OPTICAL RADIATION MEASUREMENTS

Volume 4

PHYSICAL DETECTORS OF OPTICAL RADIATION

W RUDDE

OPTICAL RADIATION MEASUREMENTS

Volume 4

PHYSICAL DETECTORS OF OPTICAL RADIATION

W. BUDDE
Division of Physics
National Research Council
Ottawa, Canada

1983

ACADEMIC PRESS
A Subsidiary of Harcourt Brace Jovanovich, Publishers
New York London
Paris San Diego San Francisco São Paulo Sydney Tokyo Toronto

ACADEMIC PRESS, INC.
111 Fifth Avenue, New York, New York 10003

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

Library of Congress Cataloging in Publication Data

Budde, Wolfgang
Physical detectors of optical radiation.

(Optical radiation measurements ; v. 4)
Includes bibliographical references and index.
1. Radiation--Instruments. 2. Radiation--Measurement. I. Title. II. Series: Optical radiation measurements (Academic Press) ; v. 4.
QC475.067 vol. 4 535'.028'7s [535'.028'7] 82-18428
ISBN 0-12-304904-0

PRINTED IN THE UNITED STATES OF AMERICA

83 84 85 86 9 8 7 6 5 4 3 2 1

Foreword

This volume in the treatise "Optical Radiation Measurements" is devoted to photodetectors. Photodetectors are used in radiometry to produce a signal in response to irradiation by light energy. The detectors described in this volume produce an electronic signal or provide electronic modulation by one of two primary detection mechanisms: the photoelectric effect and the thermal effect. The photoelectric effect is a mechanism by which a photon of light is absorbed and excites an electron to a higher energy state. Detectors of this kind are known as photon detectors. The thermal effect is a mechanism in which absorbed radiation induces molecular motion to cause an increase in the temperature of the absorbing medium. Detectors of this kind are known as thermal detectors. The conversion processes of thermal detectors include (a) changes in resistance, (b) production of a thermoelectric voltage, (c) alteration of capacitance, and (d) heat transfer to another medium in which a contact thermocouple is used to generate a voltage. Photon detectors, on the other hand, generate or change an electric signal by (a) an external photoelectric effect in which a photoelectron is emitted by a cathode and captured by a second electrode, as in phototubes and photomultipliers, or (b) by an internal photoelectric effect in which an electron is excited to move from one energy level to another, higher, level, such as in photoconductors and both semiconductor and avalanche photodiodes. In general, the spectral responsiveness of photon detectors is selective, being determined largely by the chemico-physical composition of the materials used to absorb photons, while the spectral responsiveness of thermal detectors tends to be nonselective. Detectors of both kinds differ in their detectivity or ability to respond to light. They also differ in their capacity to produce and transfer random variations in electron flow called noise. These different kinds of detectors are each more or less appropriate for different applications. The purpose of this volume is to provide the reader with information about detectors—the ways in which they operate and their characteristics—so that measurements of optical radiations can be effected by the device and technique that is best suited to a particular task. In addition, the author of this volume has drawn upon his many years experience in working with detectors to provide useful insights and practical methods for accurate and precise measurements of light. In short, we hope that this volume will help the reader to understand photodetectors in terms of how they work and what they do and to gain an appreciation for what considerations should go into practical attempts to measure optical radiations with the aid of photodetectors.

FRANC GRUM
C. JAMES BARTLESON

Preface

This volume of the treatise "Optical Radiation Measurements" deals with physical detectors of radiation. It provides useful information about the physical characteristics of detectors and their application to measurement of optical radiation. The volume is directed to the practitioners of light measurement and to designers of instruments for measuring light. It should also be useful to students of colorimetry, photometry, and radiometry. The text brings together in one volume information about many kinds of physical detectors; it details both advantages and disadvantages of various detectors. We believe that this volume provides information that supplements the other volumes in the treatise, and sets forth guidance for selection and use of physical detectors of optical radiation.

Acknowledgments

The stimulus for this book came from F. Grum and C. J. Bartleson, and their confidence in my ability, their helpful discussions, and their and the publisher's patience in waiting for the delivery of the manuscript are indeed greatly appreciated. It is my sincere hope that this material complies with their standards and expectations.

Much valuable information was received from many sources but particularly from colleagues at the National Research Council. L. P. Boivin contributed greatly to the chapter on thermal receivers, offering his expertise in absolute radiometry, and he suggested the section on continuous-wave laser measurements. C. X. Dodd performed many experiments and contributed a wealth of data that were either cited when available in published papers or presented here as "NRC measurements." D. Gignac gave valuable advice on detector electronics and optical attachments for spectral and geometrical matching. A. A. Gaertner, A. R. Robertson, and N. Rowell helped in many valuable discussions.

The supply of technical data and application notes from many manufacturers is highly appreciated. The new (1980) edition of the "RCA Photomultiplier Handbook," the Philips application books "Photomultipliers" and "Fast Response Photomultipliers," the La Radiotechnique-Compelec (RTC) book "Photomultiplicateurs" (in French) and the application notes on Si photodiodes prepared by EG & G Electro Optics and United Detector Technology (UDT) are only a few examples of the valuable books and pamphlets received and often consulted.

The typing of the manuscript was expertly done by Paulette Desloges and Gloria Dumoulin and most of the drawings were done by Annelore Thompson with valuable advice from Michal Kotler. Mary van Buskirk, Trudy Leclerc, and Morna Tuttle from the Physics Division Library provided many journals and books for reference. All this help, given untiringly, with patience and always with a smile, is appreciated with sincere thanks.

The benevolent interest in and support of this project by Dr. P. A. Redhead, Director of the Division of Physics, and by Dr. G. W. Wyszecki is gratefully acknowledged.

It is a pleasure to express my thanks for the valuable advice and friendly cooperation of various members of the staff of Academic Press. Their expert guidance in the final stages of the preparation of the manuscript is greatly appreciated.

Finally I wish to acknowledge the help I received from my wife. It takes much patience, understanding, and sacrifice to help an author through the period of delivery. She gave this support generously and wholeheartedly.

WOLFGANG BUDDE

Contents

1

Introduction

Photon detectors and thermal detectors are used in radiometry to produce an electrical signal in response to radiant energy.

The purpose of this book is to present those operating considerations and facts on detectors of optical radiation that are important for the person who, in the course of a more or less complex experiment, has to measure some optical radiation and is looking for the most suitable detector. The book may also be useful for the industrial designer who intends to develop an instrument (a radiometer, a photometer, or a colorimeter) for series production. Consequently the emphasis is on the final properties of radiation detectors and on what they are doing, not on why and how they are doing it. In looking at detectors from this viewpoint, preference is given to facts about those detectors that are commercially available. Only little space will be devoted to the physical processes on which the conversion from an incident radiant flux to a measurable signal is based. The reader wishing to understand these processes better is advised to consult the relevant literature: Sommer (1968), Hudson and Hudson (1975), Keyes (1977), Kingston (1978), and Grum and Becherer (1979, Chapter 6). This is not a book for a person who wants to design a detector or improve the performance of an existing type by design changes. It is for the person who wants to use available detectors sensibly and with some knowledge of their capabilities, pitfalls, and limitations.

Chapter 2 lists the most important terms on detectors and their operation, together with the definitions of the Commission Internationale de l'Eclairage (CIE) (1970). A simple classification of detectors for the purposes of this book is included. In Chapter 3 a more detailed discussion of the most important detector properties (responsivity, detectivity, linearity, and time constants) is given, together with some presentation of the methods for their determination. The next three chapters present facts and data on thermal detectors (Chapter 4), photoemissive detectors (Chapter 5), and semiconductor detectors (Chapter 6). In Chapter 7 optical attachments such as filters for modifying the spectral responsivity curve, diffusers for achieving a desired angular responsivity distribution, and neutral attenuates are discussed. An appendix presents some comparative tables.

In all the chapters and the Appendixes typical data for the properties and the behavior of detectors are given. Such data are often taken from catalogs, specification sheets, or manufacturers' application notes. It is emphasized that such data are quoted to illustrate a point, a behavior, a characteristic, not to compare products from different manufacturers. Such data are intended to give the reader an idea of the magnitude of an effect, of an achievable or useful level of a quantity, and of the pitfalls and error sources that must be taken into account and possibly eliminated by proper corrective measures. Consequently using a manufacturer's name or its data for a specific detector model implies no preference for the manufacturer or a judgment on the quality of its products. Similarly, omitting a manufacturer's name is not intentional and should not be taken as adverse judgment. For the selection of a detector for a specific application, this book may give general guidance on a suitable type of detector, but for actual specifications, catalogs or compilations such as the semiannual "Optoelectronics D.A.T.A. Book" or the "Annual Laser Focus Buyers Guide" should be consulted. These compilations offer not only information on most recent products, but also names of manufacturers that still exist. Of course, even manufacturers' specifications are only typical, and for actual data on a specific detector, measurements of the relevant properties often cannot be avoided.

"Optical radiation" in this book is confined to the wavelength range 200–3000 nm, that is, the ultraviolet (but not vacuum-UV), visible, and near-infrared radiation. The radiation may be unchopped (or "continuous wave" in the language of laser techology), chopped, or pulsed.

The limitation of the wavelength range implies some restriction of the methods of measurements used with the detectors described. Several techniques and precautions used with measurements in the IR will not be considered here in detail, because the difficulties encountered in the middle- and far-IR ranges are absent for many of the detectors for the above-mentioned wavelength range. Therefore sophisticated techniques such as heterodyne detection or the use of detectors that are cooled to cryogenic temperatures will not be considered.

It is difficult for an author to avoid expanding on those aspects of the subject on which he has done extensive work. The Physics Division of the National Research Council of Canada is concerned with basic and applied research and with calibrations of primary and secondary standards. Radiation measurements, photometry, and colorimetry are the mandate of the Optics Section, where the calibration of all types of detectors, their spectral responsivity, linearity, angular responsivity, etc., is a major project. Being closely involved with this work may cause an uneven distribution of the treatment of various details, and therefore this book may not satisfy all demands. For such overemphasis on one side or omissions on the other, apologies are offered.

It may be mentioned here that previously unpublished results from the many special investigations, made in the course of our work, will be presented occasionally. Such graphs or tables will be marked as "NRC measurements."

REFERENCES

Commission Internationale de l'Eclairage (CIE) (1970). "International Lighting Vocabulary." Publ. No. 17. CIE, Paris.

Grum, F., and Becherer, R. J. (1979). "Optical Radiation Measurements," Vol. 1. Academic Press, New York.

Hudson, R. D., and Hudson, J. W. (1975). "Infrared Detectors." Dowden, Hutchinson & Ross, Stroudsburg, Pennsylvania.

Keyes, R. J. (1977). "Optical and Infrared Detectors." Springer-Verlag, Berlin and New York.

Kingston, R. H. (1978). "Detection of Optical and Infrared Radiation." Springer-Verlag, Berlin and New York.

Sommer, A. H. (1968). "Photoemissive Materials: Preparation, Properties, Uses." Wiley, New York.

2

Terminology

In this chapter the terminology pertaining to radiation detectors, their operation, and radiation-detection processes is presented. An attempt will be made to adhere to the terminology proposed by the CIE. At the time of this writing, however, a new edition of the CIE vocabulary is in preparation. Many existing terms have been changed or different wordings of their definitions have been suggested and many new terms have been proposed. Every effort will be made to present the most up-to-date terms and definitions according to these proposals. However, the reader is reminded that these are not final and that changes may still occur.

Besides these terms, several other terms that were not considered by the CIE will be defined here. They will be used because they describe important properties of detectors.

Some of these definitions have already been presented in Vol. 1 of this treatise (Grum and Becherer, 1979). They will be repeated here to present a comprehensive set.

In this chapter the CIE definitions and related notes are presented in quotation marks. There are additional explanations, however, which are not part of the CIE definition. The terms for the most important properties of detectors (responsivity, detectivity, linearity, and response time) are discussed in considerably more detail in Chapter 3.

2.1 TERMS RELATED TO TYPES OF DETECTORS

2.1.1 Detector (of Optical Radiation)

"Device in which incident optical radiation produces a measurable physical effect."

This is a very general term referring to any measurable physical effect, which may be an electrical signal (see next definition); a temperature increase (see "thermal detector"); the heating and expansion of a gas, a process used in the Golay detector; or a heating of a liquid as used in calorimeters.

2.1.2 Photoelectric Detector

"A detector of optical radiation which utilizes the interaction between radiation and matter resulting in the absorption of photons and the liberation of electrons from their initial states, excluding electrical phenomena caused by temperature changes."

This type of detector is used mostly for practical field measurements of optical radiation. It comprises the photoemissive and the semiconductor detectors.

2.1.3 Photo(emissive) Cell, Phototube

"A photoelectric detector which utilizes emission of electrons caused by optical radiation."

2.1.4 Photomultiplier

"A photoelectric detector comprising a photocathode and one or more stages of electron multiplication using secondary emission electrodes (dynodes) between cathode and anode.

"*Note:* In some cases discrete dynodes are replaced by an electron multiplier of continuous structure, in general tubular."

The photoelectric effect in a photomultiplier is, of course, identical to that of the photocell. The dynode structure provides an amplification or gain of many decades.

2.1.5 Photoresistor, Photoconductive Cell

"A photoelectric detector which utilizes a change of resistivity under the action of optical radiation."

2.1.6 Photoelement, Photovoltaic Detector

"A photoelectric detector in which absorbed radiation produces an electromotive force."

2.1.7 Photodiode

"A photoelectric detector in which absorption of radiation in the neighbourhood of a *p–n* junction between two semiconductors, or between a semiconductor and a metal, produces a change of resistance for current flowing in one direction.

"*Note 1:* Photodiodes are mostly used in series with a bias emf, but some may also be used as photovoltaic detectors.

"*Note 2:* Some photodiodes, called avalanche photodiodes, can be operated with a bias exceeding the breakdown voltage so that each electron excited into the conduction band results in a pulse of electrons at the output."

This definition includes, of course, *n–p* junction diodes and *p–i–n* diodes also. Note 1 appears to favor the photoconductive operation of photodiodes. However, it will be explained later (see Chapter 6) that for accurate and precise measurements of optical radiation, photovoltaic operation of photodiodes is in fact preferable.

That a photodiode may be used as a photovoltaic detector, if no bias is applied, or as a photoconductive detector, by applying a reverse bias, makes this terminology difficult. A classification and the usage proposed for this book is given in Section 2.3.

2.1.8 Phototransistor

"Photoelectric detector utilizing semiconductors in which the photoelectric effect is produced in the neighbourhood of a double *p–n* junction (*p–n–p* or *n–p–n*) which possesses amplification properties."

2.1.9 Thermal Detector of Radiation, Thermal (Radiation) Detector

"A detector of optical radiation in which a measurable physical effect is produced by the heating of the part that absorbs radiation."

It should be noted that the primary effect is the temperature increase of the radiation absorber because of the incident radiation and that various secondary effects are used to measure the temperature increase.

2.1.10 Radiation Thermocouple

"Thermal detector of radiation in which a single pair of thermovoltaic junctions is used as sensor of temperature changes."

2.1.11 (Radiation) Thermopile

"Thermal detector of radiation in which more than one pair of thermo-voltaic junctions are used as a sensor of temperature changes."

2.1.12 Bolometer

"Thermal detector of radiation in which the heating of the part that absorbs the radiation gives rise to a change in its electrical resistance."

2.1.13 Pyroelectric Detector

"Thermal detector of radiation which utilizes the temperature dependence of the spontaneous electric polarization of certain dielectric materials.

"*Note:* This definition is also extended to include materials in which a long-lived but non-spontaneous electric polarization can be included."

2.1.14 Nonselective Quantum Detector

"Detector of optical radiation whose quantum efficiency is independent of wavelength over the spectral range considered."

A distinction is necessary between a "nonselective detector" in the ordinary sense, which has a constant spectral responsivity in amperes per watt throughout the spectrum, and the nonselective quantum detector, which has a constant quantum efficiency (term 2.2.9). Details are given in Section 3.1.

2.2 TERMS RELATED TO THE OPERATION OF DETECTORS

2.2.1 Detector Input

"The radiometric or photometric quantity that a detector is being used to measure or detect.

"*Note 1:* This quantity may, for example, be radiant flux, irradiance, photon flux, photon irradiance, luminous flux, illuminance or the value of such a quantity integrated over a given period of time.

"*Note 2:* If photometric quantities are used it is recommended that the detector be corrected to a $V(\lambda)$ or $V'(\lambda)$ response."

Photometric quantities are radiometric quantities spectrally weighted by the spectral response function of the human eye (see Section 3.1.3). Internationally, the spectral response functions proposed by the CIE in 1931 and 1967 for the so-called CIE standard photometric observer have been accepted. The 1931 data are valid for a solid angle of 2°, and the 1967 data for a solid angle of 10°. These data are usually given as relative data, normalized at 555 nm with the absolute value at 555 nm being 683 lm/W. These relative values are given in Appendix B, Table 1. If a distinction between radiometric and photometric quantities is necessary, it is indicated by subscripts e (for energy related) and v (for visual), respectively.

2.2.2 Detector Output

"The physical quantity, usually electrical, yielded by a detector in response to a detector input.

"*Note:* This quantity may, for example, be current, voltage or a change in resistance."

2.2.3. Photocurrent

"That part of the output current of a photoelectric detector which is caused by incident radiation.

"Symbol: I_{ph}

"*Note:* In photomultipliers a distinction must be made between the cathode photocurrent and the anode photocurrent."

2.2.4 Dark Current

"The current flowing in a photoelectric detector in the absence of irradiation.

"Symbol: I_0"

2.2.5 Responsivity (Sensitivity)

"Quotient of the detector output (quantity Y) by the detector input (quantity X)

"Symbol: s, $s = Y/X$

"*Note 1:* If there exists a detector output (quantity Y_{w}) without irradiation and the measured total detector output is Y_{t}, the detector output (quantity Y) caused by a detector input (quantity X) is $Y = Y_{\mathrm{t}} - Y_{\mathrm{w}}$.