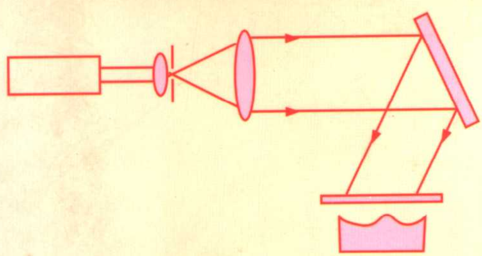
W. Lauterborn — T. Kurz — M. Wiesenfeldt

Coherent Optics

Fundamentals and Applications

相干光学



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Fundamentals and Applications

With 183 Figures,
1 Hologram,
73 Problems and Complete Solutions

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Preface

Since the advent of the laser, coherent optics has developed at an ever increasing pace. There is no doubt about the reason. Coherent light, with its properties so different from the light we are surrounded by, lends itself to numerous applications in science, technology, and life. The bandwidth of coherent optics reaches from holography and interferometry, with its gravitational wave detectors, to the CD player for music, movies, and computers; from the laser scalpel, which allows surgical cutting in the interior of the eye without destruction of the layers penetrated in front of it, to optical information and data processing with its great impact on society. According to its importance, the foundations of coherent optics should be conveyed to students of natural sciences as early as possible to better prepare them for their future careers as physicists or engineers.

The present book tries to serve this need: to promote the foundations of coherent optics. Special attention is paid to a thorough presentation of the fundamentals. This should enable the reader to follow the contemporary literature from a firm basis. The wealth of material, of course, makes necessary a restriction of the topics included. Therefore, from the main areas of optics, wave optics and the classical description of light is given most of the space available. The book starts with a quick trip through the history of physics from the viewpoint of optics. Thereby, the contributions of optics to virtually all fundamental issues of physics are addressed, and a short overview of the four main areas of optics is given.

The notion of coherence gets its own chapter. The different forms of coherence are presented, starting from the most basic description possible, including the applications they give rise to. The phenomenon of speckle formation, often disturbing but also of potential usefulness, is treated, as is multiple-beam interference. Special attention is paid to holography, with its applications, and to Fourier optics, an elegant method for treating diffraction phenomena. The hologram included demonstrates the state of the art in producing bright holograms that can be viewed in white light. The laser, of course, cannot be missed in a book on coherent optics. But it has become an instrument so widely used that it has its own detailed literature. Therefore, just one modern aspect of the laser is put forward here: its nonlinear dynamics. The fundamentals of nonlinear optics are presented in a separate chapter. There, photons are split and combined!

Fiber optics, including solitons, finds its home in the chapter on optical information and data processing.

A book is not born in a day and not without the interaction of the authors with their environment. Thus, the selection of topics is strongly biased by the experience of one of the authors (W. L.) with 29 two-week courses on laser physics and holography given at the University of Göttingen, and repeatedly given lectures on optics at the Technical University of Darmstadt. He takes this opportunity to thank the numerous coworkers making the courses a success, in particular K. Hinsch, K.-J. Ebeling, W. Hentschel and A. Vogel, and also the participants who, with their questions, add to a clear presentation. The illustrations mainly stem from these courses. Input also came from the research work of the authors on nonlinear oscillators, for example.

This text was set by the authors using LaTeX and Postscript. Only the white-light hologram on the cover page could not be translated into electronic form although some means exist in the form of digital holograms that are described in depth.

May this book be of value to the reader, and may he or she also read it with pleasure.

Göttingen, January 1995

W. Lauterborn
T. Kurz
M. Wiesenfeldt

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Table of Contents

1. History of Optics

Optics has developed from human sight. Sight is one of our most important faculties, whereby we interact with nature and gain knowledge of the physical world surrounding us. Therefore optical phenomena have attracted attention since ancient times.

1.1 Past

The first optical instrument could have been a mirror. In any case, mirrors were known to the ancient Egyptians and Chinese and have been found in excavations, often in good condition.

Besides mirrors, the Greeks were in possession of burning glasses. We also know that they contemplated about the nature of light and found a few laws by observing the propagation of light. They knew about the rectilinear propagation and the law of reflection. *Claudius Ptolemaeus* (about 100–170 A.D.) had found a law of refraction for small angles (angle of refraction proportional to the angle of incidence) and knew that the propagation of light should proceed incredibly fast. *Empedocles* (about 495–435 B.C.) was of the opinion that the speed of light is finite.

The Romans mainly conserved the knowledge of the Greeks. It is believed that they used the magnifying properties of lenses in arts and crafts for producing delicate parts. After the decline of the Western Roman Empire (475 A.D.) the knowledge of optics was preserved and augmented in the Arabic–Moslemic world, in particular by *Ibn al Haitham* (965–1039 A.D.), named *Alhazen* in the Middle Ages. He found that the law of refraction of *Ptolemaeus* is not valid for large angles, but was unable to formulate the correct law.

Alhazen was an experimental physicist, as we would call him today, because he conducted experiments for all optical questions he posed, long before *Sir Francis Bacon* (1215–1294) and *Galileo Galilei* (1564–1642), whom we consider the fathers of experimental science and who both have furthered optics. Progress in the Middle Ages was slow. It was not before *Leonardo da Vinci* (1452–1519) that the set of optical instruments was enlarged by the camera obscura (pinhole camera).

In the 17th century the telescope and the microscope were invented in the Netherlands. *Snellius* (1591–1626), a professor in Leyden, discovered the law of refraction in 1621. It was cast into its present form by *René Descartes* (1596–1650). This was a big step forward as the engineering of optical instruments now became feasible.

The diffraction of light was mentioned first by *Francesco Maria Grimaldi* (1618–1663) in Bologna. He observed, among other things, diffraction seams (fringes) in the shadow of a rod illuminated by a small light source. *Robert Hooke* (1635–1703) also observed diffraction effects and investigated diffraction phenomena at thin sheets. As an explanation he suggested the interference of light reflected from the front with the light reflected from the back. He further suggested that we imagine light as being made up of fast oscillations; that is, he suggested a wave theory of light. He was unable, however, to explain the colors of thin sheets. Fundamental insight into colored light was obtained by *Isaac Newton* (1642–1727) in 1666. He discovered that white light can be decomposed into a spectrum of colored light and put forward a corpuscular theory of light [1.1].

Christiaan Huygens (1629–1695) furthered the development of the wave theory and discovered the polarization of light. In 1676 the speed of light was measured by *Olaf Römer* (1644–1710).

Optics did not advance again until 1801 with *Thomas Young* (1773–1829). He introduced the principle of interference, which can be considered as a principle of linear superposition of waves, and roughly estimated the wavelength light should have. Combining this principle with Huygens' principle, *Auguste Jean Fresnel* (1788–1827) calculated the diffraction of light at various objects. At that time light was considered as being composed of longitudinal waves. It was the phenomenon of polarization which led *Young* to the assumption that light is a transverse wave. In 1850 *Léon Bernard Foucault* (1819–1868) discovered that the speed of light in water is lower than in air. This was considered as the final triumph of the wave theory of light, as the corpuscular theory had postulated a larger velocity to explain refraction towards the normal for light passing from air to water.

Further progress in optics came from a new direction: the investigation of electricity and magnetism. In 1845 *Michael Faraday* (1791–1867) discovered a connection between electromagnetism and light. He found that the direction of polarization of light in a crystal can be altered by a strong magnet. *James Clerk Maxwell* (1831–1879) cast the then known phenomena into a theory: Maxwell's equations. From this theory he postulated the existence of electromagnetic waves. They were experimentally detected by *Heinrich Hertz* (1857–1894) in 1888. Around this time it was strongly believed that light, too, was an electromagnetic disturbance in the form of a wave propagating in a supporting medium, called the ether, with the finite speed $c = \nu\lambda$ (ν = frequency, λ = wavelength).

The next task was obvious: to determine the properties of the medium supporting electromagnetic waves, that means, also of light. Soon difficulties were encountered, since the postulated ether had to have strange properties. It had to be very transmissive because celestial bodies obviously move through it undisturbed, but simultaneously had to have strong restoring forces to produce the extremely high frequencies ($\approx 10^{15}$ Hz) and high speed of light. Experimental efforts to measure the motion of the earth with respect to the ether culminated in the experiment of *Albert Abraham Michelson* (1852–1931). The result, published in 1881, was negative. No influence of the motion of the earth on the propagation of light in the ether could be found. But since *James Bradley* (1693–1762), the stellar aberration was known. To explain this phenomenon with the help of the wave theory a relative motion between earth and the ether had to be postulated. Additional difficulties arose with the phenomenon of light carried in moving media (experiments of *Armand Hippolyte Louis Fizault* and *Sir George Briddell Airy*). The solution to these difficulties was given by *Albert Einstein* (1879–1955) in 1905 in a surprising way. In his theory of special relativity he declares the ether to be superfluous:

> Die Einführung eines "Lichtäthers" wird sich insofern als überflüssig erweisen, als nach der zu entwickelnden Auffassung weder ein mit besonderen Eigenschaften ausgestatteter "absoluter Raum" eingeführt, noch einem Punkte des leeren Raumes, in welchem elektromagnetische Prozesse stattfinden, ein Geschwindigkeitsvektor zugeordnet wird. [1.2][1]

The new state of knowledge was: light is an electromagnetic wave propagating in empty space, the vacuum.

In some sense, mankind had come full circle with respect to the ancient thoughts of the Greeks handed down to us by *Lucretius* (about 55 B.C.) in his fundamental work *De rerum natura* (On the nature of things) [1.3]. Therein, the postulate is attributed to *Epicurus* (341–270 B.C.): there are only objects and empty space.

But the theory of light was not at all finished. Many open questions remained, for instance, concerning the spectrum of blackbody radiation or the generation of light (absorption and emission, existence of sharp spectral lines). They led to a further great revolution in our knowledge about nature: quantum theory. Quantum theory was initiated in 1900 by *Max Planck* (1858–1947). He stated that for an explanation of the measured spectrum of blackbody radiation it must be supposed that the elctromagnetic field can exchange energy only in discrete portions of size

$$E = h\nu , \tag{1.1}$$

[1]The introduction of a light ether will turn out to be superfluous insofar as, according to the theory to be developed, neither an "absolute space" with special features will be introduced, nor to a point in empty space, in which electromagnetic processes take place, will a vector of velocity be associated.

$h = 6.626176 \cdot 10^{-34}$ Js being a constant, now Planck's constant, and ν being the frequency of the light wave.

Planck first found the formula for the spectrum of blackbody radiation by fitting a curve to experimental data. Written for the spectral energy density, that is, the energy per volume and frequency interval, it reads:

$$\rho(\nu)\,\mathrm{d}\nu = \frac{8\pi}{c^3}\nu^2 \frac{h\nu}{\exp\left(\frac{h\nu}{kT}\right) - 1}\,\mathrm{d}\nu, \tag{1.2}$$

with T being the temperature in K and $k = 1.380662 \cdot 10^{-23}$ JK^{-1} being the Boltzmann constant.

In the attempt to derive theoretically the radiation formula, *Planck* put forward his famous quantum hypothesis:

> Wir betrachten aber – und dies ist der wesentlichste Punkt der ganzen Berechnung – E als zusammengesetzt aus einer ganz bestimmten Anzahl endlicher gleicher Teile und bedienen uns dazu der Naturkonstanten $h = 6,55 \cdot 10^{-27}$ (erg·s). [1.4] [2]

In 1905, *Einstein* went a step further and postulated that the electromagnetic field itself is composed of quanta of energy $E = h\nu$. Then the photoelectric effect could be explained easily [1.5]. These energy portions were later given the name "photon".

Quantum theory rapidly developed in the years 1925 – 1930 with the wave mechanics of *Erwin Schrödinger* (1887–1961) and the matrix mechanics of *Werner Heisenberg* (1901–1976). The equivalence of both theories was shown by *John von Neumann* (1903–1957) in Göttingen. Beautifully simple relations were found. Particles now also acquired a wave character: a particle of momentum p has a wavelength $\lambda = h/p$ (*Louis de Broglie*, 1892–1987). This discovery gave rise to the construction of, for instance, the electron microscope (*Ernst Ruska*, 1906–1988). *Einstein* had shown earlier that mass is just a different form of energy: $E = mc^2$. The particles of light have energy, therefore a mass can be attributed to them:

$$E = h\nu = mc^2 \rightarrow m = \frac{h\nu}{c^2}. \tag{1.3}$$

Similarly, they have the momentum

$$p = \frac{h}{\lambda} = \frac{h\nu}{c} = mc. \tag{1.4}$$

The old controversy between the corpuscular and the wave theory of light is overcome in the quantum theory of light. Light has particle and wave aspects depending on the phenomenon considered. They find a unified description only in quantum mechanics. This wave–particle dualism is not only a speciality of light but pervades all phenomena. Optics initiated the discovery of this fact.

[2] But we consider – and this is the most important point in the whole calculation – E as being composed of a certain number of finite equal parts, and for that use the constant of nature $h = 6.55 \cdot 10^{-27}$(erg · s)

1.2 Present

Optics made a big step forward through the invention of the laser by *Theodore Harold Maiman* (born 1927) in 1960. Coherent light, that is, light of extremely high spectral purity, is available today with high intensity in the visible and far into the deep ultraviolet and infrared spectral regions. This has enriched optics with new methods and devices. They have influence on our daily life, for instance in telecommunications, and also allow us to gain insight into deep and subtle physical questions, for instance with respect to the foundations of quantum mechanics. The deepest impression on the general public has surely been left by holography [1.6] with its possibility of recording and reconstructing three-dimensional images as they directly appeal to our visual abilities. The reader will find an example in this booklet.

But of deeper importance is the fact that the speed of light in a vacuum has gained a place as a constant of nature,

$$c_0 = 299\,792\,458\,\mathrm{ms}^{-1}, \tag{1.5}$$

in the present system of units. The unit of length, the meter, thereby has become a derived unit. It is defined, with the help of c_0, as the distance light travels in a vacuum in the time interval of 1/299 792 458 second.

Optical techniques and devices for measuring virtually all types of variables have been invented and installed. Just a few are listed here:

- holographic interferometry and speckle photography to measure small deformations of even rough surfaces;
- dual-recycling interferometry proposed for the detection of gravitational waves;
- laser-doppler (LDA) and phase-doppler anemometry (PDA) for measuring the velocities of particles in fluid flows;
- photon correlation techniques for determining the diameter of stars, for instance;
- laser vibrometer for measuring the vibration of object surfaces;
- scanning-laser and near-field-scanning optical microscopy that allows unprecedented resolution up to the visualization of individual molecules;
- fiber-optic sensors such as optical microphones;
- all-optical filtering of images for picture processing and pattern recognition;

- the generation of harmonic waves (more than 135 times the fundamental frequency) and wave mixing;
- phase conjugation in real time to obtain phase conjugating mirrors;
- optical bistability and chaos;
- nonlinear spectroscopy;
- femtosecond technology.

This variety has a reason: light, in particular in the form of coherent light, has proven to be an ideal measuring and scanning instrument, as it normally does not disturb the object investigated. Optics is combined with electronics, acoustics, and mechanics. There are acoustooptic deflectors and electrooptic devices such as Pockels cells. Mechanically deformable mirrors are used in adaptive optics to get high-resolution images of the sky. Optics gets "integrated", that is, miniaturized on chips, and more and more takes over tasks in telecommunications. Information is transmitted via glass fibers and stored in optically readable format on compact and magnetooptic disks.

Besides refractive optics, making use of the different refractive indices of materials, diffractive optics is developed which is based on the diffraction of light at fine structures. The number of diffracting structures is practically unlimited, thereby opening up novel ways for using light. A hologram, for instance, that has stored a three-dimensional image, is a diffracting structure and thus belongs to diffractive optics in a wider sense. Hummingbirds make use of diffractive optics with their brilliant iridescent plumage. In technical applications, diffractive optics is used in the X-ray region of the spectrum, for instance in X-ray microscopy, as materials with large refractive indices are not known in this wavelength region. Diffractive optical elements are calculated and manufactured for many special applications in the form of digital holograms, then called holographic optical elements. Examples are beam splitters, deflectors, and holographic lenses with several focal points.

The digital electronic computer has become a device indispensable for the lens designer and can be considered itself as a universal optical element since it is capable of modifying images and of performing filter operations or image transforming tasks. It is capable of calculating the Fourier transform of images, a task that can also be done by a lens. Powerful parallel computers, equipped with many processors, and optics mix in a peculiar way to create a new type of reality, called "virtual reality". Wearing a helmet display and a data glove or even suit, you can move interactively in a computer-generated world to explore complex structures such as a DNA molecule or the interior of the human body, a totally new way of optical experience.

1.3 Future

What does the future carry in its cornucopia? Several challenging areas can be identified where optics will have a great impact.

In technical applications, optics will expand deeply into the areas of communications and information processing. Fast communication channels on the basis of fiber networks will be developed and installed worldwide. Electronic data processing will increasingly be supported by optical data processing. Thereby diffractive and integrated optics will play an important role. As photons do not interact when propagating in a linear medium, much more complex, in particular parallel, circuits are realizable optically than electronically. Neural nets with optical elements are presently implemented and will remain a challenge for some time to come. First arrangements of a digital, purely optical computer demonstrate the possibility of computing with photons. After "electronics", the newly developing area in communications and data processing with photons is called "photonics".

In physics, nonlinear optics, with its main areas of laser physics and quantum optics, promises new insight into the laws of nature. The X-ray laser and laser fusion wait to become feasible. Femtosecond lasers open up new intensity regions in the laboratory for experimentation. Laser instabilities and chaotic laser-light dynamics are expected to add to our understanding of nature, of deterministic chaos in particular. Both the question of how determinism and predictability are related and the not quite intuitive world of quantum physics presumably can best be demonstrated with experiments in laser physics and nonlinear optics.

Light thus may help us in answering the question: what will we be able to know? But do we already know the answer to the question: what is light?