Education in Applied and Instrumental Optics at the University of Helsinki

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Abstract:

The teaching of applied and instrumental optics at the University of Helsinki Department of Physics originally grew out of the needs of the research group of Molecular physics as a basis for the experimental work in the group. The training program starts with a one-year course for senior undergraduates and graduates comprising geometrical optics, eikonal theory, image forming components, matrix methods, optical instruments, the optics of laser beams, radiometry and photometry, ray tracing methods, optics of anisotropic media, diffraction theory, general image formation theory and Fourier optics. The course starts from fundamentals, but the mathematical level is kept adequate for serious work. Further applications are treated in courses on molecular spectroscopy, where ruled and holographic diffraction gratings (both plane and spherical), interferometric spectroscopy and imaging properties of spectral equipment are treated. Aspects of image analysis, information in optics, signal-to-noise ratio, etc. are treated in separate courses on Fourier methods and digital spectral analysis. The applicability of optical techniques to various fields of physics and engineering and the analogies with them are especially brought out. Experimental and calculational and skills are stressed throughout. Computer programming is introduced as an indispensable tool for the optics practitioner, and the students are required to write programs of their own. The students gain practical experience, e.g., by working in the Molecular physics group. Close cooperation is maintained with other research groups in laser physics, ultrasonics and physical chemistry. The training in optics has proved very useful, with students frequently ending up working in the industry on optics and spectroscopy problems. Parts of these courses have also been given at other universities and to engineers and scientists working in the industry.

Keywords: Optics courses, applied optics, instrumental optics

1. INTRODUCTION

Teaching optics for physics students is sometimes a confusing task because of the ambiguous role of optics regarded as an academic discipline. On the one hand, optics as a field of physical research as such has experienced a renaissance probably unseen so far in the field of natural research with the advent of stimulated emission, quantum optics, optoelectronic devices and innumerable other novel phenomena and methods. This development has been accompanied by a similar upsurge of new applications of optics in virtually all fields of natural science and engineering. On the other hand, good old 19th century geometrical optics with all its applications still stands as the basis for a multitude of applications. For a

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teacher, who has to steer between the newest front-line and, after all, the perennially needed old-fashioned applications, this state of matters presents a very serious, if inspiring challenge. Designing a university level teaching package in optics involves more choices of means and ends right from the beginning as compared to, e.g., a course on atomic physics or on mathematical methods in physics. This paper describes a particular program of teaching of Applied and Instrumental Optics as implemented at the University of Helsinki Department of Physics.

2. BACKGROUND

Optics in Finland has a rather narrow tradition to fall back on; an understandable state of matters in a country with the largest amount of growing wood per capita in the world within economical reach for harvesting equipment and with the largest amount of mobile telephones per capita in the world. There is little basic manufacturing industry in optics in Finland, with only a few small companies active in, e.g., component manufacturing. However, those who do, are also of high level and provide adequate supply for various projects in instrumental optics. On the other hand, the number of companies engaged in manufacturing of various types of optical equipment both for scientific, industrial and medical purposes is steadily increasing. On the academic side of instrument development in Finland, one could list the Vaisala long-base interferometer used for comparing kilometer distances with down to micrometer accuracy, the original corrector plate for large-angle telescopes (also devised by Vaisala long before the physicist eventually credited with the discovery), the manufacturing of the large optical telescope mirror for the Canary Islands observatory, the construction of a 0.0004 cm^{-1} resolution Fourier spectrometer and the construction of the four-grating MEGA spectrometer with resolving power in excess of 4 million. It is something of a strange coincidence that all these projects originated in the universities in the city of Turku in southwestern Finland. However, anyone who has experienced the average local fall and winter will readily appreciate the protection from the outside weather offered by the occupation of building an optical instrument safely below ground level.

Research and teaching at the University of Helsinki Department of Physics has traditionally been strongly oriented towards solid-state and material physics, applied physics and nuclear physics with high-energy physics, ultrasonics and molecular physics emerging as new disciplines during the last few decades. The small research group in molecular physics, mainly active in experimental and theoretical vibrational spectroscopy and lead by the present author since the late sixties, early became engaged also in various instrumental development projects for its own purposes. During these projects, a reasonable amount of practical knowledge in optics was accumulated, and the need naturally arose for systematizing this knowledge into a regular teaching program in optics. Incidentally, as an offspring from these activities, several (occasionally successful) industrial enterprises in the field have also emerged.

As part of the history it can be recalled that after the Second World War a new faculty of Technical physics was founded in the Helsinki University of Technology. As lecturer in optics Dr. Yrjö Arvola was hired, an outstandingly gifted mechanical engineer and teacher who during the war was extensively engaged in testing, servicing and developing military optical equipment. He eventually collected part of his experience into a doctoral thesis with binocular eyepieces as subject. His teaching, directed mainly towards the geometrical optics of optical instruments, constituted an excellent basis for direct applications and also for taking up further activities in the field. The present author had the pleasure of attending Dr. Arvola's courses long ago, and his teaching is still remembered and even used in practice as a source of knowledge and inspiration.

3. GOALS OF THE EDUCATION IN OPTICS

After joining the permanent staff of the University of Helsinki Department of Physics in 1973, the present author decided to formalize the teaching of optics, first in the shape of a two-semester course comprising 56 lecture hours and 56 hours of problem sessions. This course has later been supplemented by courses given by the present author on, e. g., Fourier methods in Physics, Molecular spectroscopy and Digital spectral analysis, all of which carry considerable material of relevance to Optics.

The first problem to solve was to examine the boundary conditions of the teaching program in a sensible way. To a first approximation, they were the following:

1) Biannually taught courses in optics for second-year students had been discontinued ten years earlier because of declining demand. The courses were situated in the teaching program so that their level was not sufficient as a background for serious work. In particular, almost no treatment of diffraction was given. Therefore, the new course was aimed at third-year students and up.

2) The course was aimed at students from different disciplines ranging from molecular physics through solid-state physics, electronics, biophysics, physical chemistry and X-ray physics.

3) The scope of the course should involve both geometrical optics, diffraction theory and Fourier optics, with ample reference to optical instrumentation and methods.

4) The goals of the course were to be of a mainly practical nature, although leading students to the level of sophistication where they would be able to apply optical techniques in their own work in possibly other fields and to join industrial development projects in optics.

5) The students were supposed to do considerable homework on their own. Nowadays, with personal computers becoming readily available, various programming projects along the course are presupposed. The problem sessions were planned as a very important part of the course, and they are taken care of by some of the most experienced teaching assistants or junior lecturers in the department.

6) Experimental work is built into the course through the regular lab sessions for Physics students, and additional opportunities to participate in various

experiments in optics are available a. o. in the Molecular physics laboratory, the Laser physics laboratory and the Electronics research laboratory in the department.

The level of the courses was set such that the main parts of e. g. the well-known advanced books by Born and Wolf (1), Goodman (2) and Sommerfeld (3) should be accessible by the students already during the course. Although no single book is directly used as textbook for the course, a. o. the excellent texts by Hecht and Zajac (4), Lipson and Lipson (5), Klein and Furtak (6) and Guenther (7) have been recommended as supplemental reading as the course proceeds. The list implies no ranking between different books in any other respect than their immediate suitability for these particular courses. In all, the students have been exposed to some twenty or more books during the course. The lecture notes themselves are handed out to the students for photocopying, and as of this year, in electronic form.

For practical reasons, mainly related to material resources, the teaching program did not aim at large-scale new research projects in optics, although the activities have lead to the odd paper on optical problems every once in a while by people active in the project. Serious research projects were at that time, and even more so now, aptly catered for by other groups at Helsinki University or at other Finnish universities in related fields, notably in quantum optics, diffraction optics and holography. However, the need for a course with a strong practical inclination combined with an adequate level of presentation of the general propagation theory of light was quite evident.

4. CONTENTS OF THE PROGRAM

The optics course proper is divided in two parts, one based on the solution of the wave equation by separation of variables, the optics of plane waves, eikonal theory and geometrical optics, and the other based on the integral solution of the wave equation in the Rayleigh-Sommerfeld approximation, leading to general propagation and diffraction theory. As the mathematics goes a bit heavy at times for some of the third-year students, the difficult pieces are incorporated in the course material and taught alongside with the physics as needed. The contents of the courses goes briefly as follows:

Optics I: Plane wave solution of the wave equation, refraction and reflection of plane waves, eikonal theory, reflection and refraction in spherical surfaces, lenses and mirrors, lens systems, matrix formulation of optical systems, ray tracing methods, aberrations, optical instruments, commercial optical components, properties of Gaussian laser beams, imaging of laser beams, radiometry and photometry, interferometers, plane waves in anisotropic media (crystal optics.

Optics II: Fourier series and Fourier transforms (brief review but adequate), integral solution of the wave equation, Fresnel and Fraunhofer approximations, plane wave expansion of optical fields, optical transfer functions, the transfer function of free space, description of optical systems using diffraction theory and using the optical transfer function, plane and spherical diffraction gratings, elements of Fourier optics, spatial filtering, elements of Fourier spectroscopy, the propagation of Gaussian laser beams described using both the plane-wave expansion and the diffraction integral and the elements of X-ray diffraction.

Other subjects related to optics as taught in other courses by the present author comprise a. o. algorithms for performing discrete Fourier transforms (Fourier methods in physics), optimization of spherical holographic gratings, ray tracing of the imaging properties of Czerny-Turner and Eberth spectrographs and interferometric spectroscopy (Molecular spectroscopy), convolution, deconvolution and linear prediction in spectroscopy and optics, image analysis and resolution enhancement and noise and filtering of images and spectra (Digital spectral analysis). The optics courses are usually given biannually alternately with the other above mentioned courses. Not all of the subjects listed are taught each time; about 80 % of them are covered each time separately, with the particular choice often dictated by the interests of the participants. For example, when the majority of the attendants are molecular physicists or physical chemists, considerable attention is given to the analysis of spectrometric equipment. These courses, or parts of them, have been given over a period of twenty years or so, e.g., at the Helsinki Technical University to students of Technical physics and of Electrical engineering, at the Swedish university in Finland Åbo Akademi and on several occasions for engineers and physicists in the industry.

To pass the courses a student is required either to pass a formal examination or to write a separate term paper on a suitable subject. Typical term paper subjects have been, e. g., calculating the path of a light ray in Earth's atmosphere as a function of the angle of incidence (a highly satisfying task in view of the good agreement with experimental data), describing a laser beam as an eigenfunction of the Fourier transform, writing a ray tracing program of your very own, a comparison of European and Japanese trends in the development of photographic objectives, analysis of the aberrations of a spherical mirror and a ray-tracing simulation of the imaging properties of the uncorrected Hubble space telescope. In addition, reasonable activity in the problem sessions is a prerequisite for the highest grades. The use of modern calculational tools (programming in C, C++ or some other language, spreadsheets, MATLAB, MATHCAD, Maple V, Mathematica etc.) is in practice necessary in order to get through the problem sessions and to prepare the term paper. Most students choose the term paper over a formal examination, either because they can write a report related to an experimental research project of their own, or in order to deepen their knowledge of some particular subject and to sharpen their calculational skills.

5. OBSERVATIONS AND CONCLUSIONS

The teaching program in optics has been well received. As envisaged at the start, the participants range from physics students interested in optics as such and not yet specializing in any particular discipline to students and graduates already engaged in other fields of research, e.g., ultrasonics, molecular physics and spectroscopy, electronics, physical chemistry, X-ray physics and material physics.

In the author's opinion, among the main reasons for the success on the local scale are the following:

1) The theoretical level is adequate for serious applied work, so that students are able to embark on e. g. industrial projects in optics and to use their knowledge in their own research. In spite of the highly observational and even qualitative aspects to successful design and construction work in optics, there is no room for compromise as to the formal level of exposition if consistent success is to be achieved.

2) The subject matter is sufficiently closely tied to actual, practical applications so that the knowledge is readily applicable or at least related to practical problems.

3) There is sufficient breadth in the course material for the students to take up problems of their own and to apply their skills in computer programming to optical problems.

4) The problem sessions have developed into an integral part of both the course and the earlier mentioned related courses, with their own profile. This is largely due to the experience and skill of the teacher responsible for them, and the success in that respect so far has been of crucial importance.

Many of the students and teachers who have taken part in the optics program and/or the related courses have ended up working in the industry on designing and building optical instruments. These applications include e. g. laser instrumentation for ophthalmic surgery (a highly successful line of instruments in its time), various imaging systems for medical use, interferometric spectrometers for high-resolution infrared spectroscopy (0.0004 cm^{-1} resolution) and for environmental analysis, diffraction-theoretic analysis of the multigrating spectrometer, design of various illumination systems and optimization of the design of holographic spherical gratings.

In this context it is again natural to ask in which ways the optics program differs from other physics courses on the same level, such as Quantum mechanics or Atomic physics. Firstly, the optics program as implemented here, although being a course on optics, exhibits contact surfaces to a very different multitude of subjects such as molecular spectroscopy and molecular physics, ultrasonics, material physics, acoustics and signal analysis. Secondly, as given primarily to third-year students and up, and not being coupled to a regular research project in optics, the subject matter can easily be tailored according to the needs of the participants without breaking up any pedagogical entities.

In all, shaping the teaching program in optics has been a most rewarding experience. The close contact with students in many different fields and with physicists and engineers working on optical problems in the industry has been a constant source of inspiration. This circumstance has had a very positive influence on the subject matter chosen for presentation in the lectures and problem sessions and has also lead to a certain amount of original research results.

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