Ion-Beam Etching
DCG	DiChromated Gelatin
GRIN	GRaded INdex
HEBS	High-Energy Beam-Sensitive Glass
H-PDLC	Holographic-Polymer Dispersed Liquid Crystal
HTPS	High-Temperature PolySilicon
IC	Integrated Circuit
LBW	Laser Beam Writer
LC	Liquid Crystal
LCD	Liquid Crystal Display
LCoS	Liquid Crystal on Silicon
LIGA	LIthography/GAlvanoforming
MEMS	Micro-Electro-Mechanical System
MOEMS	Micro-Opto-Electro-Mechanical System
OCT	Optical Coherence Tomography
OE	Opto-Electronic
PLC	Planar Lightwave Circuit
PSM	Phase Shift Mask
RIBE	Reactive Ion-Beam Etching
SLM	Spatial Light Modulator
VLSI	Very Large Scale Integration

Application-related Acronyms

BD	Blu-ray Disk
CATV	CAble TV
CD	Compact Disk
CWDM	Coarse Wavelength Division Multiplexing
DVD	Digital Versatile Disk
DWDM	Dense Wavelength Division Multiplexing
HMD	Helmet-Mounted Display
HUD	Head-Up Display
LED	Light-Emitting Diode
MCM	Multi-Chip Module
OPU	Optical Pick-up Unit
OVID	Optically Variable Imaging Device
VCSEL	Vertical Cavity Surface-Emitting Laser
VIPA	Virtual Image Plane Array (grating)
VOA	Variable Optical Attenuator

Introduction

Why a Book on Digital Optics?

When a new technology is integrated into consumer electronic devices and sold worldwide in supermarkets and consumer electronic stores, it is usually understood that this technology has then entered the realm of mainstream technology.

However, such progress does not come cheaply, and has a double-edge sword effect: first, it becomes widely available and thus massively developed in various applications, but then it also becomes a commodity, and thus there is tremendous pressure to minimize the production and integration costs while not sacrificing any aspects of performance.

The field of digital optics is about to enter such a stage, which is why this book provides a timely insight into this technology, for the following prospective groups of readers:

- for the research world (academia, government agencies and R&D centers) to have a broad but condensed overview of the state of the art;
- for foundries (optical design houses, optical foundries and final product integrators) to have a broad knowledge of the various design and production tools used today;
- for prospective industries – 'How can I use digital optics in my products to make them smaller, better and cheaper?'; and
- for the mainstream public – 'Where are they used, and how do they work?'

This book is articulated around four main topics:

1. The state of the art and a classification of the different physical implementations of digital optics (ranging from waveguide optics to diffractive optics, holographics, switchable optics, photonic crystals and metamaterials).
2. The modeling tools used to design digital optics.
3. The fabrication and replication tools used to produce digital optics.
4. A review of the main applications, including digital optics in industry today.

This introductory chapter will define what the term *digital optics* means today in industry, before we start to review the various digital optics implementation schemes in the early chapters.

Applied Digital Optics: From Micro-optics to Nanophotonics Bernard C. Kress and Patrick Meyrueis

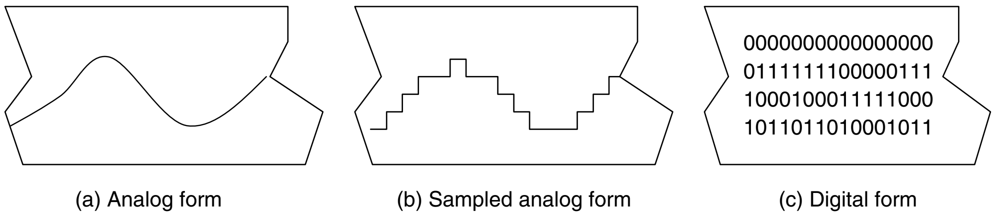

Figure 1 Analog systems versus digital systems

Digital versus Analog

In attempting to define the term 'digital' as introduced in the title of this book, one has to consider its counterpart term 'analog'. The 'digital' versus 'analog' concept can also be understood when considering the term 'continuous' versus 'discrete' (see Figure 1).

History has proved that the move from analog systems to digital systems in technology (especially in electronics) has brought about a large number of improvements, for example:

- added flexibility (easy to program) and faster, more precise, computers;
- new functionalities (built-in error detection and correction algorithms etc.);
- ease of miniaturization (very large scale integration, VLSI); and
- ease of mass replication (microlithographic fabrication techniques).

What are Digital Optics?

As far as optics are concerned, the move from analog (conventional lenses, mirrors and fiber optics) to digital (planar optical elements composed of microscopic structures) has been mainly focused on the last two points: miniaturization and mass replication. This said, new or improved optical functionalities have also been discovered and investigated, especially through the introduction of digital diffractive optics and digital waveguide optics, and their hybrid combination, as will be discussed in detail in the chapters to come.

Miniaturization and mass-production have begun to lead the optical industry toward the same trend as in the micro-electronics industry in the 1970s, namely to the integration of densely packed planar systems in various fields of application (optical telecoms, optical data storage, optical information processing, sensors, biophotonics, displays and consumer electronics).

At first sight, the term 'digital optics' could lead one to think that such elements might be either digital in their functionality (in much the same way that digital electronics provide digital signal processing) or digital in their form (much like digital – or binary – microscopic shapes rather than smooth shapes). Well, it actually takes none of these forms.

The adjective 'digital' in 'digital optics' refers much more simply to the way they are designed and fabricated (both in a digital – or binary – way). The design tool is usually a digital computer and the fabrication tool is usually a digital (or binary) technology (e.g. by using binary microlithographic fabrication techniques borrowed from the Integrated Circuit, or IC, manufacturing industry).

Figure 2 details the similarities between the electronic and optic realms, in both analog and digital versions. In the 1970s, digital fabrication technology (binary microlithography) helped electronics move from single-element fabrication to mass production in a planar way through very large scale integration (VLSI). Similarly, identical microlithographic techniques would prove effective in helping the optics industry to move from single-element fabrication (standard lenses or mirrors) down to planar integration

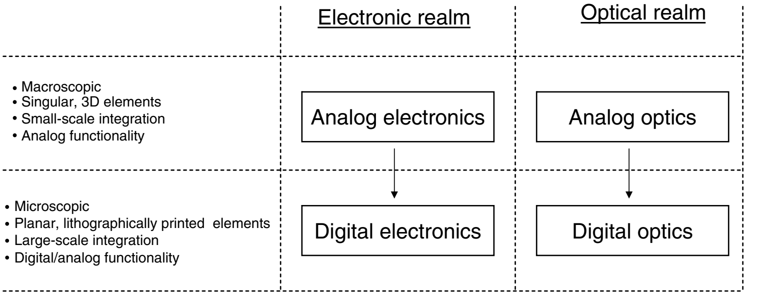

Figure 2 Analogies between the electronics and optics realms

with similar VSLI features. The door to planar optics mass production has thus been opened, exactly as it was for the IC industry 30 years earlier, with the noticeable difference that there was no need to invent a new fabrication technology, since this had already been developed for digital electronics.

However, it is important to understand that although the fabrication technique used may be a binary microfabrication process, the resulting elements are not necessarily binary in their shape or nature, but can have quasi-analog surface reliefs, analog index modulations, gray-scale shades or even a combination thereof.

Also, their final functionality might not be digital – or binary – as a digital IC chip would be, but could instead have parallel and/or analog processing capabilities (information processing or wavefront processing). This is especially true for free-space digital optics, and not so much for guided-wave digital optics.

It is therefore inaccurate to draw a quick comparison between analog electronics versus digital electronics and analog (refractive) optics versus digital (diffractive or integrated) optics, since both optical elements (analog or digital) can yield analog or digital physical shapes and/or processing capabilities.

The Realm of Digital Optics

Now that we have defined the term ‘digital optics’ in the previous section, the various types of digital optical elements will be described.

The realm of digital optics (also referred to as ‘micro-optics’ or ‘binary optics’) comprises two main groups, the first relying on free-space wave propagation and the second relying on guided-wave propagation (see Figure 3).

The various optical elements defining these two groups (free-space and guided-wave digital optics) are designed by a computer and fabricated by means similar to those found in IC foundries (microlithography).

Figure 3 shows, on the free-space optics side, three main subdivisions, which are, in chronological order of appearance, refractive micro-optical elements, diffractive and holographic optical elements, and nano-optics (photonic crystals). On the guided-wave optics side, there are also three main subdivisions, which are, again in chronological order of appearance, fiber optics, integrated waveguide optics and nano-optics. It is worth noting that nano-optics (or photonic crystals) can actually be considered as guided-wave optics or free-space optics, depending on how they are implemented (as 1D, 2D or 3D structures).

This book focuses on the analysis of free-space digital optics rather than on guided-wave optics. Guided-wave micro-optics, or integrated optics, are well described in numerous books, published over

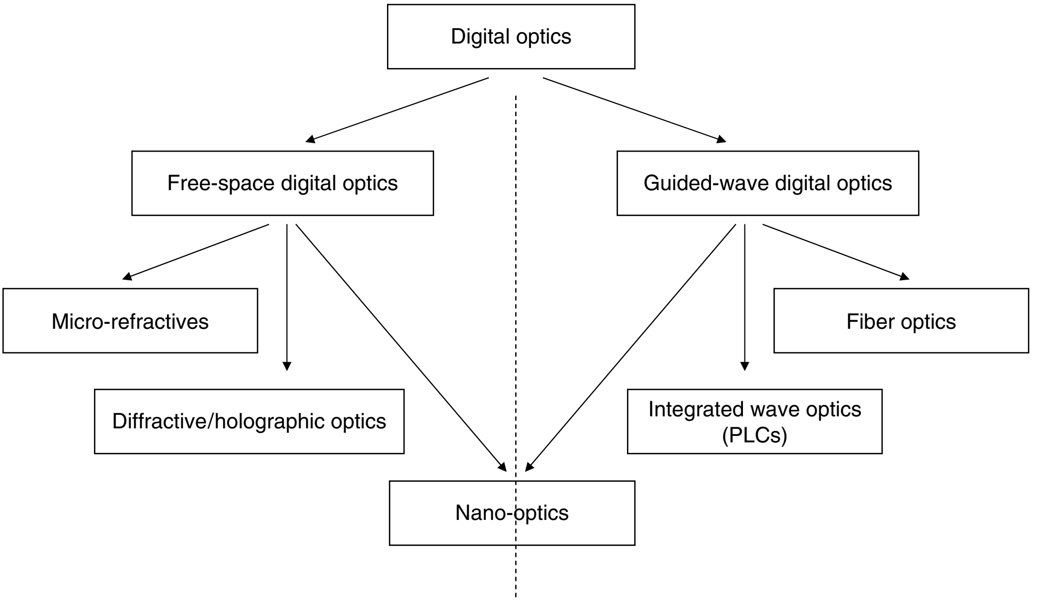

Figure 3 The realm of digital optics

more than three decades, and dedicated books on 'guided-wave' photonic crystals have been available for more than five years now.

However, the combination of free-space digital optics and guided-wave digital optics is a very important and growing field, sometimes also referred to as 'planar optics', and that is what will be described in this book.

Supplementary Material

Supplementary book material is available at www.applieddigitaloptics.com including information about workshops and short courses provided by the authors. The design and modeling programs used in the book can be downloaded from the website.

1

From Refraction to Diffraction

1.1 Refraction and Diffraction Phenomena

In order to predict the behavior of light as it is affected when it propagates through digital optics, we have to consider the various phenomena that can take place (refraction, reflection, diffraction and diffusion). Thus, we have to introduce the dual nature of light, which can be understood and studied as a corpuscle and/or an electromagnetic wave [1].

The corpuscular nature of light, materialized by the photon, is the basis of ray tracing and the classical optical design of lenses and mirrors. The wave nature of light, considered as an electromagnetic wave, is the basis of physical optics used to model diffractive optics and other micro- or nano-optical elements, such as integrated waveguides, and photonic crystals (see Chapters 3–10).

In the simple knife-edge example presented in Figure 1.1, the corpuscular nature of light (through ray tracing) accounts for the geometrical optics, whereas the wave nature of light (physical optics) accounts not only for the light present in the optical path, but also for the light appearing inside the geometrical shadow (the Gibbs phenomenon). According to geometrical optics, no light should appear in the geometrical shadow. However, physical optics can predict accurately where light will appear within the geometrical shadow region, and how much light will fall in particular locations.

In this case, the laws of reflection and refraction are inadequate to describe the propagation of light; diffraction theory has to be introduced.

1.2 Understanding the Diffraction Phenomenon

Diffraction comes from the limitation of the lateral extent of a wave. Put in simple terms, diffraction arises when a wave of a certain wavelength collides with obstacles (amplitude or phase obstacles) that are either singular or abrupt (the knife-edge test, Young's holes experiment) smooth but repetitive (the sinusoidal grating), or even abrupt and repetitive (binary gratings). The smaller the obstacles are, the larger the diffraction effects become (and also the larger the diffraction angles become).

Today, when harnessing diffraction to be used in industrial applications, the obstacles are usually designed and fabricated as pure phase obstacles, either in reflection or in transmission [2–4]. Fine-tuning of the obstacle's parameters through adequate modeling of the diffraction phenomenon can yield very specific diffraction effects with a maximum intensity (or diffraction efficiency).

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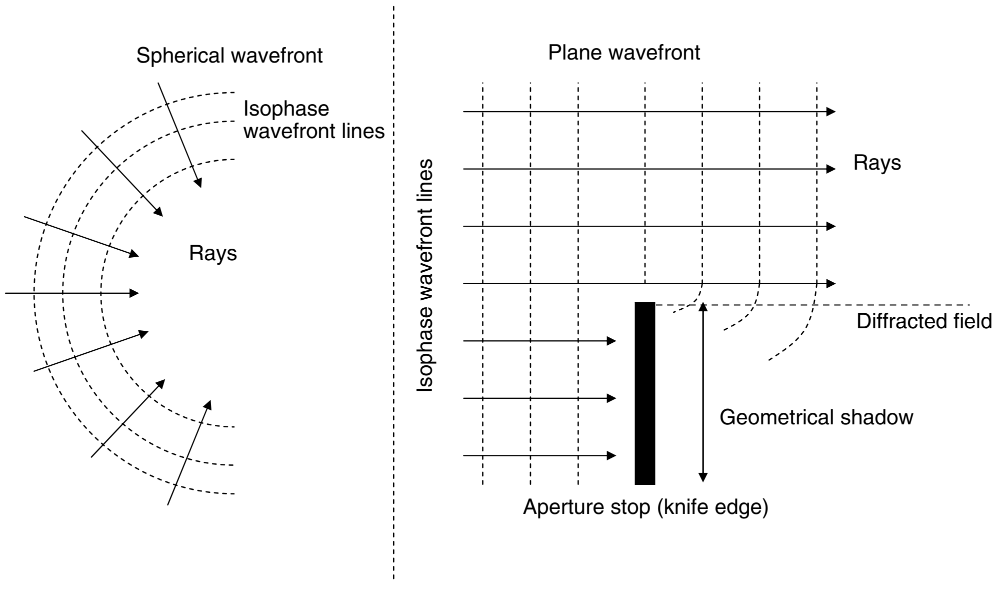

Figure 1.1 The dual nature of light: geometrical and physical optics

1.2.1 Chronological Stages in Understanding Diffraction Phenomena

The diffraction phenomenon was demonstrated for the first time by Leonardo da Vinci (1452–1519) in a very rudimentary way. The first accurate description of diffraction was introduced by Francesco Maria Grimaldi (1618–1663) in his book published in 1665, two years after his death. In those times, corpuscular theory, which was widely believed accurately to describe the propagation of light, had failed to explain the diffraction phenomenon. In 1678, Christian Huygens (1629–1695) proposed a wave theory for the propagation of light that described diffraction as a source of secondary spherical disturbance (see Appendix B). Sir Isaac Newton (1642–1727) had been a strong advocate of the corpuscular theory since 1704. His strong influence over contemporary scientists had halted progress in understanding diffraction during the 18th century. In 1804, Thomas Young (1773–1829) introduced the concept of interference, which directly proceeds from the wave nature of light. Augustin Jean Fresnel (1788–1827) brought together the ideas of Huygens and Young in his famous memoir. In 1860, James Clerk Maxwell (1831–1879) identified light as an electromagnetic wave (see Appendix A). Gustav Kirchhoff (1824–1887) gave a more mathematical form to Fresnel's expression of diffraction. His work basically relied on two assumptions concerning the field at the diffraction aperture. Although those assumptions were quite empirical, his formulation provided a good approximation of the real diffracted field. In 1884, Arnold J.W. Sommerfeld (1868–1951) refined Kirchhoff's theory. Thanks to Green's theorem, he suppressed one of the two assumptions that Kirchhoff had made earlier, to derive the so-called Rayleigh–Sommerfeld diffraction theory.

Table 1.1 summarizes, in a chronological way, the understanding of optics as both a corpuscular phenomenon and an electromagnetic field.

When studying the propagation of light in a homogeneous or nonhomogeneous medium – such as a lens, a waveguide, a hologram or a diffractive element (through refraction, diffraction or diffusion) – the refractive index is one of the most important parameters. Light travels through a transparent medium (transparent to its specific wavelength) of index n at a speed v_n that is lower than its speed c in a vacuum. The index of refraction, n, in a transparent medium is defined as the ratio between the speed of light in a

Table 1.1 Chronological events in the understanding of optics

Refraction/reflection			…
		130	Claudius Ptolemaeus tabulates angles of refraction for several media
		1305	Dietrich von Freiberg uses water filled flasks to study the reflection/refraction in raindrops that leads to rainbows
		1604	Johannes Kepler describes how the eye focuses light
		1611	Marko Dominis discusses the rainbow in *De Radiis Visus et Lucis*
		1611	**Johannes Kepler discovers total internal reflection, a small-angle refraction law and thin lens optics**
	1621	**1621**	**Willebrord Snell states his law of refraction**
		1637	René Descartes quantitatively derives the angles at which rainbows are seen with respect to the the Sun's elevation
	1678	**1678**	**Christian Huygens states his principle of wavefront sources**
		1704	Isaac Newton publishes *Opticks*
		1728	James Bradley discovers the aberration of starlight and uses it to determine the speed of light
		1752	Benjamin Franklin shows that lightning is electricity
		1785	Charles Coulomb introduces the inverse-square law of electrostatics
		1800	William Herschel discovers infrared radiation from the Sun
		1801	Johann Ritter discovers ultraviolet radiation from the Sun
Diffraction	1801	**1801**	**Thomas Young demonstrates the wave nature of light and the principle of interference**
		1809	Etienne Malus publishes the law of Malus, which predicts the light intensity transmitted by two polarizing sheets
		1811	François Arago discovers that some quartz crystals will continuously rotate the electric vector of light
		1816	David Brewster discovers stress birefringence
		1818	Siméon Poisson predicts the Poisson bright spot at the center of the shadow of a circular opaque obstacle
		1818	François Arago verifies the existence of the Poisson bright spot
		1825	Augustin Fresnel phenomenologically explains optical activity by introducing circular birefringence
		1831	Michael Faraday states his law of induction
		1845	Michael Faraday discovers that light propagation in a material can be influenced by external magnetic fields
		1849	Armand Fizeau and Jean-Bernard Foucault measure the speed of light to be about 298 000 km/s
		1852	George Stokes defines the Stokes parameters of polarization
		1864	James Clerk Maxwell publishes his papers on a dynamical theory of the electromagnetic field
		1871	Lord Rayleigh discusses the blue sky law and sunsets
EM wave	1873	**1873**	**James Clerk Maxwell states that light is an electromagnetic phenomenon**
		1875	John Kerr discovers the electrically induced birefringence of some liquids
		1895	Wilhelm Röntgen discovers X-rays
		1896	Arnold Sommerfeld solves the half-plane diffraction problem
			…

Table 1.2 Refractive indices for conventional (natural) and nonconventional materials

Media	Refractive index	Type	Examples
Conventional materials			
Vacuum	1 exactly	Natural	—
Air (actual)	1.0003	Natural	—
Air (accepted)	1.00	—	—
Ice	1.309	Natural	—
Water	1.33	Natural	Liquid lenses
Oil	1.46	Natural/Synthetic	Immersion lithography
Glass (typical)	1.50	Natural	BK7 lenses
Polystyrene plastic	1.59	Natural/Synthetic	Molded lenses
Diamond	2.42	Natural	TIR in jewelry
Silicon	3.50	Natural	Photonic crystals
Germanium (IR)	4.10	Natural	IR lenses
Media	Refractive index	Type	Examples
Nonconventional materials			
Metamaterials	Negative indices	Synthetic, active materials (plasmon)	High-resolution lens, Harry Potter's invisibility cloak
Bose–Einstein condensate	$n \gg 1$, validated at $n > 1\,000\,000\,000$!	Synthetic, $T = 0°K$ ($v < 1$ mph)	Low-consumption chips, telecom
?	$0 < n < 1.0$	Improbable ($v > c$)	Telecom, time machine,...

vacuum (c) and the speed of light in the medium. This index can also be defined as the square root of the product of the permittivity and permeability of the material considered for the specific wavelength of interest (for most media, $\mu = 1$):

$$\begin{cases} n = \dfrac{c}{v_n} \\ n = \sqrt{\varepsilon.\mu} \end{cases} \tag{1.1}$$

At this point, one could ask whether there would be a medium with indices that are positive but lower than 1 (which would mean that light would travel faster than the speed of light in a vacuum). This is largely improbable: however, there are media in which the phase velocity of light is greater than c, but cannot be used to send energy or signals at a speed in excess of c.

It is worth noting that the range of refractive indices in nature is much higher than one would imagine (from air = 1.0 to glass = 1.5). For example, silicon (Si) has a quite high index of 3.5 for infrared (IR) wavelengths, which enables the fabrication of photonic crystals in which the index change has to be the highest possible in order to achieve full photonic band gaps (see Chapter 10). Table 1.2 lists the refractive indices for some common materials. Interestingly, the range of refractive indices found in nature can be extrapolated by the fabrication of synthetic materials known as metamaterials (see also Chapter 10), and even materials with negative indices can be produced.

1.3 No More Parasitic Effects

History shows us that optical engineering has usually considered diffraction effects to be negative and parasitic. These effects usually manifest when the imaging resolution limit is approached. They are