Photonics I

The theory of light & its advanced applications

Lecture notes

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The lecture course introduces the five models of light & its interaction with matter: i) ray (geometrical) optics, ii) wave optics, iii) electromagnetic optics, iv) semiclassical theory of light-matter interactions and v) quantum optics, postulates their laws and – with the help of these successively more advanced [i) → v)] models – addresses the generation, propagation, manipulation, and advanced applications of light.

CONTENTS

I Introduction: modelling light and its interaction with matter.

II Ray optics: propagation of light rays through simple optical components and systems. *Postulates:* Fermat's principle. *Mathematical tools & approximations:* paraxial rays, ray-transfer matrix of optical components (lenses, mirrors). *Phenomena & applications*: imaging and guiding.

III Wave optics: propagations of light waves through optical components and systems. *Postulates:* Scalar wave equation, intensity. Derivation of the laws of ray optics from those of wave optics. *Approximations:* paraxial waves, complex amplitude transmittance of optical components, paraxial wave equation. *Phenomena & applications*: Fourier optics: imaging and X-ray computed tomography, optical beam propagation and transformation including filtering and focusing.

IV Electromagnetic theory of light: description of light waves in terms of electric and magnetic fields. *Postulates:* Maxwell's equation, electromagnetic power flow: Poynting vector. Derivation of wave optics from electromagnetic theory. *Approximations:* paraxial electromagnetic waves, linear and nonlinear[1] polarizability of matter. *Phenomena & applications*: absorption and dispersion, light pulse propagation, polarization of light and its manipulation, reflection and refraction, electro- and acousto-optics: modulation and switching of light.

V Semiclassical theory of light-matter interactions. *Postulates:* electromagnetic theory of light + quantum theory of the electron. *Approximations:* perturbation theory, Fermi's Golden Rule. *Phenomena & applications*: derivation of the linear polarizability of matter: light-induced atomic transitions: absorption and stimulated emission of light, principles of lasers[2].

VI Quantum optics: description of light in terms of photons. *Postulates:* laws of quantum electrodynamics. Classical fields (of electromagnetic theory): expectation values of field operators. *Approximations:* transverse electromagnetic fields. *Phenomena & applications*: lifetime of excited atomic states, spontaneous emission of light, photon detectors, quantum noise.

Literature:[3]

1. C. C. Davis, Lasers and Electro-Optics, Cambridge University Press.
2. H. A. Haus, Waves and Fields in Optoelectronics, Prentice-Hall, Inc.
3. R. Loudon, The Quantum Theory of Light, Oxford Univ. Press.
4. D. Marcuse, Principles of Quantum Electronics, Academic Press, Inc.
5. G. Reider, Photonik (in German), Springer.
6. B. E. A. Saleh, M. C. Teich, Fundamentals of Photonics, John Wiley and Sons, Inc.
7. A. Siegman, Lasers, University Science Books.
8. E. G. Steward, Fourier Optics – an Introduction, Ellis Horwood Limited.
9. O. Svelto, Principles of Lasers, Plenum Press.
10. A. Yariv, Quantum Electronics, John Wiley and Sons, Inc.

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[1] An in-depth coverage of the nonlinear polarizability of matter and the broad range of phenomena originating from nonlinear interactions is given by Prof. Dr. Theodor W. Hänsch: A: Nichtlineare Optik.

[2] An in-depth coverage of laser physics is given by Prof. Dr. Wolfgang Zinth: Laserphysik

[3] Many figures have been borrowed from the above given literature, particularly from Refs. 6 and 7.

I. Introduction: modelling light and its interaction with matter

The most sophisticated and most comprehensive theory of light (incl. its interaction with matter) is *quantum electrodynamics,* which is – thanks to advanced computational methods and precision laser techniques – the most accurately tested theory of physics. For optical phenomena, this theory is also referred to as *quantum optics.* It introduces the concept of the *photon* as the elementary excitation of the electromagnetic modes of a cavity and accounts for all known light phenomena to within an accuracy that can be currently achieved in computational and experimental physics. The (so far) complete coverage of light & light-matter-interaction phenomena comes, however, at the expense of a level of complexity that calls for simplification whenever possible.

Fortunately, the quantum nature of light tends to be masked ever more by classical wave properties as the energy stored in the cavity modes becomes large compared to the photon energy and consequently the resultant wave is intense enough to be able to excite or deexcite a large number of atomic dipoles (in the language of quantum mechanics: induce a large number of resonant atomic transitions) in any infinitesimal volume of space. For radiation that is sufficiently intense to fulfil this condition, *Maxwell's electromagnetic theory* provides an excellent description of all light phenomena in terms of two mutually coupled *vector* waves, an electric-field wave and a magnetic field wave. These include all propagation phenomena through any objects and – if supplemented with *the quantum theory of the electron* – the interaction of light with matter.

In many cases the vector properties of light do not manifest themselves, in these instances the theory can be further simplified to what has been referred to as a *scalar wave theory*, accounting for a wide range of interference and diffraction phenomena as well as imaging.

When light waves propagate through and around objects whose dimensions are large compared to the wavelength, the wave nature of light is not readily discerned, so that its behaviour can be adequately described by a set of geometrical rules. This (simplest) model of light is called *geometric optics* or *ray optics*.

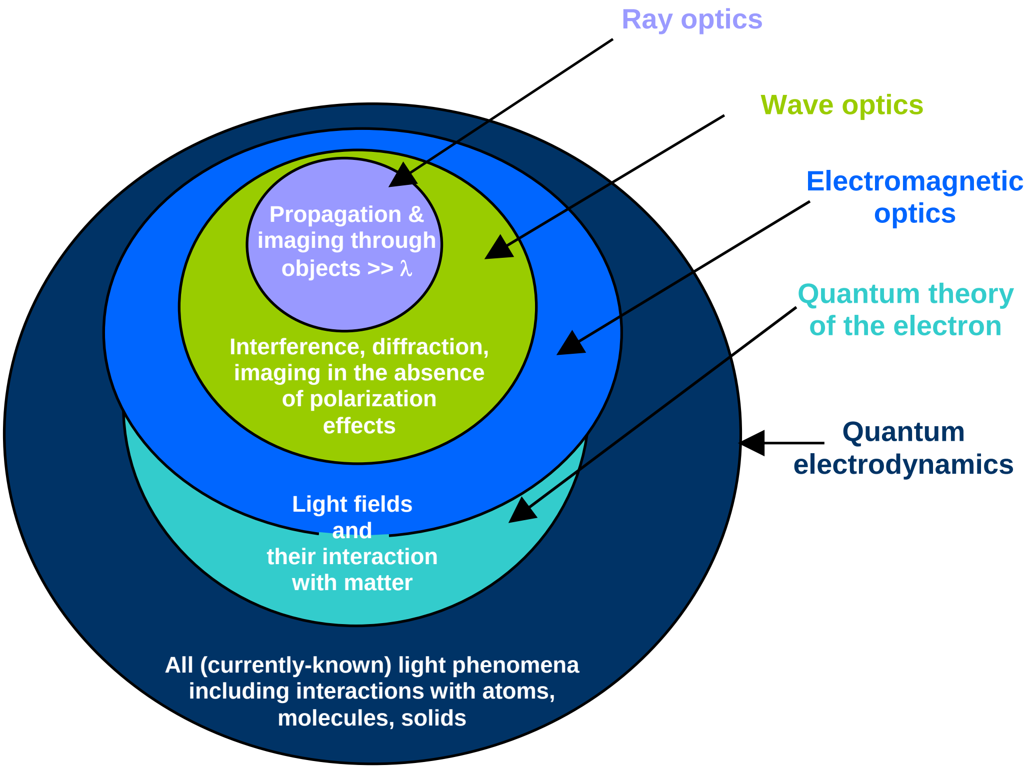

Fig. I-1

Quantum optics accounts for all currently known light phenomena, a large fraction of which, however, can be adequately described by replacing the quantum theory with the simpler electromagnetic theory of light, allowing a more convenient treatment. Further restrictions of the range of phenomena allow further simplifications, leading to (scalar) wave optics and ray optics. The borders of validity of these models gets ever more confined (see Fig.I-1), but even the simplest model covers a sufficiently broad range of phenomena so that its treatment in any comprehensive course on light phenomena is more than justified.

The lecture course will introduce these models in historical order, starting out from the simplest one. Each model is based upon a set of postulates (provided without proof), from which explanation and description of a number of phenomena can be derived within the frame of validity of the respective model. When proceeding to a more sophisticated description, the postulates of the previous (simpler) model will be shown to naturally follow from the next-higher-level model, justifying the representation in Fig. 1. The light phenomena discussed in some detail have been selected to justify the introduction of ever more sophisticated theories and on the basis of their importance for advanced optical techniques and technologies. In terms of the phenomena discussed, there will be some overlap with the *Kursvorlesung PIII: „Wellenlehre und Optik“,* however, apart from the extension towards the quantum theory of light (which is absent from *PIII*) the approach is completely „orthogonal“: in striking contrast with the phenomenological description of optical phenomena and devices in *PIII,* in this lecture course the theory of light will be in the focus, with its postulates and framework rigorously introduced and its relevance to modern optical technologies explained by means of selected examples.

The topics covered in the course will follow those included in these lecture notes, which have been edited in a way so it allows grasping the essential physics even if not each of the lectures could be attended. Nevertheless, the text accompanying the maths and connecting the steps of mathematical derivations is rather succinct and therefore attendance of the lectures is highly recommended. The mission of this lecture course is to provide a comprehensive theoretical background accounting for the phenomena presented (mostly phenomenologically) in *PIII* and suitable for describing any effects and phenomena relevant to modern optical techniques and technologies rapidly proliferating in an ever increasing number of fields if science, technology and medicine. Many of these will be covered by a follow-up 3-hour lecture **Photonics II: intense-laser/matter interactions for science, technology and medicine** in the summer semester.

The evolution of the theory of light and its treatment in this course also exemplifies how physics works in general:

i) how a theory is created by means of a set of postulates,

ii) how its usefulness and region of validity is established by testing its ability to give accurate account for phenomena observed in reproducible experiments performed under well-controlled and well-specified conditions,

and

iii) how the theory evolves to the next-higher-level model, driven by experimental findings that can not be explained on the grounds of the previous model.