Dieter Meschede

Optics, Light and Lasers

The Practical Approach to Modern Aspects of Photonics and Laser Physics

Second, Revised and Enlarged Edition

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Cover
The picture shows the light field emerging from a photonic crystal fibre excited with red and green light. The fibre which consisted of a solid core and a cladding with a periodic array of 300 nm holes spaced by about 2-3 µ is shown in Fig. 3.23, upper left. The fibre shows striking single mode behaviour no matter how short the wavelength is. In the fibre, red and green light propagate in a common single transverse lobe which appears white due to superposition of red and green. Details on photonic fibres are found in Sect. 3.4.6.

Courtesy of Professor Philip Russell, Max-Planck Research Group, University of Erlangen, Germany. The PCF used was fabricated at the University of Bath, U.K.

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Preface

Though being taught as a traditional subfield of classical electrodynamics, the field of optics is now once again considered to be an important branch of the physical sciences. Some even say that the 21st century will be the century of the photon, following the era of the electron.

In teaching physics, wave optics and interferometry are important topics with beneficial propaedeutic contributions to the theory of classical fields and quantum mechanics. In lecture halls today we can easily demonstrate wave, i.e., coherence phenomena with laser light sources. It is hence appropriate also in lecturing to devote more room to the concepts of optics created since the 1960s.

This textbook attempts to link the central topics of optics that were established 200 years ago to the most recent research topics such as nonlinear optics, laser cooling or photonic materials. To compromise between depth and breadth, it is assumed that the reader is familiar with the formal concepts of electrodynamics and also basic quantum mechanics. This new edition has not only grown by an entire new chapter introducing the field of quantum optics. It also presents new material describing the rapidly rising role of photonic materials and fibres. Last but not least about 100 problems with varying degrees of difficulty have been included.

In scientific education, this textbook may serve as a reference for the foundations of modern optics: classical optics, laser physics, laser spectroscopy, concepts of quantum optics, nonlinear optics as well as applied optics may profit. Teaching will be complemented through materials presented by new media such as the internet. Nevertheless, the author strongly believes that conventional textbooks will continue to be a prime source of learning. Novel materials and complements will be made available, however, through the following website: www.uni-bonn.de/iap/oll.

Bonn, October 2006 *Dieter Meschede*

1
Light rays

1.1
Light rays in human experience

The formation of an image is one of our most fascinating emotional experiences. Even in ancient times it was realized that our 'vision' is the result of rectilinearly propagating light rays, because everybody was aware of the sharp shadows of illuminated objects. Indeed, rectilinear propagation may be influenced by certain optical instruments, e.g. by mirrors or lenses. Following the successes of Tycho Brahe (1546–1601), knowledge about *geometrical optics* made for the consequential design and construction of magnifiers, microscopes and telescopes. All these instruments serve as aids to vision. Through their assistance, 'insights' have been gained that added to our world picture of natural science, because they enabled observations of the world of both micro- and macro-cosmos.

Fig. 1.1 Light rays.

Thus it is not surprising that the terms and concepts of optics had tremendous impact on many areas of natural science. Even such a giant instrument as the new Large Hadron Collider (LHC) particle accelerator in Geneva is basically nothing other than an admittedly very elaborate microscope, with which we are able to observe the world of elementary particles on a subnuclear length scale. Perhaps as important for the humanities is the wave theoretical description of optics, which spun off the development of quantum mechanics.

In our human experience, rectilinear propagation of light rays – in a homogeneous medium – stands in the foreground. But it is a rather newer understanding that our ability to see pictures is caused by an optical image in the eye. Nevertheless, we can understand the formation of an image with the fundamentals of ray optics. That is why this textbook starts with a chapter on ray optics.

1.2
Ray optics

When light rays spread spherically into all regions of a homogeneous medium, in general we think of an idealized, point-like and isotropic luminous source at their origin. Usually light sources do not fulfil any of these criteria. Not until we reach a large distance from the observer may we cut out a nearly parallel beam of rays with an aperture. Therefore, with an ordinary light source, we have to make a compromise between intensity and parallelism, to achieve a beam with small divergence. Nowadays optical demonstration experiments are nearly always performed with laser light sources, which offer a nearly perfectly parallel, intense optical beam to the experimenter.

When the rays of a beam are confined within only a small angle with a common optical axis, then the mathematical treatment of the propagation of the beam of rays may be greatly simplified by linearization within the so-called 'paraxial approximation'. This situation is met so often in optics that properties such as those of a thin lens, which go beyond that situation, are called 'aberrations'.

The direction of propagation of light rays is changed by refraction and reflection. These are caused by metallic and dielectric interfaces. Ray optics describes their effect through simple phenomenological rules.

1.3
Reflection

We observe reflection of, or mirroring of light rays not only on smooth metallic surfaces, but also on glass plates and other dielectric interfaces. Modern mirrors may have many designs. In everyday life they mostly consist of a glass plate coated with a thin layer of evaporated aluminium. But if the application involves laser light, more often dielectric multi-layer mirrors are used; we will discuss these in more detail in the chapter on interferometry (Chap. 5). For ray optics, the type of design does not play any role.

1.3.1 Planar mirrors

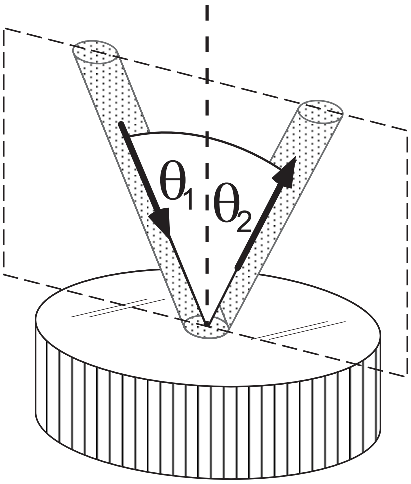

Fig. 1.2 Reflection at a planar mirror.

We know intuitively that at a planar mirror like in Fig. 1.2 the *angle of incidence* θ_1 is identical with the *angle of reflection* θ_2 of the reflected beam,

$$\theta_1 = \theta_2, \tag{1.1}$$

and that incident and reflected beams lie within a plane together with the surface normal. Wave optics finally gives us a more rigid reason for the laws of reflection. Thereby also details like, for example, the intensity ratios for dielectric reflection (Fig. 1.3) are explained, which cannot be derived by means of ray optics.

1.4 Refraction

At a planar dielectric surface, like e.g. a glass plate, reflection and transmission occur concurrently. Thereby the transmitted part of the incident beam is 'refracted'. Its change of direction can be described by a single physical quantity, the 'index of refraction' (also: refractive index). It is higher in an optically 'dense' medium than in a 'thinner' one.

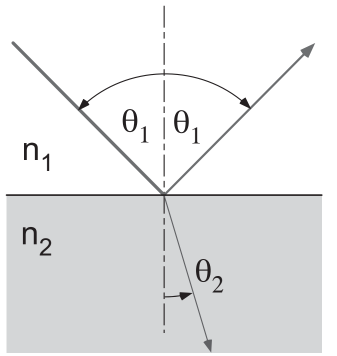

Fig. 1.3 Refraction and reflection at a dielectric surface.

In ray optics a general description in terms of these quantities is sufficient to understand the action of important optical components. But the refractive index plays a key role in the context of the macroscopic physical properties of dielectric matter and their influence on the propagation of macroscopic optical waves as well. This interaction is discussed in more detail in the chapter on light and matter (Chap. 6).