Springer Handbook of Lasers and Optics

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Springer Handbook of Lasers and Optics

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Foreword

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After working for more than four decades in the field of laser science, I am delighted that Springer-Verlag has devoted one of the first volumes of the new Springer Handbook series to lasers and optics. The exhilarating pace of technological advances in our field is still accelerating, and lasers and optical techniques are becoming ever more indispensible as enabling tools in almost any field of science or technology. Since no single physicist, engineer, or graduate student can be an expert in all the important subfields of optical science, a concise, balanced, and timely compilation of basic principles, key applications, and recent advances, written by leading experts, will make a most valuable desk reference. The chosen readable style and attractive, well-illustrated layout is even inviting to casual studying and browsing. I know that I will keep my Springer Handbook of Lasers and Optics close at hand, despite the infinite amount of information (and misinformation) that is readily accessible via the Internet.

Munich, February 2007 — Theodor W. Hänsch

Preface

It is often said that the 21st century is the century of the photon. In fact, optical methods, materials, and components have reached an advanced state of sophistication hitherto unknown. Optical techniques, particularly those based on lasers, not only find applications in the classical fields of physics and engineering but have expanded into many other disciplines such as medicine, the life sciences, chemistry and environmental research, to mention only a few examples. Nevertheless, progress in optics, photonic materials and coherent light sources continues at a rapid pace: new laser materials are being developed; novel concepts such as optics far beyond the diffraction limit, or nanooptics, are being explored; and coherent light sources generate wavelengths in ranges not previously accessible.

In view of the pronounced interdisciplinary nature of optics, the *Springer Handbook of Lasers and Optics* is designed as a readable desk reference book to provide fast, up-to-date, comprehensive, and authoritative coverage of the field. The handbook chapters are grouped into four parts covering basic principles and materials; fabrication and properties of optical components; coherent and incoherent light sources; and, finally, selected applications and special fields such as terahertz photonics, X-ray optics and holography.

I hope that all readers will find this Springer Handbook useful and will enjoy using it.

Kassel, February 2007 Frank Träger

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Contents

List of Abbreviations

A

AEL	accessible emission limit
AFM	atomic force microscope
ANL	Argonne National Laboratory
AOM	acoustooptic modulator
AOPDF	acoustooptic programmable dispersive filter
APCVD	atmospheric pressure chemical vapor deposition
AR	antireflection
ARS	angle-resolved scattering
ASE	amplified spontaneous emission
AWG	arrayed waveguide

B

BBO	β-Barium-Borate
BH	buried heterostructure
BLIP	background-limited infrared photodetector
BZ	Brillouin zone

C

C–D	Cole–Davidson fractional exponent β
CALIPSO	Cloud-aerosol lidar and infrared pathfinder satellite observations
CARS	coherent anti-Stokes Raman scattering
CAT	coplanar air transmission
CCD	charge-coupled device
CCIS	charge-coupled image sensor
CCRF	capacitively coupled RF
CGH	computer generated hologram
CIPM	Comité International des Poids et Mesures
CMOS	complementary metal–oxide–semiconductor detector
COC	cyclic olefin copolymer
COP	cyclic olefin polymer
CPA	chirped-pulse amplification
CRDS	cavity-ring-down spectroscopy
CRI	color rendering index
CTIS	charge transfer image sensor
CVD	chemical vapor deposition
CW	continuous wave

D

DARPA	United States Defense Advanced Research Projects Agency
DBF	distributed feedback
DBR	distributed Bragg reflector
DCF	dispersion-compensating fiber
DEPFET	depleted field effect transistor structure
DESY	Deutsches Elektronen-Synchrotron
DEZn	diethylzinc
DFB	distributed feedback
DFG	difference-frequency generation
DFWM	degenerate four-wave mixing
DGD	differential group delay
DIAL	differential absorption LIDAR
DLA	direct laser acceleration
DOE	diffractive optical element
DOM	dissolved organic matter
DOS	density of states
DRO	doubly resonant OPO configurations
DRS	double Rayleigh scattering
DWDM	dense wavelength division multiplexed

E

ECDL	extended-cavity diode laser
EDFA	erbium-doped fiber amplifier
EEDF	electron energy distribution function
EFDA	Er-doped fiber amplifiers
EFS	equi-frequency surface
EL	electroluminescence
ELA	excimer laser annealing
EM	electromagnetic
EMC	electromagnetic compatibility
EMT	effective-medium theory
EO	electrooptic
EOM	electrooptic modulator
erf	error function
ESA	excited-state absorption
ESRF	European Synchrotron Radiation Facility
EUV	extreme ultraviolet
EWOD	electrowetting on dielectrics
ErIG	erbium iron garnet

F

FBG	fiber Bragg grating
FDPM	frequency-domain phase measurement
FDTD	finite-difference time domain
FEL	free-electron laser
FET	field effect transistor
FIFO	first-in first-out
FLASH	free-electron-laser Hamburg
FOM	figure of merit
FOV	field of view

FP Fabry–Pérot
FR Faraday rotator
FROG frequency-resolved optical gating
FTS Fourier-transform spectroscopy
FWHM full width at half-maximum
FWM four-wave mixing
FZP Fresnel zone plate
FoM figure of merit

G

GAC grating assisted coupler
GASMAS gas in scattering media absorption spectroscopy
GC gain-coupled
GCF geometrical configuration factor
GDD group delay dispersion
GLAS geoscience laser altimeter system
GLS sulfide glasses GaLaS
GRIN gradient index
GSA ground-state absorption
GTI Gires–Tournois interferometer
GVD group velocity dispersion

H

HDPE high-density polyethylene
HDSS holographic data storage system
HHG high-order-harmonic generation
HMO heavy metal oxide
HOMO highest occupied molecular orbital
HR highly reflecting
HVPE hydride-vapor-phase epitaxy

I

IAD ion-assisted deposition
IBAD ion-beam-assisted deposition
IBS ion-beam sputtering
ICLAS International Coordination Group for Laser Atmospheric Studies
ICP inductively coupled plasma
IL interference lithography
ILRC International Laser Radar Conferences
IR infrared
ITO indium–tin oxide

K

KB Kirkpatrick–Baez

L

lcp left-circularly polarized light
LC–SLM liquid-crystal spatial light modulator
LCVD laser(-induced) chemical vapor deposition
LCoS liquid crystal on silicon
LD laser diode
LEAF large effective area
LH left-handed
LIBS laser-induced breakdown spectroscopy
LIDAR light detecting and ranging
LIDT laser-induced damage threshold
LIF laser-induced fluorescence
LMJ laser megajoule
LOQC linear optics quantum computing
LPCVD low-pressure CVD
LPE liquid-phase epitaxy
LSHB longitudinal spatial hole burning
LSO laser safety officer
LT low-temperature
LT-GaAs low-temperature GaAs
LTG-GaAs low-temperature-grown GaAs
LUMO lowest unoccupied molecular orbital
LWFA laser wakefield acceleration

M

MCP microchannel plate
MCVD modified chemical vapor deposition
MFD multilayer fluorescent disk
MI modulation instability
MIS metal–insulator–semiconductor
MMA methyl methacrylate
MOCVD metalorganic chemical vapour epitaxy
MOPA master-oscillator power-amplifier
MOS metal–oxide–semiconductor
MOT magnetooptical trap
MPC metallic photonic crystal
MPE maximum permissible exposure
MPMMA modified poly(methyl methacrylate)
MQW multiquantum well
MSR magnetic super-resolution
MTF modulation transfer function

N

NA numerical aperture
NCPM noncritical phase matching
NEP noise equivalent power
NFL nanofocusing lenses
NGL next-generation lithography
NIF National Ignition Facility
NIM nearly index-matched
NLSE nonlinear Schrödinger equation
NLSG nonlinear signal generator
NLTL nonlinear transmission line
NOHD nominal ocular hazard distance
NRI nonresonant intrinsic
NSIC National Storage Industry Consortium

O

OCT	optical coherence tomography
OFA	optical fibre amplifier
OFHC	oxygen-free high conductivity
OFI	optical-field ionization
OLED	organic light-emitting device
OP	oriented-patterned
OPA	optical parametric amplifier
OPCPA	optical parametric chirped pulse amplification
OPD	optical path difference
OPG	optical parametric generation
OPL	optical path length
OPO	optical parametric oscillator
OPS	optically pumped semiconductor laser
ORMOSIL	organically modified silicates
OSNR	optical signal-to-noise ratio
OTF	optical transfer function
OVD	outside vapor deposition

P

PA	photon avalanche
PB	photonic band
PBG	photonic band gap
PBS	photonic band structure
PBS	polarizing beam splitter
PC	photonic crystal
PCB	printed circuit board
PCF	photonic-crystal fibers
PD	photodetector
PDH	Pound-Drever-Hall technique
PDLC	polymer-dispersed liquid crystal
PDMS	polydimethylsiloxane
PECVD	plasma-enhanced chemical vapor deposition
PEDT/PSS	polyethylenedioxythiophene/ polystyrylsulfonat
PESRO	pump-enhanced SRO
PG	polarization gate
PIC	particle-in-cell
PICVD	plasma impulse CVD
PL	photoluminescence
PLD	pulsed-laser deposition
PMD	polarization mode dispersion
PMMA	polymethylmethacrylate
PMT	photomultiplier tube
POLLIWOG	polarization-labeled interference versus wavelength for only a glint
PPE	personal protective equipment
PPKTP	periodically poled potassium titanyl phosphate
PPLN	periodically poled lithium niobate
PPV	poly-para-phenylenevinylene
PQ	phenanthraquinone
PS	polystyrene
PSA	projected solid angle
PSF	point spread function
PTV	peak-to-valley
PVD	physical vapor deposition
PWM	pulse width modulator
PZT	piezoelectric transducer

Q

QC	quasicrystals
QCL	quantum cascade laser
QD	quantum dot
QDIP	quantum-dot infrared photodetector
QND	quantum nondemolition
QPM	quasi-phase matching
QW	quantum well
QWIP	quantum well infrared photodetector
QWOT	quarter-wave optical thickness
QWP	quarter-wave plate

R

RAM	residual amplitude modulation
rcp	right-circularly polarized light
RCWA	rigorous coupled wave analysis
RDE	rotating disc electrode
RDS	relative dispersion slope
RE	rare-earth
RESOLFT	reversible saturable optical fluorescence transition
RF	radio frequency
RFA	Raman fiber amplifier
RGB	red, green and blue
RIE	reactive-ion etching
RIKE	Raman-induced Kerr effect
RLVIP	reactive low-voltage ion plating
RMS	root-mean-square
RPE	retinal pigment epithelium
R/W	rewritable

S

SAR	synthetic-aperture radar
SASE	self-amplified spontaneous emission
SBS	stimulated Brillouin scattering
SC	supercontinuum
SCP	stretcher–compressor pair
SEM	scanning electron microscope
SFG	sum-frequency generation
SG	sampled grating
SHG	second-harmonic generation
si	semiinsulating
SI	Système International
SIL	solid-immersion lens
SLAR	side-looking airborne radar

SLM spatial light modulator
SM-LWFA self-modulated laser wakefield acceleration
SMF single-mode fiber
SMSR side-mode suppression ratio
SNR signal-to-noise ratio
SOA semiconductor optical amplifier
SOI silicon-on-insulator
SOS silicon-on-sapphire
SPDC spontaneous parametric down conversion
SPIDER spectral phase interferometry for direct electric field reconstruction
SPM self-phase modulation
SRO singly resonant OPO
SRS stimulated Raman scattering
SS stainless-steel
SSDL solid-state dye laser
SSFS soliton self-frequency shift
SSG superstructure grating
SSI spatial–spectral interference
STED stimulated emission depletion
STP standard temperature and pressure
STPA sequential two-photon absorption
STRUT spectrally temporally resolved upconversion technique
SVEA slowly varying envelope approximation

T

TADPOLE temporal analysis by dispersing a pair of light E-fields
TCE transient collisional excitation
TDSE time-dependent Schrödinger equation
TEF trap enhanced field
TEM transverse electric magnetic
TF thin film
THG third-harmonic generation
THz-TDS THz time-domain spectroscopy
TIP truncated inverted pyramid
TIR total internal reflection
TNSA target normal sheath acceleration
TOD third-order dispersion
TRO triply resonant OPO
TS total scattering
TTF TESLA test facility
TTG tunable twin guide
TV television

U

UV ultraviolet

V

VC vertical cavity
VCSEL vertical-cavity surface-emitting laser
VLSI very large scale integration
VPE vapor-phase epitaxy

W

WDM wavelength division multiplexing
WG waveguide
WGP wire-grid polarizer
WORM write-once, read-many times

X

XFEL X-ray FELS
XPM cross-phase modulation
XUV extreme ultraviolet (soft X-ray)

Y

YAG yttrium aluminium garnet
YAP yttrium aluminium perovskite
YLF yttrium lithium fluoride
YSZ yttria-stabilized zirconia
YVO yttrium vanadate

Z

ZAP zero additional phase
ZAP-SPIDER zero-additional-phase SPIDER

Part A

Basic Prin

Part A Basic Principles and Materials

1. The Properties of Light

The mystery of light has formed the core of creation stories in every culture, and attracted the earnest attentions of philosophers since at least the fifth century BCE. Their questions have ranged from how and what we see, to the interaction of light with material bodies, and finally to the nature of light itself. This chapter begins with a brief intellectual history of light from ancient Greece to the end of the 19th century. After introducing the physical parameterization of light in terms of standard units, three concepts of light are introduced: light as a wave, light as a quantum particle, and light as a quantum field. After highlighting the distinctive characteristics of light beams from various sources – thermal radiation, luminescence from atoms and molecules, and synchrotron light sources – the distinctive physical characteristics of light beams are examined in some detail. The chapter concludes with a survey of the statistical and quantum-mechanical properties of light beams. In the appropriate limits, this treatment not only recovers the classical description of light waves and the semiclassical view of light as a stream of quanta, but also forms a consistent description of quantum phenomena – such as interference phenomena generated by single photons – that have no classical analogs.

1.1 Introduction and Historical Sketch

1.1.1 From the Greeks and Romans to Johannes Kepler

The history of optics from the fifth century BCE until the early 17th century CE can be read as a single, prolonged attempt to elucidate, first qualitatively and then quantitatively, the nature of light as it is revealed through the phenomena of propagation, reflection and refraction.

The earliest known theories about the nature of light originated with Empedocles of Agrigentum (fifth century BCE) and his contemporary, Leucippus. To the latter is attributed the notion that external objects are enveloped by eidola, "a kind of shadow or some material simulacrum which envelopes the bodies, quivers on the surface and can detach itself from them" in order to convey to the soul "the shape, the colors and all the other qualities of the bodies from which they emanate" [1.1]. A century later, Plato and his academy characterized light as a variant of elemental fire and theorized that seeing results from a conjunction of a ray emitted by the object seen and a "visual ray," emitted by the seeing eye [1.2]. This picture was contentious from the start: Plato's pupil Aristotle fumed that "to say, as the Ancients did, that colors are emissions and that this is how we see, is absurd" [1.1]. Nevertheless, the emission theory was debated well into the 16th century.

Another of Plato's pupils, the mathematician Euclid, wrote treatises on optics and catoptrics that were still being translated seven centuries later. Euclid's work is distinguished from that of his predecessors by conclusions deduced from postulates; in the *Optics*, he adduces a model of ray optics that can be translated into recognizable principles of geometrical optics including the law of reflection from a plane surface; the concept of a near point for the eye; and the focusing of light by concave surfaces [1.3]. The Roman philosopher Lucretius (early first century BCE) gave to the world in his *De Rerum Natura* the most detailed ancient understanding of not only the geometry of light propagation, but also the effects of intensity on the observer.

Two other ancient texts – by Hero (first century CE) and Ptolemy (second century CE), both of Alexandria – are important historically. Hero postulated the law of reflection in a form strikingly similar to that which emerged much later as Fermat's principle of least time. Heros's countryman Ptolemy produced a text on optics distinguished by its use of axiomatics coupled to experimental studies of reflection from curved surfaces and an attempt at developing a law of refraction. The data on refraction are remarkably accurate, [1.4] and his attempt to provide a mathematical model, though unsuccessful, nevertheless stamps the work as modern.

Building on the philosophical foundation laid by Aristotle, medieval opticians focused primarily on the phenomenon of refraction and made important predictions about the nature of light [1.1]. The ninth-century Baghdad philosopher Abu Hsuf Yaqub Ibn Is-haz (Alkindi) improved on the concept of the visual ray by requiring that it should have a physiological effect on the eye. In *De Aspectibus*, he mounted the first serious attack, supported by observations, on the theory of light as a stream of simulacra. Abu Ali al-Hasan ibn al-Haitham – known widely by his Latin name, Alhazen – published *The Book of Optics* (*De aspectibus*, or *On Vision*) in the 11th century CE. This text was translated into Latin and used until the early 17th century. His diagrams of the human visual apparatus correct some, though not all, the errors made by Galen, who worked only from dissections of animals. Because Alhazen understood how the eye lens refracted incoming rays of light, he was able to show that every point on the surface of an object in the visual field of the eye maps onto a point on the optic nerve to make a faithful, small-scale image of the object.

By the beginning of the 12th century, western European scholars had in their possession both the works of the Greeks and those of the Muslim scholars. These centuries see a working out of the contradictions inherent in these competing views by late-medieval thinkers in England, France and Italy, [1.5] including Robert Grosseteste and Roger Bacon who were unwilling to accept the dogmatism of the Scholastics. In particular, they saw the phenomenology of the rainbow as a key to the understanding of refraction and reflection. The origin of the rainbow was correctly explained for the first time by Theodoric of Freiburg in the 15th century.

1.1.2 From Descartes to Newton

By the time of Johannes Kepler's death in the mid-17th century, the concept of light as a geometrical ray emanating from an object and collected by the eye was firmly established, and the emphasis shifted to theoretical questions about the mechanisms of refraction and reflection that could only be answered by understanding the properties of light. Moreover, there was increasing emphasis from the mid-17th century onward on carefully controlled experimentation, not simply observation. Harmonized with mathematical models, this experimental philosophy proved to be the way to establish scientific knowledge of light on the strongest foundation [1.6].

René Descartes and the Cartesian thinkers who followed his lead, built a science of light and optics as part of a more general mathematical theory of physics, with his *Dioptrics* and the *Discourses* [1.7]. The Cartesian theory is distinguished by the concept of light as a vibration in a diaphanous medium that transmits the undulations from object to eye, a tendency to motion in particles of the embedding medium. Robert Hooke, Thomas Hobbes and Christiaan Huygens were likewise committed to vibrational theories of light. The first experimental evidence of what would eventually be convincing evidence for the wave theory of light came in 1658 with the publication of Grimaldi's first memoir on diffraction.

Pierre Fermat (1601–1665) solved one of the problems that the *Dioptrics* had treated badly, and did so in a way that was characteristic of what Newton would later call "mathematical philosophy." Fermat's simple idea was based on the rectilinear propagation of light, and the postulate that light travels less rapidly in a dense, material medium than in air. From this, he hypothesized that a light ray always follows that path that allows it to travel a given trajectory in the shortest time. It is possible to derive Snell's law of refraction from this principle of least time [1.8].

Fermat based his theory on the assumption that the speed of light was finite, and that it was slower in material bodies than in air or vacuum – clearly contradicting Descartes, who believed the speed of light to be infinite. The Cartesian postulate was disproved when Cassini (in 1675) and Ole Römer (a year later), measured the time it took light to pass across the earth's orbit based on observation of the transit time of Jupiter: about 11 minutes. The surveyors – Cassini in Paris and Jean Richer in Guyana – were measuring the Earth's orbit. Christiaan Huygens, court astronomer to Louis XIV, proposed a figure of 12, 000 earth diameters for the orbital diameter, and thereby arrived in his *Treatise on Light* at an estimate of 2.3×10^8 m/s, within 20% of the currently accepted value and very close to the value calculated by Newton [1.9]. Grimaldi (1658) had discovered the phenomenon of diffraction, the explanation of which led in time to the ascendance of the wave theory. Progress in the science of light during this period was also aided immensely by the development of the differential and integral calculus and by the invention of high-quality clear glass for lenses, prisms and optical instruments such as telescopes, microscopes and eventually spectrometers [1.10].

1.1.3 Newton and Huygens

The early part of the 18th century saw the rise of the two competing theories about the nature of light that were to dominate the next century and a half. These are embodied in the lives and work of the two principals: Isaac Newton (1642–1728) and Christiaan Huygens (1629–1695).

The dispersion of light in a prism was known well before the young Isaac Newton "procured ... a prism with which to try the celebrated phenomenon of colors." Newton's *experimentum crucis* was designed to show that white light could be decomposed into constituent colors that were dispersed according to a corpuscular model [1.11]. However, Newton's *Opticks*, when published in 1710, was a curious admixture of *projectile* or *corpuscular* ideas and crude wave theories. Newton believed in the ether as a required medium to support the projectiles, and expected that the ether would undulate as light corpuscles passed through it. However, he was convinced on the basis of the corpuscular model that light traveled faster in material media, an assumption that would not be conclusively disproved until Foucault's experiments in 1850.

Challenges to Newton's corpuscular theory came from kinematical theories that viewed light as one or another kind of vibrational motion: a vibratory motion supported by an ether (Hooke, 1665); or a propagating pulse-like disturbance in the ether (Huygens, 1690) [1.12]. Leonhard Euler explained refraction at an interface based on the vibrational theory, arguing that dispersion resulted from a variation of vibrational motion with color [1.13]. In Germany at least, Euler was seen as the originator of a wave model that could replace Newton's corpuscular theory. In France, Huygens developed a geometrical construction of secondary wavelets to trace the propagation of a wave in time, laying a conceptual foundation for early 19th-century experiments in interference and diffraction that ultimately undermined the corpuscular hypothesis.

1.1.4 The 19th Century: The Triumph of the Wave Picture

By the last quarter of the 18th century, it was clear that Newton's corpuscular theory could not match the experimentally measured velocity of light in materials; moreover, experiments by Malus and Arago had shown that light has a new property, which came to be called polarization, that does not fit within the corpuscular picture at all. The earliest systematic studies of polarization phenomena associated with the propagation of light waves are due to Étienne Malus in 1808, in response to a prize competition offered by the Paris Academy for a mathematical description of the phenomenon of double refraction in Iceland spar (calcite). Malus's discoveries led to the recognition that light is a transverse electromagnetic wave, in which the electric and magnetic fields are perpendicular to each other and to the direction of propagation. Malus, using his ingenious refractometer, demonstrated in 1807 that the phenomenon of double refraction could be explained mathematically by Huygens' construction. Fresnel, a dozen years later, was to win the prize competition for his theory of diffraction, even anticipating the objection of Poisson that light diffracted around a tiny opaque object would produce a bright spot in the middle of the geometrical shadow – to be known afterwards as *Poisson's spot* [1.4]. Moreover, increasingly powerful mathematical descriptions [1.14] were applied to the phenomena of interference and diffraction studied experimentally by Thomas Young, the London polymath, and Fresnel. It was at last becoming clear that light constituted a qualitatively new kind of wave in which the vibrations were transverse to the direction of propagation of the light [1.15]. Indeed, the transverse character of the vibrations was first suggested by Young in a letter to Arago in 1812, thus hinting that Young was already reinterpreting his interference experiments in a way that differed sharply from previous thinking based on analogies with acoustic waves [1.16].

At virtually the same time, Biot and Savart, Ampère and Faraday were generating the experimental underpinnings for the eventual unification of optics and electromagnetism. Galvani's experiments on the stimulus of what was then called *animal electricity* had shifted attention from electrostatics, the major preoccupation of the eighteenth century, to time-dependent phenomena associated with electricity. However, it was Alessandro Volta who successfully showed that this phenomenon was not due to some *vital* magnetic force, but that it was no different from ordinary magnetism. While electrophysiology continued to be of major interest to biologists and students of medicine, it was thereafter studied by physicists primarily in relation to other electromagnetic phenomena. Oersted, by showing the deflection of a compass placed next to a current-carrying wire, demonstrated the interconnection of electrical and magnetic phenomena. And Faraday, in 1845, showed that the polarization of light could be rotated by applying a strong magnetic field to a medium through which the light was propagating.

Thus the stage was set for the grand synthesis of classical electromagnetic theory. The first step was the publication of James Clerk Maxwell's theory of electromagnetism in 1869. Maxwell's theoretical prediction of electromagnetic radiation was verified experimentally by Heinrich Hertz in 1888 with the discovery of *Hertzian waves* in what now would be called the radiofrequency range of the spectrum. The classical theory of the electron developed by H. A. Lorentz would be the next step in the creation of a 19th-century *theory of everything*. The only clouds on the horizon were the unsolved problems of black-body radiation and the photoelectric effect, problems whose solutions would lead to the development of quantum physics and the evolution of a new view of light based on its dual character as wave and particle, and later of its accommodation into a fully quantum-mechanical field theory.

1.2 Parameterization of Light

The properties of light are parameterized in similar ways in both the classical (wave) and semiclassical (photon) pictures of light. The fundamental physical properties of an electromagnetic wave are its wavelength λ, frequency ν and polarization state; alternatively, the first two of these properties may be stated in the form of a *wave number* $k = 2\pi\lambda$ and *angular frequency* $\omega = 2\pi\nu$. The photon model associates with individual light quanta a particle-like *photon energy* $E_{\text{photon}} = \hbar\omega$ and momentum $p_{\text{photon}} = \hbar k$, where $h = 2\pi\hbar$ is Planck's constant. Photons are also associated with a helicity (photon spin) of ± 1 that can be related to wave polarization.

The properties of light have been defined by international commissions in four kinds of units now in general use, depending on what properties are to be emphasized: radiometric units, based on the physical units, such as energy, and power, are used to describe the properties of electromagnetic waves or photons; photometric units, which refer to the properties of light as discerned by the human eye; photon units analogous to radiometric units that are normalized to photon energy; and spectral units that parameterize light in terms of its properties at specific frequencies or wavelength.

1.2.1 Spectral Regions and Their Classification

The electromagnetic spectrum extends over an enormous range of frequencies and wavelengths, from low-frequency radio wavelength vibrations to extremely high-energy, short-wavelength nuclear gamma radiation. Figure 1.1 shows a typical classification scheme, relating wavelengths, frequencies, wave numbers and photon energies to the common designations of spectral regions of interest in optics, extending from the vacuum ultraviolet through the far-infrared. Some of the units employed match the Système International (SI) convention, others are habitually used in specialized science or technology communities.

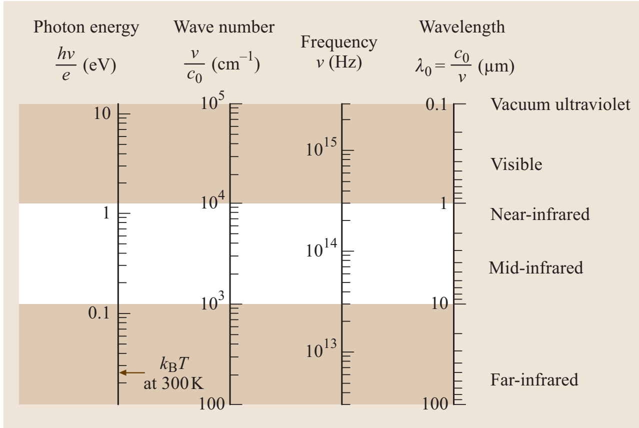

Fig. 1.1 Chart showing the wavelengths, frequencies, wave numbers and photon energies of electromagnetic radiation of interest in optics. (After [1.17])

1.2.2 Radiometric Units

Radiometric units measure the properties of light in terms of physical units of energy and power, without reference to wavelength, and are therefore the most fundamental of the parameters used to describe light [1.19, 20]. The fundamental radiometric units are: radiance, a vector $\boldsymbol{L}$ whose magnitude is the power passing through a surface of unit area into a unit solid angle about the normal to the surface; irradiance, again a vector $\boldsymbol{E}$, defined as the total power per unit spectral interval passing through a surface of unit area. As shown in Fig. 1.2, the magnitude of the radiance and irradiance depends on the shape of the surface over which one integrates, that is, over the projected area $A_\perp$ as well as the solid angle $\mathrm{d}\Omega$ into which light is emitted and the perpendicular area of the detector. The definition of spectral interval is not uniform; depending on the resolution or the parameterization desired, it might be given in Å, nm, cm^{-1} (not the same as 1/cm), or Hz, as here. To convert any radiometric unit X to the corresponding spectral radiometric unit X_ν, recall that $X = X_\nu\,\mathrm{d}\nu$ for values of the frequency lying between ν and $\nu + \mathrm{d}\nu$.

1.2.3 Photometric Units

Photometry refers to the measurement of light as it is perceived by the human eye; thus these units pertain principally to light with wavelengths of 380–760 nm. In astronomy, photometry also refers to the measurement of apparent magnitudes of celestial objects. Since these quantities depend on the spectral amplitude of light, it is not possible to convert photometric values directly into energy values. The photometric units use the same terminology and symbols as the radiometric units, but with a subscript V for *visual*.

The four fundamental photometric quantities, listed in Table 1.2, are: *luminous intensity*, the amount of light emitted by a source; *luminous flux*, the quantity of light transmitted in a given direction; *illuminance*, the measure of light falling on a surface; and luminance, which measures the brightness of a surface

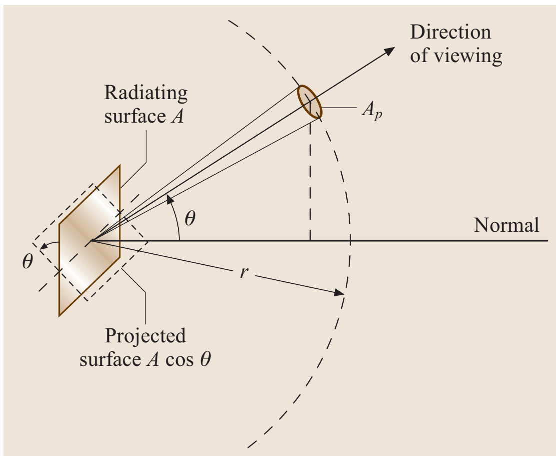

Fig. 1.2 Geometry used to define radiometric units of radiance and irradiance in terms of emitting area, detecting area and solid angle of emission. The projected surface area in a given angular direction Θ is $A_\perp = A\cos\Theta$, while the solid angle in radiometric units is determined by the projected detector area A_p perpendicular to the viewing direction, $\mathrm{d}\Omega = A_\mathrm{p}/r^2$. (After [1.18])

Table 1.1 Radiometric units

	Symbol	SI unit	Definition
Radiant energy	Q_e	J = W s	–
Radiant energy density	w_e	J/m^{-3}	$w_e = \langle dQ_e/dV \rangle$
Radiant flux (power)	Φ_e	W	$\Phi_e = \langle dQ_e/dt \rangle$
Radiant exitance	M_e	$W\ m^{-2}$	$M_e = \langle d\Phi_e/dA \rangle$
Irradiance	E_e	$W\ m^{-2}$	$E_e = \langle dQ_e/dt \rangle$
Radiant intensity	I_e	$W\ sr^{-1}$	$I_e = \langle d\Phi_e/d\Omega \rangle$
Radiance	L_e	$W\ m^{-2}\ sr^{-1}$	$L_e = I_e/\Delta A \equiv \langle d^2\Phi_e/d\Omega \cdot dA \rangle$

Table 1.2 Photometric units

	Symbol	SI unit	Photometric unit	Definition
Luminous energy	Q_V	J=W s	lm s (talbot)	—
Luminous energy density	W_V	J/m^3	$lm\ s/m^3$	$w_V = \overline{dQ_V/dV}$
Luminous intensity	I_V	$W\ sr^{-1}$	$lm\ sr^{-1}$ = candela (cd)	$I_V = \overline{d\Phi_V/d\Omega}$
Luminous power	Φ_V	W	lm (lumen)	$\Phi_V = \overline{dQ_V/dt}$
Luminous exitance	M_V	$W\ m^{-2}$	$lm\ m^{-2}$	$M_V = d\Phi_V/dA$
Illuminance	E_V	Wsr^{-1}	lux (lx) = $lm\ m^{-2}$	$E_V = d\Phi_V/dA$
Luminance (Apostilb)	L_V	$W\ m^{-2}\ sr^{-1}$	asb = $1/\pi\ cd/m^2$	$L_V = \overline{d^2\Phi_V/dA \cdot d\Omega}$

considered as a light source. The standard source, or international standard candle, is defined as the intensity of a black-body radiator with an area of $1/60\,cm^2$

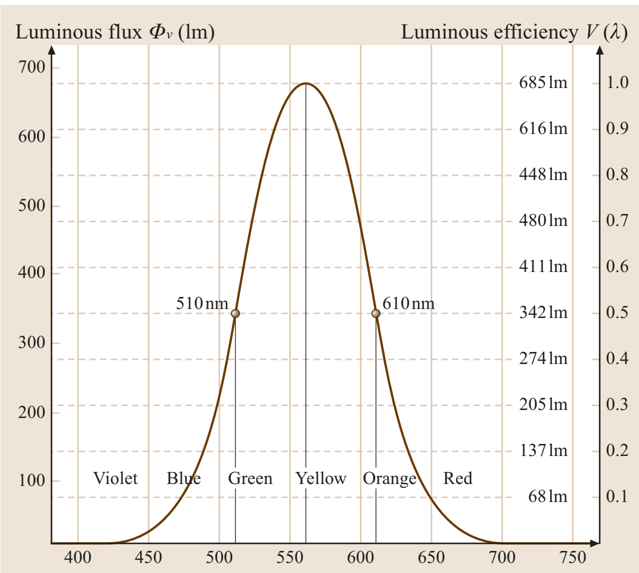

Fig. 1.3 The standard CIE luminous efficacy curve for the human eye, used as the basis for converting between photometric and radiometric units

heated to the melting point of platinum. Two auxiliary quantities, *luminous energy* and *luminous energy density*, correspond to the analogous radiometric units. The photometric units carry a subscript V for *visual*, to distinguish them from their radiometric counterparts; the overbar in the table below signifies an averaged quantity.

The Commission Internationale de l'Eclairage (CIE) has developed a standard luminous efficacy curve for the human eye, with respect to which the photometric units are referred (Fig. 1.3). The lumen is defined such that the peak of the photopic (light-adapted) vision spectrum of an average eye has a luminous efficacy of 683 lm/W.

1.2.4 Photon and Spectral Units

In the photon picture, there is a different set of descriptive quantities normalized to photon energy or photon number, as shown in Table 1.3. The overbarred quantities denote an average over photon wavelengths as well as over area and solid angle.

In some cases – for example, when discussing the spectral brightness of laser or synchrotron sources – it is useful to distinguish physical quantities by their frequency ν. For example, in most cases involving spectroscopy or materials processing with lasers, the