advanced optical techniques

ADVANCED OPTICAL TECHNIQUES

EDITED BY

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FOREWORD

Between the well-known introductions into the theory and the practical side of optics and the often highly specialized articles on particular subjects a gap is to be filled. It is an impossible task to try filling this hiatus in one book. The series 'Progress in Optics' fulfills already an important part of this work. A book presenting modern subjects in a comprehensive form seems helpful in those cases where a connection between the more elementary treatises and the specialized publications is missing. The present volume is an attempt in this direction. Completeness has not been aimed at, neither in the choice of subjects nor within each chapter.

It need not be emphasized that it is unfeasible to be up to date in all subjects treated (lasers, fibers, lens design, transformation function). These branches of the optical science are in full bloom. The respective chapters can be considered as introductions to the pertinent literature.

Some chapters are more or less rounded-off studies of the subject matter (modern spectroscopic methods, coherence and image formation, crystal interferometry, thin films, geometrical optics)

Another group of chapters deals with matters of practical importance that are scattered in different journals and of which even a short but general review has its utility (modern light sources, modern applications of interference, precision measurements, optical glass, fabrication of optical parts, coronagraphy). To this group also three other small chapters may be reckoned, which call attention to special subjects of some importance, but are apt to be overlooked (three-slit method, alignment, optical glass spheres).

Three points must be stressed: each author wrote his text under his own responsibility; there is no uniformity between the different chapters, the subjects (and the authors) being often too wide apart; the reader is supposed to possess a general knowledge of the optical principles. Matter that can easily be found in well-known books is, in many cases, not included.

The editor is aware of the fact that the inclusion in or omission from this book of certain subjects will meet criticism from competent workers in the optical field. He can only hope that it will be understood that within the scope of one volume no agreement can be reached between more than a few persons, even if they come from one school.

One of the clearest examples is the area of lens design: each lens designer is perfectly aware of the fact that his methods are the best in the world and it is impossible to convince him by any length of argument that other methods are more rapid or give more easily a larger amount of information. The reader, therefore, either has to comply to the author or to reject his way of thinking. The editor can only declare that he has done his best to assemble a number of writers who have won their spurs in their field, and who devoted their time making a collection of texts which to his opinion will prove useful to those who feel the need of modern optical knowledge. For a long time technical optics has been neglected by the research workers in the domain of space physics, of atomic energy, and of other disciplines with a flavour of actuality and even of romanticism; workers, who begin to feel now the need of a sound optical background for the benefit of their own work.

A. C. S. VAN HEEL

Delft, 1966

PREFACE

As a result of intensive fundamental research since the Second World War, optics, one of the oldest branches of physics, has developed dramatically, not only in the more novel fields, but also in the well-established areas of geometrical and physical optics.

Among the more important advances and discoveries which may be mentioned are:

Computer techniques in lens design and the use of new optical glasses, leading to better corrected lenses.

Extensive use of reflecting optics in X-ray relay cameras, air reconnaissance cameras, microscope objectives, and other new fields.

The laser, which has made holography practicable and has led to new applications of interferometry.

Thin film optics, which now has reached the stage of elaborate computer programmes for automatic design.

Fibre optics.

Application of Fourier transform techniques to spectroscopy and to lens assessment.

These developments indicated to Professor A. C. S. van Heel the need for a new book which gathered together the relevant details and presented new ideas and devices together with all the necessary background information. Although not all the possible topics can be treated within a single volume, the aim of the book is to stimulate physicists, both pure and applied, working on optical problems, and engineers engaged in designing new equipment. The book should also serve as a guide to all who are interested in advanced optical techniques.

In order to ensure that each field was covered by an author with first-hand knowledge of it, Professor van Heel invited outside contributions, though he himself wrote two chapters dealing with his own special interests: alignment and the use of spheres.

Unfortunately these plans were interrupted tragically by his sudden death on 18th May, 1966. We have lost in him a friend as well as an able, prominent and enthusiastic physicist.

I was asked to co-ordinate some of the work which remained to be done; Professor van Heel's staff and North-Holland Publishing Company together performed the greater part of this task.

I am convinced that the volume will constitute an invaluable aid for all who are concerned with optical problems, both in research and in the application thereof.

B. S. BLAISSE

Delft, April 1967

Technological University, Delft

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CHAPTER 1

PRECISION MEASUREMENTS

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1. Introduction

The development of precision measurements has remained one of the outstanding efforts of scientific research. The term means measurements beyond the realm of ordinary measurements such at those made with a scale and protractor. The Egyptians made precision measurements as early as 4700 B.C. Proof of this currently exists in the geometrical regularity of the great pyramids of Khufu at Gizah.

Precision measurements do not require rigidly defined units. The cubit, used by the Egyptians, is defined as the distance from the elbow to the tip of the middle finger. Obviously the Egyptians must have transferred this unit from some person's arm to a stable scale that was either used throughout the pyramid project or distance measured with it was used to calibrate other standard scales. When multiple measurements are combined, as in modern engineering developments, there must be consistency between the units used and the standards of reference must be stable. The need for consistency between standards used by different countries has led to the establishment of international standards. The need for high precision had led to the selection of standards that have the highest available stability and the values of the standards are specified to a degree of accuracy that is comparable with the most precise measurements that are currently anticipated.

2. Reliability of measurements

If the result of any measurement is to be of value it is necessary to have some numerical estimate or measure of its reliability. The results of a measurement may be rendered almost useless, unless the investigator is able to state the degree of reliance which can be placed upon it. A brief description of the several types of errors that enter into measurements is given by WILSON [1952].

A single measurement can have no precision value. The precision of a measurement depends upon the deviations of several measurements from the mean of these several measurements. The precision measure or reliability of a result is increased appreciably by increasing the number of individual measurements. In general, five measurements yield a precision that is approximately twice that for two observations. However, it does not pay to increase the number of observations beyond a certain limit, say ten or fifteen, as the time and labor involved soon become excessive, with very little increase in the precision.

3. Units and standards

The fundamental quantities used in most optical measurements are length, angle, time (or frequency) and intensity. The meter is defined as 1 650 763.73 wavelengths in vacuum of the transition $2P_{10}$–$5d_5$ in Kr^{86}. The inch is defined as 25.4 millimeters. The length of most reference standards of length is given either in inches or in millimeters. The basic angle (360 degrees) is not an accepted unit. This angle is basic to all angular measurements and is the angle swept over by a straight line while rotating in a plane, about a point in this plane, and making one revolution. There are two units of angle – the degree, which is subdivided into minutes and seconds, and the radian. There are 2π radians or 360 degrees in the basic angle. Most of the standard reference angles are given in degrees and/or subdivisions of it. The unit of time usually used for optical measurements is the second which is 1/31 556 925.974 7 of the tropical year at 12^h E.T. of January 0, 1900. The units of length and time are based on relatively invariant natural quantities. The basic angle is a geometrical concept. The unit for intensity is an arbitrarily chosen unit.

4. Precision optical instruments

Optical instruments for precision measurements may be simple or complex. The basic requirement for most precision optical instruments is that they be made with high quality optics that have been assembled accurately. A poorly aligned system of precision optical elements would not be suitable for a precision instrument. When the instrument depends upon mechanical parts, these parts should be made and adjusted with the same care used in making and mounting the optical elements. Similarly the scales, indexing heads and reference lines that are used in optical instruments must be made with a high degree of accuracy. The precision with which an image of a line can be adjusted to coincide with a reference mark depends as much on the quality of the mark as it does on the quality of the image. The image quality depends upon the quality of the optics and sharpness of the object.

A precision optical instrument should be handled with care. Mechanical and thermal shocks should be avoided. When the instrument is not in use it should be protected from dust, fumes and humidity as far as covers and environmental storage places will permit. Optical surfaces should be cleaned only when this results in significant improvement in its performance.

5. Operation of precision instruments

An instrument will not yield precision results unless it is adjusted precisely and due consideration is given to environmental conditions. Cleanliness and gentleness are essential in making precise adjustments. Small temperature gradients are detrimental to the image forming properties of optical elements because of the relatively large coefficient of thermal expansion in most optical glasses. The shape and size of scales are adversely affected by both temperatures and thermal gradients.

A precision built and properly adjusted instrument will yield best results only when used by a skilled operator. The operator must therefore become familiar with the instrument and its operation. This can only be attained by experience acquired during a period of training.

6. Index of refraction

6.1. GASES

The refractive index of a gas is most precisely measured by interferometry. The interferometers most frequently used for this purpose are the Jamin interferometer and the Rayleigh refractometer. These instruments are described in many textbooks (e.g. JENKINS and WHITE [1957]) on optics. In the Rayleigh refractometer, shown in fig. 1, monochromatic light from a slit source S_1 is collimated by the lens L_1 and

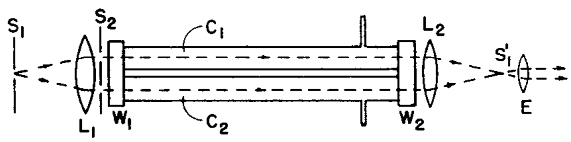

Fig. 1. Rayleigh refractometer.

divided into two beams by two relatively broad slits in the screen S_2. These two slits should be parallel to the slit source. The two gas chambers, C_1 and C_2, are of equal length and are sealed by cementing two glass windows, W_1 and W_2, to their ends. The lens L_2 forms an image of S_1 at S_1'. Fringes of interference are observed in S_1' by means of the eyepiece E. The gas chambers are connected by means of gas lines, with suitable valves, to a pump that permits evacuation of either or both chambers.

The procedure for obtaining the refractive index of a gas is to evacuate both chambers, C_1 and C_2; set the cross-hair of the eyepiece on the zero order of interference; slowly fill one chamber with the gas to the desired temperature and pressure while observing the change in the order of interference, ΔN. The refractive index, n, is computed from the formula $\lambda \cdot \Delta N = L(n-1)$ where λ is the wavelength of the light and L is the length of the gas chambers.

The sensitivity of the test, assuming the temperature and pressure of the gas to be known, is proportional to the length of the gas chambers. The choice for an optimum value for L depends upon the accuracy with which the temperature, pressure and the fractional part of ΔN can be measured. The integral part of ΔN is assumed to be free from error and the errors in λ and pressure are assumed to be negligible, because these are easy to obtain in practice.

In general, the uncertainty in L varies directly with the error in temperature whereas the percentage error in ΔN decreases with increase in L. An optimum choice for L is one that tends to equalize the error due to temperature and the error in reading ΔN.

The index of most gases, in the range of visible wavelengths, is usually known to an approximation that permits the use of the 'method of exact fractions' (PEROT and FABRY [1899]) for ascertaining the integral part of ΔN. Even when ΔN is obtained by counting fringes it is advisable to check the integral part by applying the method of exact fractions to the values computed for three or more wavelengths. If the value of ΔN is known for one wavelength λ_1, the corresponding value for any other wavelength

λ_2 may be obtained by observing the fractional part of ΔN_2 and computing the integral part, which is the integer that most closely approximates $\Delta N_1 \lambda_1/\lambda_2$.

The modified Michelson interferometer, shown in fig. 2a, is more sensitive than a Rayleigh refractometer of the same length chamber because the light path in the

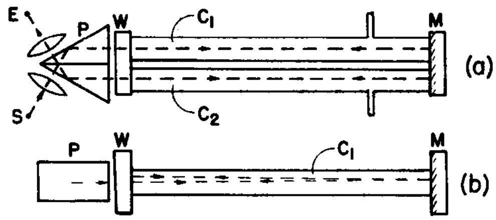

Fig. 2. Gas interferometer. (a) Section normal to the dividing plane. (b) Section parallel to the dividing plane.

gas chambers is doubled by reflection of the light. This interferometer pemits more light because a larger source can be used. The fringes are localized near the mirror, M, and may be observed without an eyepiece. However, a low power telescope with micrometer eyepiece is preferred. The window, W, should have a 20 to 30 minute wedge between its faces, and the vertex of this wedge should be normal to the beam dividing plane of the Köster's prism P (Saunders [1957]), so as to eliminate unwanted reflected light.

If the pressure and temperature of the gas and the length of the gas chambers are known to a higher accuracy than ΔN, then improved accuracy can be obtained either by increasing the length of the chambers or by using multiple reflection in the chambers. The effective length of the gas chamber may be doubled by having a small (three or four minute) wedge between M and the inner surface of W and having this surface of W coated to reflect and transmit equal amounts of light. See fig. 2b. The prism is adjusted so that the two collimated beam of light, after being first reflected from M, is incident normally onto W, from which it returns to M and then to the prism. A suitable diaphragm, located in the focal plane of the collector lens, permits isolation of all undesirable beams of light; one of which is that reflected from the base of the prism.

6.2. LOW ABSORBING MATERIALS

The minimum deviation method of measuring the refractive index of solids and liquids remains the most practical for precision tests. The principle of this method is described in many textbooks on optics. An accuracy approximating $\pm 2 \times 10^{-6}$ can readily be achieved, in the range of visible wavelengths, if certain goniometrical requirements (Tilton [1929]) are fulfilled and proper techniques (Tilton [1931, 1935]) are adhered to.

This method requires that solid materials be made into the form of prisms with two polished faces and an appropriate included angle which, for highest accuracy, depends upon the refractive index of the material. Liquids may be measured by placing them in prismatic cells that have two plane-parallel windows, with the appropriate angle between them.

6.3. HIGH ABSORBING MATERIALS

The refractive index of liquids in spectral regions of high absorption may be measured by placing a thin layer of the liquid between two identical prisms, as shown in fig. 3. The index of refraction and angles of the prisms may be measured by means of the minimum deviation method. The index of the prisms must exceed that of the liquid. The optimum angles of the prism (fig. 3) are: $\alpha = 90°$ and $\beta \approx \arcsin(n/n')$ where

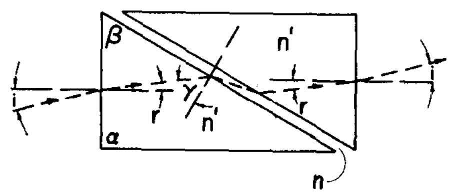

Fig. 3. Prisms for measuring refractive index of high absorption materials.

n and n' are the indices of the liquid and prisms, respectively. Measurement is made by allowing a collimated beam of monochromatic light to fall on the entrance face and measuring the angle of incidence, i, that corresponds to the critical angle of incidence of the light on the glass–liquid boundary. The index of the liquid may be computed by means of the formulas (VINCENT-GEISSE and LECOMTE [1962])

$$\sin i = n' \sin r,$$

$$n = n' \sin \gamma = n' \sin(\beta - r).$$

Thin parallel sheets (or plates) of high absorbing solids may also be measured by this method if a suitable liquid of known index is used between the prisms and sample. The precision obtained with this method is approximately $\pm 1 \times 10^{-3}$.

6.4. OPAQUE MATERIALS

Neither of the above methods permits measurement of the index of refraction of materials in regions of very high absorption, such as metals. Observation must be made by reflection if precision is to be obtained. Methods for measuring the optical constants of solids and liquids are described by VINCENT-GEISSE and LECOMTE [1962]. An ellipsometer, such as that described by ROTHEN [1945], is usually used for studying the optical properties of metals and thin films. A good discussion on techniques in polarimetric measurements is given by WINTERBOTTOM [1946].

7. Wavelength of light in air

Precise measurement of length by interferometry requires that the wavelength of the light be accurately known. If such measurements are to be made in air they should include a measurement of the wavelength of the light under the same conditions. Engelhard [1957] enclosed a wavelength and a length measuring interferometer into a single unit. The NBS wavelength interferometer (Saunders [1963a]) is a separate unit and is designed to measure the wavelength of light under the ambient conditions of a gage testing laboratory.

The wavelength interferometer developed at NBS is identical to the gas interferometer shown in fig. 2 except that one chamber is open to ambient conditions. One component beam of light traverses a one meter space two times. This space is either evacuated or filled with standard air. The other component beam traverses an equal space filled with ambient air. The wavelength of light is accurately known for both vacuum and standard air (Barrell [1951]). If the geometrical path length and the order of interference is known for any spectral line, the corresponding wavelength is known in the enclosed gas chamber. If the enclosed chamber contains standard air, the order will always be relatively small. A calibrated optical wedge, located between the window and the prism, may be used for reducing the order to zero. The fringe count, as the order of interference is reduced to zero, gives the order and consequently the difference in wavelength between ambient and standard air. The zero order of interference is readily identified by replacing the monochromatic light source with a white light source.

8. Testing optical flats

An optical flat is a surface that approximates a plane. Attempts have been made to produce natural surfaces that could be used for master references planes. Barrell and Marriner [1948], and Von Bünnagel [1956] have produced liquid surfaces of high quality over small areas. An undeformed liquid surface approximates the curvature of the earth. Since the curvature is known corrections can be applied for correcting these to plane surfaces. These liquid surfaces, however, have not been satisfactory for testing large optical flats.

Optical flats are usually tested by measuring the separation of two surfaces placed close together and nearly parallel to each other. Fig. 4 shows an arrangement that permits the comparison of two optical surfaces. The upper plate, M_1, must be transparent, with both of its surfaces polished for transmitting the light. Usually the upper surface of the lower plate, M_2, is the unknown surface to be tested against the master surface of M_1. Interference is obtained by the combination of light reflected from the two adjacent surfaces of M_1 and M_2.

If the shape of the lower surface of M_1 is known from previous tests it can be considered a primary or secondary standard, depending upon the method used for calibrating it. If the accuracy of its shape depends directly upon the accuracy of the surface with which it was compared then it is a secondary standard. The accuracy of a primary standard flat does not depend directly upon the accuracy of the surfaces used for its calibration. Furthermore, two additional surfaces must be used to calibrate