0 Light and Matter

0.1 Introduction

Even the simple act of reading these notes is possible only thanks to a chain of interactions between light and matter. First of all, the light that we see was generated by spontaneous emission from a hot filament, the solar corona or the cooler electrical discharge and coating of a fluorescent lamp. In most cases, that light will have been scattered from walls, buildings or clouds, before striking the printed page, where the different scattering rates of ink and paper allow the words to be distinguished. In the eye, refraction allows the collected light to be focussed to form an image, and absorption finally converts the light back in to an electronic excitation within the species of the rods and cones of the retina. The laser printer that produced this document will itself have exploited light-matter interactions: light, this time produced via stimulated emission, will have been scanned and modulated by its interaction with acoustic waves in an optical crystal, to sweep out an image that is repainted in electrical charge by its effect upon the photosensitive print drum. If, on the other hand, you are reading an electronic version on your laptop computer, then the text is formed by controlled changes in polarization as the incident light passes through liquid crystal molecules between polarizing filters.

http://www.howstuffworks.com/lcd.htm

Just as matter can influence the propagation of light, so light can affect the behaviour of matter. Optical tweezers and scalpels are finding ever more uses in biology, medicine and biophysics, yet are just the pathfinders for a wider range of optical force applications that may include fractionation, mesoscopic assembly and the transmission of power to nanoscale mechanisms. Optical cooling and trapping have meanwhile allowed atomic vapours to be cooled to within nanoKelvin of absolute zero – a regime in which their behaviour is completely dominated by quantum phenomena. Meanwhile, the modern theory of quantum electrodynamics (QED) views the electrostatic force as due to the exchange of momentum through the emission and absorption of optical photons.

This third-year course will cover a range of light-matter interactions, including those responsible for refraction in the eye and the operation of the acousto-optical modulator (the heart of the laser printer) and the liquid crystal display. Generally, we shall neglect the processes by which light is emitted and absorbed, for you should have met these already; instead, we shall address mechanisms by which light can be controlled though its interaction with matter, and matter can be controlled through its interaction with light.

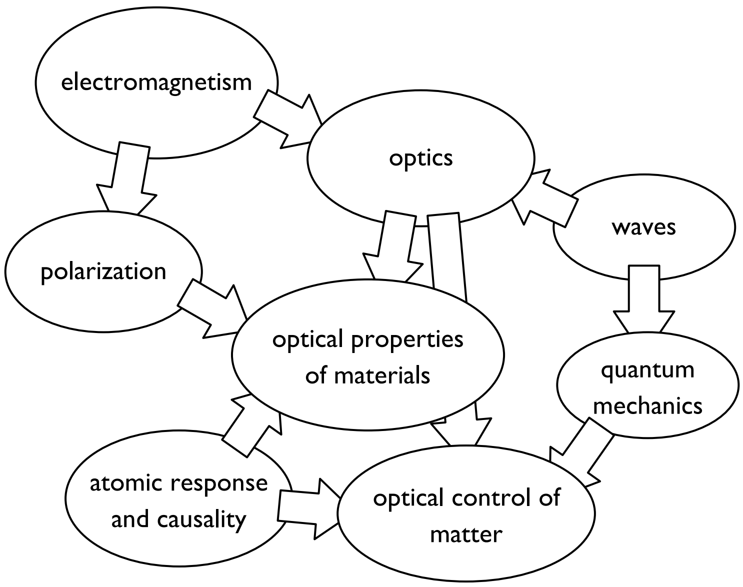
0.2 Course structure

The course comprises around 30 lectures. The majority of these will follow the traditional lecture format, but there will also be a handful of tutorial classes, and occasional guest lectures given by researchers active in the area.

We shall begin by revisiting the theory of electromagnetic waves and their propagation, found in textbooks under headings such as “classical electrodynamics,” which describes the passage of light through bulk media characterized by a few, general and rather abstract properties. We’ll then spend a little time examining what these abstract parameters correspond to at a detailed, microscopic level, and some of the constraints that result for real physical systems. We’ll then consider in detail the property of polarization, which I suspect you’ve wisely given only cursory examination so far. The beginning of this course is, then, like so many others: somewhat dry revision and expansion of subjects that you’ve already met elsewhere.

The polarizing properties of optical materials already give us considerable power to control the passage of light, and we’ll look at some of the effects underlying operation of liquid crystal displays and various more traditional optical components. Arguably more powerful, however, are those effects which exploit nonlinear light-matter interactions, so we’ll move on to look at the phenomena that allow fast electro-optical switching, optical isolators and frequency conversion. We thus move from methods of controlling light with matter to methods in which light itself can control such interactions.

As the course proceeds, we’ll begin to introduce a quantum mechanical view of the subject, and will see that it ultimately provides a simple description that unifies wave and particle descriptions and treats light and matter as largely equivalent. Finally, with a move from the solid state to the vapour phase, we shall look at some of the most exciting fields of current research, in the way that matter can be controlled using light alone.



Lectures

The course will be composed roughly as follows.

Part 1: Foundations

1 Wave mechanics

Wave equations and their solution; linearity, dispersion and superposition; Fourier analysis; phase and group velocities; energy and power; continuity and boundary conditions; operators; uncertainty

2 Classical electrodynamics

Maxwell's equations; continuity and boundary conditions; electromagnetic waves and energy flow

Part 2: Controlling light with matter

3 The classical interaction between light and matter

Drude and Lorentz models, dielectrics, conducting solids, electron gas; reflection at metal and dielectric interfaces; causality and the Kramers-Krönig relations; dispersion relations

4 The polarization of light

Light as a vector field; polarization and the Fresnel equation; Jones vectors, Stokes vectors and Müller matrices; the Poincaré sphere; polarization in nature and technology; optical activity and chirality

Part 3: Controlling light with light

5 Optical nonlinearity

The nonlinear susceptibility; the electro-optic and magneto-optic effects; the optical isolator; sum and difference frequency mixing and harmonic generation; phase matching; self-focussing; field quantization

6 The tensor nature of susceptibility

Anisotropic media; tensors, principal axes and diagonalization; Fresnel and index ellipsoids and the ray velocity surface; the optic axis; symmetry; locality and linearity; optical activity and nonlocality; nonlinear tensor susceptibilities

Part 4: Controlling matter with light

7 The quantum mechanical interaction of light and matter

Time-dependent quantum mechanics; the two-level atom; quantum mechanical description of atomic polarization; the light shift; dressed states

8 Optical forces and wave-particle duality

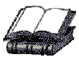
The mechanical effect of the photon; phonons and acousto-optic modulation; the optical dipole force; the optical scattering force; the magneto-optical trap; Bragg scattering and Feynman diagrams; atom interferometry and the Bloch vector

0.3 Suggestions for study

It is difficult to exaggerate the value of independent study and practice exercises, for they lead to oft-neglected parts of understanding: acceptance and familiarity. Here is Feynman's introduction to quantum mechanics:

> *I am going to tell you what nature behaves like. If you will simply admit that maybe she does behave like this, you will find her a delightful, entrancing thing. Do not keep saying to yourself, if you can possibly avoid it, 'But how can it be like that?' because you will get … into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.*

These lectures, notes and classes form, as always, just part of the material at your disposal, and you should expect to draw upon other resources, including textbooks, journal articles, discussions with colleagues and tutors and – with due caution, for it is often wrong – the internet. There is no universal recipe, for while some prefer phenomenological descriptions, others favour more analytical assaults, and that which one finds pedantic may be too superficial to another. Try to adopt a little of Heaviside's approach, which led him to cast Maxwell's equations in the form we know today:



http://www-gap.dcs.st-and.ac.uk/history/Mathematicians/Heaviside.html

> *It took me several years before I could understand as much as I possibly could. Then I set Maxwell aside and followed my own course. And I progressed much more quickly.*

0.4 Further reading

There are numerous text books, of all ages and levels, that cover the course to a greater or lesser extent. Meschede's *Optics, Light and Lasers* and Band's *Light and Matter* are perhaps the most appropriate single volumes, but no book is complete or ideal and what is explained poorly in one may be devastatingly clear elsewhere. The following are suggested starting points, rather than definitive recommendations.

General

D. Halliday, R. Resnick, J. Walker, *Fundamentals of Physics*, 6th edition, Wiley, New York (2000) ISBN 0 471 39222 7

E. Hecht, *Optics*, 4th edition, Addison-Wesley, Harlow (2001) ISBN 0 805 38566 5

D. Meschede, *Optics, Light and Lasers*, Wiley-VCH, Weinheim (2004) ISBN 3 527 40364 7

Y. B. Band, *Light and Matter*, Wiley, Chichester (2006) ISBN 0 471 89931 3

A. E. Siegman, *Lasers*, University Science Books, Sausalito (1986) ISBN 0 935 70211 3

A. Yariv, *Optical Electronics in Modern Communications*, 5th edition, O U P, New York (1997) ISBN 0 195 10626 1

H. J. Metcalf, P. van der Straten *Laser Cooling and Trapping*, Springer-Verlag, New York (1999) ISBN 0 387 98728 2

Waves

H. H. Pain, *The Physics of Vibrations and Waves*, 6th edition, Wiley, Chichester (2005) ISBN 0 470 01296 X

I. G. Main, *Vibrations and Waves in Physics*, 3rd edition, C U P, Cambridge (1993) ISBN 0 521 44701 1

A. P. French, *Vibrations and Waves*, various publishers: Chapman and Hall, London; W W Norton, New York; Nelson Thornes, Cheltenham (1971) ISBN 0 442 30784 5, 0 393 09936 9, 0 748 74447 9

Electromagnetism

I. S. Grant, W. R. Phillips, *Electromagnetism*, 2nd edition, Wiley, Chichester (1996) ISBN 0 471 92712 0

Optics

F. G. Smith, J. S. Thomson, *Optics*, 2nd edition, Wiley, Chichester (1988) ISBN 0 471 91535 1

M. Born, E. Wolf *et al*, *Principles of Optics*, 7th edition, C U P, Cambridge (1999) ISBN 0 521 64222 1

Polarization and crystal optics

J. F. Nye, *Physical Properties of Crystals*, O U P, Oxford (1985) ISBN 0 198 51165 5

Nonlinear optics and devices

R. Boyd, *Nonlinear Optics*, 2nd edition, Elsevier, London (1994) ISBN 0 121 21682 9

Mathematics

M. L. Boas, *Mathematical Methods in the Physical Sciences*, Wiley, New York (2006) ISBN 0 471 36580 7

G. B. Arfken, H. J. Weber, *Mathematical Methods for Physicists*, 5th edition, Academic Press, San Diego (2000) ISBN 0 120 59826 4

M. R. Spiegel, *Theory and Problems of Vector Analysis*, Schaum's Outline series, McGraw-Hill, New York (1974) ISBN 0 070 99009 3

Feynman's short book *QED – the strange theory of light and matter* (Penguin (1990) 0 140 12505 1) offers an illuminating and thought-provoking account of the wave-mechanical view of physics. More general, but no less inspiring, *The Character of Physical Law* (Penguin (1965) 0 140 17505 9) is based upon his Messenger Lectures; I shall show Lecture 6 (*Probability and Uncertainty – the Quantum Mechanical View of Nature*) during the course.

0.5 Reading these notes

These notes are intended to support the lectures, not necessarily to reproduce them. Some parts will be examined more minutely in lectures, while the notes include suggestions for further reading, worked examples (framed), and optional sections (grey) that illuminate historical aspects or indicate features considered beyond the general level of this course.