Invited Paper

# Basic education in Optics for physicists.

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*To Quim Carrera, a Ph.D. student of our research group, who died recently.*

**Abstract**

The concept of Optics, its situation as a branch of Physics and the educational value of a course of Optics for a physicist are analyzed in this paper. A list of contents is proposed with a discussion about the importance of the different topics.

## 1 Introduction

A programme in Physics prepares students for productive employment in their field upon graduation, and endeavors to develop students abilities in critical thinking, communication skill and problem solving.

An important objective is to inculcate in students an understanding of the necessity for and methods of continued professional development, so that they may contribute to the needs and challenges of the profession in the future. The basic curriculum has to be developed in consonance with the country norms, the community needs and the progress of Physics.

The Bachellor of Science (B.Sc.) in Physics degree or the first cycle of a Physics degree is designed to provide students a professional education in natural sciences. This education should enable well-qualified graduates to succeed in any graduate programme in Physics, or else provide them with satisfying employment in technologically-oriented industries.

In this paper we propose a course of Optics which intends that students get familiar with Optics and they learn the fundamentals of light and its behaviour in certain phenomena. Optics is considered in a broad sense and this course could be given in the B.Sc.degree. The knowledge of the fundamentals of Optics will help he students to understand other branches of Physics.

Finally some of them, who are interested in Optics, will continue in a Master in Optics degree programm [1], or will choose some options in Optics inside a Master's degree in Physics [2]. The Master in Optics degree programmes are designed to provide the student who has a strong undergraduate preparation in physics or electrical engineering with the knowledge and skill to contribute to sate-of-the art Optics research and development.

In a Ph.D. program in Optics it is expected that a student who completes it will be ready to assume a role as an independent researcher in a university, industrial or government laboratory.

It is not easy to delimit the contents of a branch of Physics so old and extensive as Optics. The most adequate frame arises by considering the evolution and the present state. The course will contain the fundamentals that a physicist needs for its background.

In this paper we will summarize the historical evolution, by observing how the sphere of influence of Optics becomes wider until it arrives to the present state, where it plays a rather important role in the development of Physics. In order to emphasize the importance of Optics in present Science, one has to consider that it is an auxiliary tool for many sicences and technologies. This is due to two important characteristics of the optical methods and devices. Firstly, the capacity of the generation of radiation and the spectral and temporal analysis and secondly, the possibilities that optical systems and devices show in many scientific or technical experiments.

We will discuss a definition of Optics which will help to place it inside Physics and also to stablish the frontiers and connections with other Sciencies.

Finally we will propose a list of contents and a final discussion with our opinion about the fundamental topics which have to be kept for physicists in case to shorten the course.

# 2 Physics education at the university.

The education at the University presents two different aspects of great importance: **1**, the training of the student during the degree for the future practice of his profession; **2**, the scientific research and the training of the future researchers. These two tasks are not unlike, they are very much related and they help each other.

The principal task of the University is, really to make from the student of today a well prepared person in the future. Along the different cycles in which the University education is divided, the student receives his complete training. It is the task of the professor to combine teaching and research conveniently. Each one should be given the adequate weight for the student to reach a deep and complete education at the end of each cycle.

Teaching has to obtain from the research the base and fundamentals of science, and its application. The job of a professor is to integrate and to systematize the conclusions for the student to receive a complete information of the subject. This comunication between the professor and the student obliges the first one to think deeply about the subject he teaches.

Besides, the student considers as unusual, things that for the professor are very well known. These facts give the student opportunity to think and research about. All these reasons confirm the proximity of teaching and research.

In order to pursue the subject at the University, the student of Physics needs to combine mathematical and experimental skill with the ability to grasp new concepts, and be able to apply them to a wide range of problems. The versatility of the physicist is reflected in the wide variety of occupations in which he is to be found. Apart from Universities and research centres nearly all modern industries call on the insight and skill of physicist. In addition they are highly valued for the contributions they can make to different fields like business, commerce and education.

Most first-degree courses in Physics look much alike on a superficial examination. The list of topics covered is very similar in the universities of most countries. Although there are curricula with a theoretical tendency, others which are more experimental. Optics, in most Physics degree, is among the core topics.

# 3 Historical Evolution

The development of Optics can be divided into four periods. The first one goes from the beginning of the history until the end of the XVI century. During this time several hypothesis about the light propagations and the vision phenomenon were formulated.

The second stage comprises the development of Optics from the XVII century to the XIX century. It includes Maxwell and Hertz. During this period a deterministic and Galilean Physics is developed. It includes an Optics capable to give, firstly with the geometrical model an explanation to propagation of light and afterwards the wave model could explain the propagation phenomena and the interaction light-light phenomena which were known at that moment. Maxwell formulates the theory of electromagnetic waves. Their existence is verified by Hertz. The conexion between Electromagnetism and Optics is established. The discussion about the wave or particle character of light was finished in favour to the light as an electromagnetic wave. Using the Lorentz model of the bound electron, it was possible to explain theoretically the refraction index and the absortion, emission and scattering of light by matter. The first spectroscopic observations are also from this period. Definitively, with Classical Mechanics for the treatment of material particles and the Classical Electrodynamics of Maxwell for radiations, it looked that every physical phenomena could be explained, especially any one dealing with light.

The third period corresponds to the first half of the XX century. A series of experimental observations put in doubt many of the old theories and they produce other new ones, deeply different. It is not necessary to mention the very important role that Optics played in this evolution of the Physics, because it contributed a great part of the experimental verifications. For example, the Michelson-Morley experiment, the black body radiation, the photo-electric effect and the atomic and molecular spectra. They were the start point of the Relativity theory, the Quantum Mechanics and the Atomic Physics. Nevertheless the new physical concepts were absorbed by the new sciences which became independent. During this period Instrumental Optics had a great development.

Along the second half of this century, two very important milestones in Optics are reached: the consolidation of Quantum Electrodynamics and the laser invention. With the first one Optics acquires very strong basis. All the experiments of high accuracy made to verify the Quantum Electrodynamics give good agreement with the theoretical results. About the laser discovery, it has caused a great revolution in Optics. It generates light with new properties, which have permited the discovery of new optical processes: harmonic generation, phase conjugation and many other non- linear phenomena in the interaction light-matter.

# 4 Optics as a branch of physics

## 4.1 Physics and the models in Physics

Physics is one of the most fundamental of the sciences. It is concerned with the study of matter, energy and the interactions between them. It is important, not only as a subject in its own right, but also as an essential element in all other natural sciences, engineering and the technology. Physics tries to know and understand a given kind of natural phenomena using the scientific method. Every real knowledge of the nature comes from the direct study by the observation of the phenomena or the experiments at the laboratory. And from their study a theoretical formulation for a group of experiments is proposed.

Firstly the Sciences delt with the macroscopic study of the nature: the outside world with objective reality. They established the macroscopic rules which explained the universe behaviour. From the macroscopic rules they went to the microscopic ones by trying to explain the structure of the matter using a model or image. From it, the macroscopic rules could be explained from the behaviour of the constituent elements.

The last aim of the natural sciences is the final explanation of the Universe. But, theories and physical models created for it, can explain only a set of experiments inside the limits of observation. Outside these limits, it may happen that the proposed model and the corresponding theory are not useful any more to describe the new phenomena.

Then the problem raises again in order to deduce an adequate new physical theory that with its own model, probably more complex, would substitute the previous one. This new theory has to explain not only the new results but also the former ones. It may predict other unknown results whose discovery will confirm the new theory. Feynman [3] says: *The verification of every scientific knowledge is the experiment. The experiment is the only judge of the scientific truth.* And he adds: *The object of the science is to predict and the proof, the capacity to do so.*

In this evolution process a theory does not nullify the previous one, but it completes it. In the domain of validity of the first theory, this theory is normally used because as far as the science goes on the theories are generally more complex in their mathematical treatment.

Optics gives a clear illustration of the value and the limitations of the physical models. For example Geometrical Optics, Physical Optics, Quantum Optics.

## 4.2 What is Optics?

The evolution of Optics gives different definitions along the history. The old ones put vision and light (in the sense of visible waves) in a central place. Vision gave the name to Optics. For instance, the Dictionary of the Royal Academy of Spanish Language says that Optics is the science which deals with light and vision phenomena. Nevertheless more recent and scientific definitions widen the concept of Optics. The one accepted by the Optical Society of America in 1961 [4] says that Optics is the science which deals with radiant energy, its generation and propagation, the effects which undergoes and produces and all those phenomena closely related with it. Then the radiant energy is considered in general, not only in the small region that produces visual perception. It is also shown in the definition that Optics studies not only the propagation but also the generation and detection of this radiant energy. This definition can be useful to describe the subject of a general course of Optics in a degree in Physics. Nevertheless, there are other branches in Physics which study the electromagnetic field. So, we should delimit the frequency domain included in Optics.

The limits are given by those frequencies for which the theoretical models, valid for photons of the visible spectrum, can still be applied. One of the features of the visible photons is that their energy is very small if it is compared with the energy of the motionless electron, and they can not give it enough energy to become relativistic. This gives a limit for the Optical domain in $10^{18}$ Hz. This higher limit makes that the theoretical basic frame for Optics is the Non-Relativistic Quantum Electrodynamics. At the low frequencies side there are not essential theoretical limitations. Only the fact that at ordinary temperature, the stimulated transitions for the thermical radiation in the region of the visible spectrum are negligible. If we want to extrapolate this feature to other zones of the spectrum we have to work with frequencies higher than $10^{13}$ Hz. With these limits the optical domain is between the far infra-red ($10^{13}$ Hz.) and the soft X-rays ($10^{18}$ Hz.). Only a small region around $5x10^{14}$ Hz. is actually visible. These limits should not be considered as restrictive and exclusive. Because a definition of a branch of science should not become a fixed rule which limits its contents and so its progress and the relation with other branches of knowledge. The low limit is particularly arbitrary mainly if it is taken into account that the techniques of optical pumping permit to obtain non-thermal population distributions in the energy levels of material media. This allows to generate radiation (non-thermal) and to detect transitions in the zone of radiofrequencies and microwaves, as it is the case of the maser and the spectroscopy of double resonance.

### 4.3 Educational value of Optics

Educational value is understood in the sense that the study of Optics can influence positively the student intellectual development as a whole. It is important to consider that each subject of the syllabus has to contribute in the student global education. It is not only a series of different experiments but the student has to learn Physics as a whole. Let us say, a science which tries to obtain some objectives, in some of them the student will continue his studies and his work in the future.

A phyisicist tries to understand deeply the essential mechanism of the experiments and to obtain other conceptually different results. The student needs to study the fundamentals in order to understand the present progress of Optics and also to be prepared to understand and to work with the future developments he will find along his profession.

There are two features of Optics which have an important educational value. Firstly, in Optics the scientific side and the applied one are very much related. Secondly in Optics the student gets used to the change of the physical model, because many of the succesive models, which appeared along the history are still applied.

The models used in Geometrical Optics, Physical Optics and Quantum Optics illustrate this idea. The geometrical model can not explain the phenomena of interferences and diffraction. The vectorial characteristic of electromagnetic waves is needed to study polarization. Many of the observable diffractional experiments can be explained with a scalar aproach. The design of optical system works with geometrical Optics but in well corrected systems, criteria as the minimization of the variance of wave aberration based on diffractional theory are applied.

## 5 An Optics Course in a degree of Physics

It is not easy to propose the contents for a course of Optics, that may be valid for any degree of Physics. It has to be done in accordance with the orientation of the University and the curriculum of the degree taking also into account the contents of other related subjects. It has to reflect the evolution of Optics and the present development. The list of contents corresponds to a required course in the first cycle or a B.Sc. degree of Physics. There are two possibilities to include many topics and applications or to consider deeply the main supports of the fundamentals. We prefer the second point of view and we will mention some applications that can be given in seminars or in elective credits. The contents of this course have to fulfill two aims. Firstly it has to provide the student with the knowledge of the basic optical phenomena to continue afterwards with a M. Sc. or specialization course in Optics. Secondly, this course ought to present a wide and general scene of Optics, so that the student of Physics, who will not study more courses on Optics, obtains the minimum knowledge of the main subjects and their relation with other branches of Physics and other Sciences in general.

In this rather wide course we will consider: Geometrical Optics, Physical Optics and some models for the interaction of light and matter. Other topics and applications are added.

Optics as an experimental Science needs a laboratory course as a complement to the theory. Also, the proposal of problems for the students to solve them, is recommended.

There are some topics proposed in this course that, in some Universities, are studied in some other courses with other names (Wave Physics, Electromagnetic fields and waves, etc.). Nevertheless in many Universities, as it is the case of the Spanish ones, there exists a required course of Optics in the curriculum of the first cycle or B. Sc. degree of Physics.

The order of the contents follows more or less the chronological development. It emphasizes the value and the limitations of the optical models. At each step it is shown how the introduction of a new model does not invalidate the results obtained previously, but sets definite limits to their field of applicability.

The topics proposed in this course are developed in many well-known text books (see for instance [5-14]).

It is assumed that the students have some knowledge of mathematics. In this volume [15], Consortini analyzes the mathematics background that an optics student needs. An introductory course in electromagnetism, leading up to the Maxwell equations, is a prerequisite for the electromagnetic theory of light.

## 5.1 Contents

In the following we give a list of contents in detail. Some of them are basic and others can be omitted to shorten the length of the course and can be given in optional seminars or in some M.Sc. courses. Nevertheless, we are conscious of the lack of other important topics and applications.

1. Historical introduction and the situation of Optics in Physics.

### I- GEOMETRICAL OPTICS

2. Fundamental principles: Fermat's principle and the laws of Geometrical Optics.
3. Optical representation. Object and image. Stigmatism.
4. Paraxial Optics. Abbe invariant. Lagrange-Helmholtz invariant.
5. Correspondence equations. Lenses. Mirrors.
6. Sine condition (Abbe) and Herschel condition.
7. Optical systems with plane surfaces. Plates. Prisms. Dispersion.
8. Rays limitation. Stops. Apertures.

9. Matrix representation of paraxial optics.

10. Aberrations in axially symmetric optical systems.

11. Design of optical systems. Aberrations correction.

## II- PHYSICAL OPTICS
### i) Propagation

12. Fundamental principles of wave Optics. Huygens Principle. Electromagnetic theory. Maxwell equations.

13. Waves in homogeneous isotropic media. Wave equation solutions. Transverse waves.

14. Representation of polarized light. Superposition of waves with perpendicular electric vectors. Stokes parameters.

15. Reflexion and refraction in isotropic dielectrics. Fresnel formula. Total reflexion. Fiber Optics.

16. Metal Optics. Refraction. Reflexion. Optical metal constants.

17. Anisotropic media. Dielectric tensor. Wave propagation. Phase and energy propagation.

18. Crystal Optics. Velocities and polarization in uniaxic media. Wave surface.

19. Production and analysis of polarized light.

20. Optical activity. Electro and magneto optic effects.

21. Non linear Optics. Propagation in non linear dielectric media. Harmonic generation.

### ii) Interferences

22. Superposition of waves with parallel electric vectors. Phase and group velocity.

23. Interference conditions. Coherence. Scalar theory. Young fringes.

24. Interferences in plane parallel plates. Fabry-Perot interferometer.

25. Thin film optics. Filters.

26. Double beam interferometers. Michelson, Twyman, Mach-Zender interferometers.

27. Interferences with polarized light.

28. Coherence. Monochromatic and quasi-monochromatic light. Coherence length and spectral width. Longitudinal and temporal coherence. Contrast in interference fringes. Spatial coherence. Van-Cittert and Zernike theorem.

29. Resonant cavities. Superposition of waves propagated in opposite directions. Wave guide. Modes. Integrated optics.

### iii) Diffraction

30. Diffraction phenomena. Scalar aproximation. Huygens- Fresnel principle. Free propagation of a spherical wave.

31. Kirchhoff theory. Fresnel and Fraunhofer diffraction.

32. Fraunhofer diffraction of rectangular and circular apertures. Resolving power of optical systems.

33. Fraunhofer diffraction by a double slit. The diffraction grating. Dispersion. Spectral analysis.

34. Diffraction theory of image formation. Point spread function. Transfer function. Coherent illumination. Optical image processing.

35. Holography. Hologram recording. Image reconstruction. Holographic interferometry.

## III-APPLIED OPTICS

36. Physiological Optics. The eye as an optical instrument. Visual acuity. Thresholds.

37. Radiometry and photometry. Radiant sources. Detectors. Photometric measurements.

38. Colorimetry. Color specification by colors addition. CIE system.

39. Photographic and projection optical instruments.

40. Telescopes. Geometrical formula. Resolving power. Photometric theory. Multiple mirror telescopes.

41. Microscopes. Geometrical formula. Abbe's theory. Phase contrast microscope. Optical scanning microscope. Electron microscope.

## IV-LIGHT AND MATTER

42. Classical microscopic theory of light and matter interaction. Lorentz atomic oscillator. Dipolar radiation. Elementary classical processes of interaction light and atoms. Absortion. Emission. Scattering. Dispersion. Classical description of the different types of optical media.

43. The origins of quantum optics. Black body radiation. Planck's hypothesis. Photoelectric effect. Photons. Compton effect. Einstein derivation of Planck's law.

44. Particles and waves. Wave feature of particles. Quantum description of a particle. Uncertainty principle.

45. Introduction to the semi-classical theory of light and matter interaction. Validity of classical model. First order processes. Einstein coefficients for stimulate transitions. Higher-order processes.

46. Laser. Basic components and laser principles. Pumping. Optical resonator. Modes. Laser types. Laser light properties. Applications.

## 5.2 Final discussion

The proposed list of contents is rather long, if it is compared with the number of credits that are generally in a course of Optics. If the list has to be shorten, the Geometrical Optics would be reduced. The basis of paraxial Optics and image formation are necessary for their use in optical experiments. In some syllabi a course of Elementary Physics comprises lenses, mirrors and image formation in paraxial approximation.

The course would consist mainly of Physical Optics: wave propagation, polarization, interferences and diffraction. The anisotropic media theory could be simplified. Physical Optics is the core of a course for physicists. The chapters of interaction light-matter should also be kept.

The topics of optical instruments could be reduced or changed by others dealing with Optoelectronics.

If other courses of Optics are added in a degree of Physics, at the last year of B.Sc. degree or in M.Sc. degree, then Quantum Optics and Fourier Optics could be considered apart from others, as required or elective subjects. With Quantum Optics the student of Physics will complete the idea of the phyisical world. It is the introduction to the fundamental Physics which is on the basis of Optics. It deals with the rigorous quantum theory of light and the interaction with systems with a fixed number of non-relativistic charged particles. It is the introduction of Non-Relativistic Quantum Eletrodynamics. The general theory of optical phenomena is applied to the study of radiative processes and corrections, the laser or the spectroscopy of high resolution.

Finally, in Fourier Optics an introduction to the theory of information applied to Optics is reviewed.

In some Universities, within the Physics programme one of the areas of specialization for educational and research programmes is that of Optoelectronics. A variety of courses is offered on such topics as electro-optics devices and systems.

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## References

[1] University of Rochester. *Official Bulletin 1985-86, Graduate Studies*, 119-123, 205-210, Aug. 1985.

[2] *Guide for students. Faculty of Sciences* Universitat Autònoma de Barcelona, 1990-1991.

[3] R.P.Feynman, R.B. Leighton and M.Sands. *Lectures on Physics*, Addison-Wesley, 1963.

[4] D.B.Judd. *What is Optics?*, J.Opt. Soc. Am. **51**:1042, 1961.

[5] M.Born and E.Wolf. *Principles of Optics* Pergamon Press, 1970.

[6] R.W.Ditchburn. *Light*, Academic Press; *Optica* (*Spanish translation*) Editorial Reverté, 1982.

[7] M.V.Klein. *Optics*, John Willey Pub., 1970.

[8] F.A.Jenkins and M.E.White. *Fundamentals of Optics*, Mc. Graw-Hill, 1976.

[9] H.Haken. *Light*, North-Holland. Vol.1, 1981. Vol.2, 1985.

[10] B.Rossi. *Optics*, Addison-Wesley Pub, 1957.

[11] J.Casas. *Optica*, University of Zaragoza (Spain), 1985. (*in Spanish*).

[12] G.S.Landsberg. *Optica*, (*Spanish translation of Russian edition*). Editorial Mir, **2**. 1983.

[13] D. Sivoukhine. *Cours de Physique Generale, Tome IV, Optique*, (*French Translation of Russian*), Editions Mir, 1984.

[14] J.Ph. Perez. *Optique, Optique géométrique, matricielle et ondulatoire*, Masson, Paris, 1984.

[15] A. Consortini. *How much mathematics should optics students know?*, Proc. SPIE, **1603**, 1991.