PHYSICAL OPTICS AND LIGHT MEASUREMENTS

Edited by

DANIEL MALACARA

VOLUME 26

METHODS OF EXPERIMENTAL PHYSICS

Treatise Editors:

ROBERT CELOTTA

JUDAH LEVINE

Physical Optics and Light Measurements

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Daniel Malacara

Centro de Investigaciones en Optica
Leon, Gto
Mexico

ACADEMIC PRESS, INC.
Harcourt Brace Jovanovich, Publishers

Boston San Diego New York
Berkeley London Sydney
Tokyo Toronto

ACADEMIC PRESS, INC.
1250 Sixth Avenue, San Diego, CA 92101

United Kingdom Edition published by
ACADEMIC PRESS INC. (LONDON) LTD.
24-28 Oval Road, London NW1 7DX

Library of Congress Cataloging-in-Publication Data

Physical optics and light measurements.
(Methods of experimental physics; v. 26)
Includes bibliographies and index.
1. Optics, Physical. 2. Optical measurements. I. Malacara, Daniel, Date–
II. Series.
QC395.2.P49 1988 535'.2 88-978
ISBN 0-12-475971-8

Printed in the United States of America
88 89 90 91 9 8 7 6 5 4 3 2 1

Methods of Experimental Physics

VOLUME 26

PHYSICAL OPTICS AND LIGHT MEASUREMENTS

METHODS OF EXPERIMENTAL PHYSICS

Robert Celotta and Judah Levine, *Editors-in-Chief*

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PREFACE

Two books covering the field of modern optics have been prepared in this series "Methods of Experimental Physics", separating the material into two parts, one with the title "Geometrical and Instrumental Optics", and the other with the title "Physical Optics and Light Measurements".

The purpose of these books is to help the scientist or engineer who is not a specialist in optics to understand the main principles involved in optical instrumentation and experimental optics.

Our main intent is to provide the reader with some of the interdisciplinary understanding that is so essential in modern instrument design, development, and manufacture. Coherent optical processing and holography are also considered, since they play a very important role in contemporary optical instrumentation. Radiometry, detectors, and charge coupled imaging devices are also described in these volumes, because of their great practical importance in modern optics. Basic and theoretical optics, like laser physics, nonlinear optics and spectroscopy are not described, however, because they are not normally considered relevant to optical instrumentation.

In this volume, "Physical Optics and Light Measurements", Chapter One describes the theory and applications of interference and interferometers. Chapter Two studies diffraction, its basic theoretical fundamentals, and some practical applications. Polarized light and its uses are considered in Chapter Three. Holography and holographic methods are studied in detail in Chapter Four. The photometric and radiometric principles are covered in Chapter Five. Finally, Chapter Six considers detectors.

There might be some overlapping of topics covered in different chapters, but this is desirable, since the points of view of different authors, treating different subjects, may be quite instructive and useful for a better understanding of the material.

This book has been the result of the efforts of many people. Professor H. W. Palmer started this project and spent many fruitful hours on it. Unfortunately, he did not have the time to finish his editorial work due to previous important commitments. I would like to express my great appreciation of and thanks to Professor Palmer and all of the authors, without whom this book could never have been finished. I also thank Dr. R. E. Hopkins and many friends and colleagues for their help and encouragement. Finally, I appreciate the great understanding of my family, mainly my wife Isabel, for the many hours taken away from them during the preparation of these books.

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1. INTERFERENCE

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1.1. Introduction

The luminous phenomenon called interference is a direct consequence of the wave nature of light. Using the interference of light, we can make interferometers, which are instruments that use this phenomenon to measure very accurately many physical parameters. The general subject of interference has been treated extensively in many classical textbooks on optics like those by Born and Wolf,[1] Cook,[2] Françon,[3] Candler,[4] Steel,[5] and Tolansky.[6] There are also special chapters on the subject of interference in many advanced books like those by Baird,[7] Baird and Hanes,[8] and Dyson,[9] and others. This chapter describes very briefly the interference phenomenon and some interferometers. Special emphasis is placed on the applications of these useful instruments, which have played a very important role in the development of physics due to their extremely high accuracy.

1.1.1. Methods to Obtain Interference Fringes

To obtain interference fringes, the phases of the two interfering waves must be synchronized, that is, they must be coherent. Before the advent of lasers, this was possible only if both waves originated from the same light source. In order to produce two waves from a single source, we must have either a division of the wave front or division of its amplitude.

Division of Wave Front. This class of interference is produced when the two interfering wave fronts are taken from different portions of the original wave front. The typical examples are Young's experiment, the Fresnel biprism, and Lloyd's mirror, but there are many others.

Young's double-slit experiment is performed as shown in Fig. 1. The lenses are not strictly necessary, but their addition makes the theory easier. The light source S must be either a very narrow slit or a point, and lens L collimates the light to obtain an approximately flat wave front. Normally,

METHODS OF EXPERIMENTAL PHYSICS
Vol. 26

ISBN 0-12-475971-8

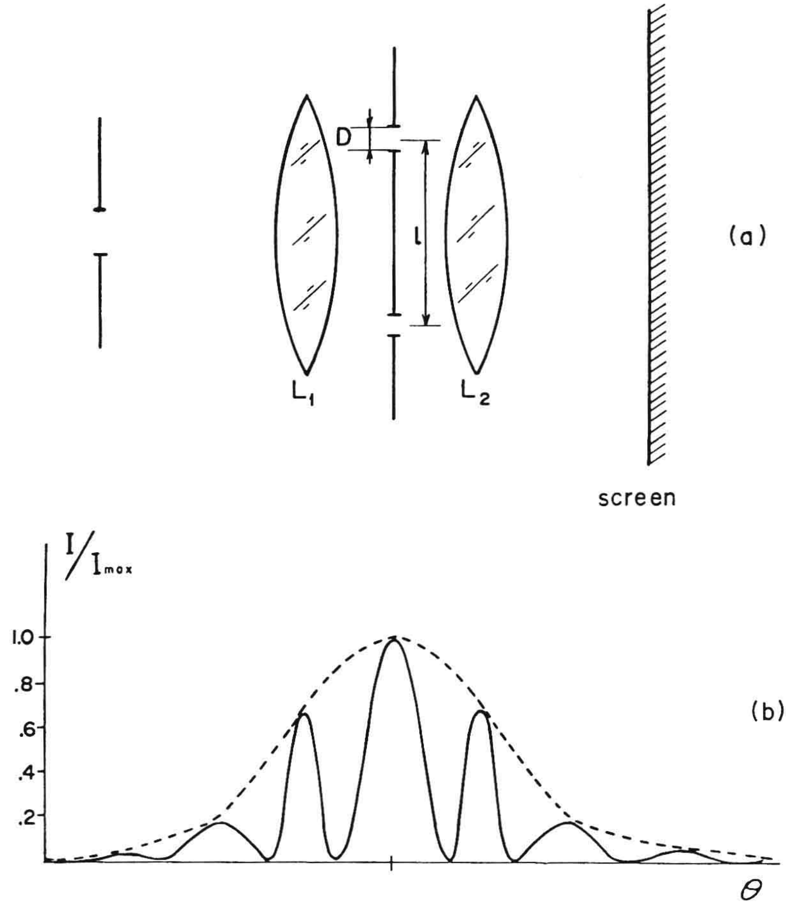

FIG. 1. Young's experiment. (a) Experimental arrangement and (b) Diffraction pattern.

the interference pattern would be observed at infinity, but lens L serves to bring the pattern closer over the screen. It can be found in almost any good textbook on optics[1] that the interference pattern is given by

$$I = I_{\max} \cos^2\left\{\frac{\pi - l}{\lambda}\sin\theta\right\} \frac{\sin\left\{\dfrac{\pi D}{\lambda}\sin\theta\right\}}{\dfrac{\pi D}{\lambda}\sin\theta}, \tag{1.1}$$

where $I_{\max}$ is the irradiance at the center of the pattern, and θ is the angular deviation from the optical axis. This radiation pattern also appears with

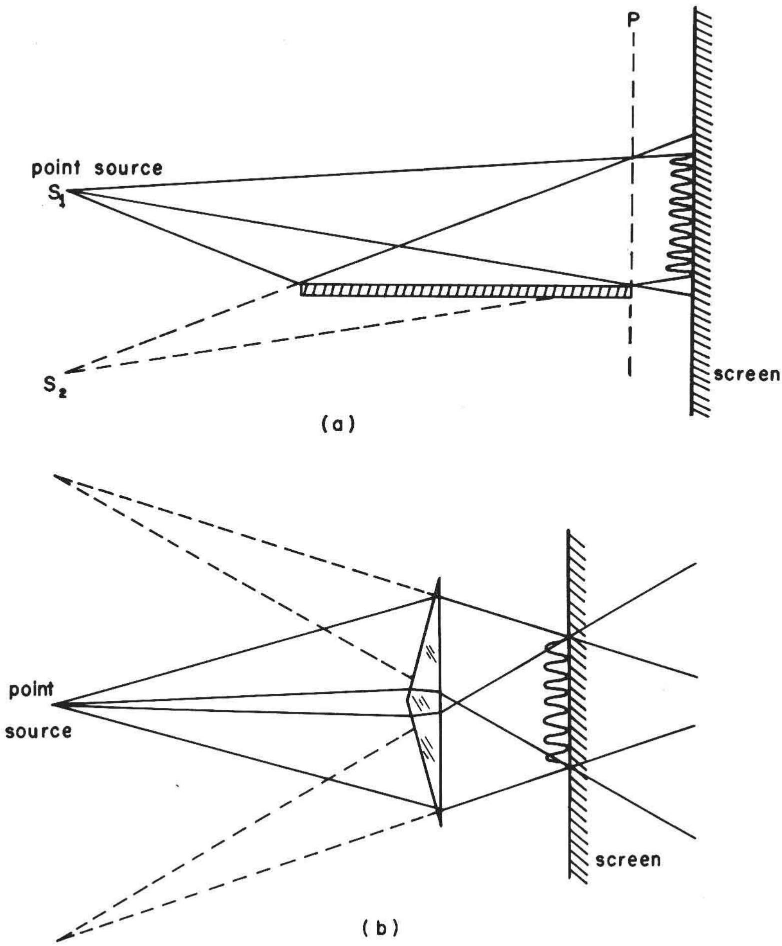

FIG. 2. (a) Lloyd's mirror and (b) Fresnel biprism.

dipole antennas and radio waves. The total width of the central maximum is given by $\sin\theta = \lambda / l$.

The Fresnel biprism and Lloyd's mirror also produce interference fringes by division of the wave front, as shown in Fig. 2. If two waves are to interfere producing fringes with good contrast, the polarization states of both waves must be the same. This condition is always satisfied in the Fresnel biprism. However, in Lloyd's system, only one beam is reflected. Therefore, the reflection coefficients and the phase shifts under reflection must remain nearly constant over the range of incident angles used. This is possible only near grazing incidence.

A second reason for using grazing incidence in the Lloyd system is that the spacing between fringes decreases rapidly as the separation between the virtual sources S_1 and S_2 is increased. The sources must be quite close to each other to make fringes visible, and this is possible only near grazing incidence. If the screen in the Lloyd system is placed near the edge of the mirror, we can observe that a dark fringe appears at this edge. This happens because there is a phase shift upon reflection with grazing incidence. Wolfe and Eisen[10] have studied the coherence requirements in Lloyd's mirrors.

Division of Amplitude. This class of interference occurs when both interfering beams are obtained by division of the amplitude of the original wave front by means of a partially reflecting optical surface. Then, both beams travel different paths, and interference occurs when they are recombined. Typical examples are Newton rings and the Michelson interferometer described in the next section.

1.1.2. Classification of Interference Fringes

A classification for interference fringes can be made according to the way they are observed, namely, fringes of equal thickness and fringes of equal inclination.

Fringes of Equal Thickness. Each fringe represents the locus of all points in which two optical surfaces (or wave fronts) have a constant separation. This is much better understood by means of the following example.

Consider the optical arrangement in Fig. 3 where the flat or convex surface of one lens is placed against the flat surface of another lens. Monochromatic light enters the first lens and impinges upon the second surface from which

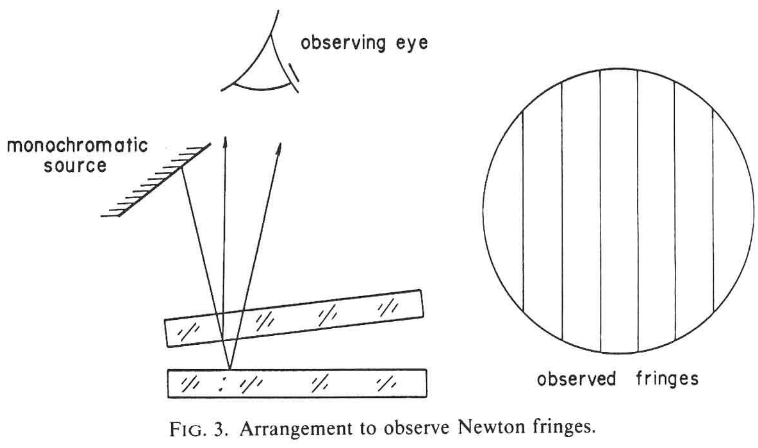

FIG. 3. Arrangement to observe Newton fringes.

some of the light is reflected. Some of the light that goes through the first lens is reflected from the upper flat surface of the second lens. The two reflected beams interfere constructively when the phase difference is an integral multiple of 2π. We can see that the optical path difference is twice the surface separation. If one of the surfaces is spherical, each fringe is a ring that represents the locus of points with equal surface separation. These circular fringes, also called *Newton rings*, are a particular case of fringes of equal thickness.

Fringes of Equal Inclination. In this case, each fringe is the locus of points in the field of view with the same angle of the incidence θ at the interferometer. As an example, let us consider two parallel reflecting surfaces as in Fig. 4. As in the previous example, the two interfering beams are produced by division of amplitude. Fringes of equal thickness cannot be formed because the optical path difference (OPD) is the same for the entire field. One way to change the phase difference and hence to observe fringes is to introduce a range of angles of incidence by using an extended light source.

Circular fringes are observed with an angular radius θ given by

$$\cos\theta = \frac{m\lambda}{2d}, \qquad (1.2)$$

where m is an integer smaller than or equal to $2d/\lambda$.

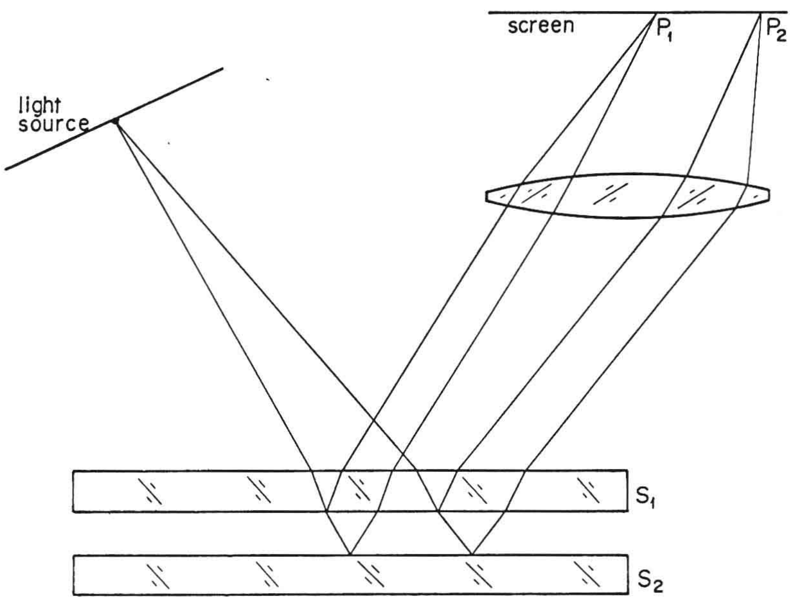

FIG. 4. Arrangement to produce fringes of equal inclination.