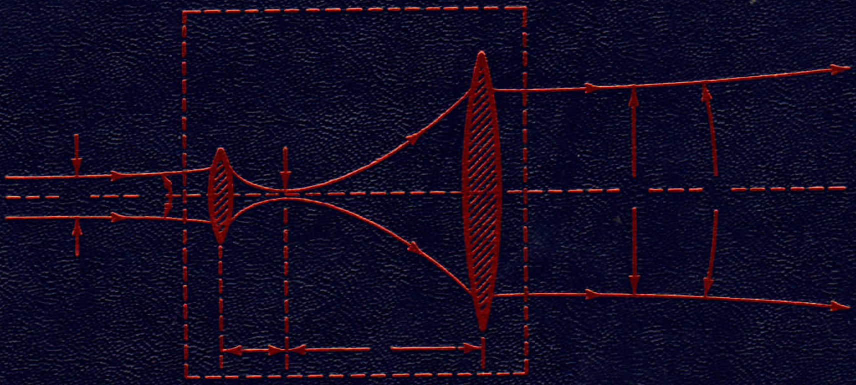
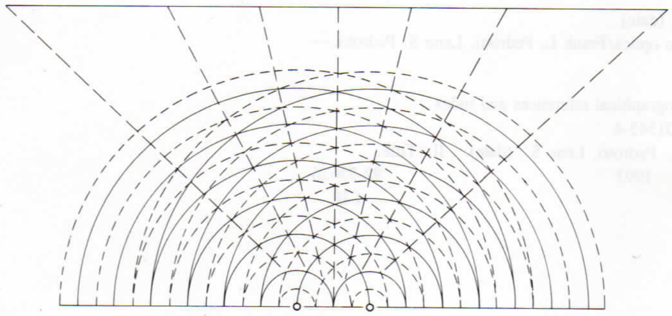
INTRODUCTION TO OPTICS

Second Edition



Frank L. Pedrotti, S.J.
Leno S. Pedrotti

IMMERVISION Ex. 2012
LG v. ImmerVision
IPR2020-00179



Second Edition

Introduction to Optics

FRANK L. PEDROTTI, S.J.
Marquette University
Milwaukee, Wisconsin
Vatican Radio,
Rome

LENO S. PEDROTTI
Center for Occupational
Research and Development
Waco, Texas
Emeritus Professor of Physics
Air Force Institute of Technology
Dayton, Ohio

Prentice Hall, Upper Saddle River, New Jersey 07458

Library of Congress Cataloging-in-Publication Data

Pedrotti, Frank L., (date)
Introduction to optics/Frank L. Pedrotti, Leno S. Pedrotti.—
2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-13-501545-6
1. Optics. I. Pedrotti, Leno S., (date). II. Title.
QC355.2.P43 1993 92-33626
535—dc20 CIP

Acquisitions Editor: *Ray Henderson*
Editorial/Production Supervision
and Interior Design: *Kathleen M. Lafferty*
Cover Designer: *Joe DiDomenico*
Prepress Buyer: *Paula Massenaro*
Manufacturing Buyer: *Lori Bulwin*
Proofreader: *Bruce D. Colegrove*

Upper Saddle River, New Jersey 07458

Printed in the United States of America

10

ISBN 0-13-501545-6

PRENTICE-HALL INTERNATIONAL (UK) LIMITED, *LONDON*
PRENTICE-HALL OF AUSTRALIA PTY. LIMITED, *SYDNEY*
PRENTICE-HALL CANADA INC., *TORONTO*
PRENTICE-HALL HISPANOAMERICANA, S.A., *MEXICO*
PRENTICE-HALL OF INDIA PRIVATE LIMITED, *NEW DELHI*
PRENTICE-HALL OF JAPAN, INC., *TOKYO*
PEARSON EDUCATION ASIA PTE. LTD., *SINGAPORE*
EDITORA PRENTICE-HALL DO BRASIL, LTDA., *RIO DE JANEIRO*

of the beam is also the radiance of the source, at the initial point of the beam, or $L_1 = L_2 = L_0$.

Suppose, referring to Figure 2-6, that we wish to know the quantity of radiant power reaching an element of area dA_2 on surface S_2 due to the source element dA_1 on surface S_1. The line joining the elemental areas, of length r_{12}, makes angles of θ_1 and θ_2 with the respective normals to the surfaces, as shown. The radiant power is $d^2\Phi_{12}$, a second-order differential because both the source and receptor are elemental areas. By Eq. (2-7) or Eq. (2-8),

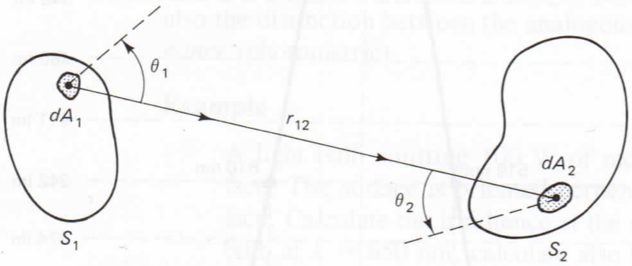


Figure 2-6 General case of the illumination of one surface by another radiating surface. Each elemental radiating area dA_1 contributes to each elemental irradiated area dA_2.

$$d^2\Phi_{12} = \frac{L\,dA_1\,dA_2 \cos\theta_1 \cos\theta_2}{r_{12}^2}$$

and the total radiant power at the entire second surface due to the entire first surface is, by integration,

$$\Phi_{12} = \int_{A_1}\int_{A_2} \frac{L \cos\theta_1 \cos\theta_2 \, dA_1\, dA_2}{r_{12}^2} \tag{2-9}$$

By adding powers rather than amplitudes in this integration, we have tacitly assumed that the radiation source emits incoherent radiation. We shall say more about coherent and incoherent radiation later.

2-3 PHOTOMETRY

Radiometry applies to the measurement of all radiant energy. *Photometry*, on the other hand, applies only to the visible portion of the optical spectrum. Whereas radiometry involves purely physical measurement, photometry takes into account the response of the human eye to radiant energy at various wavelengths and so involves psycho-physical measurements. The distinction rests on the fact that the human eye, as a detector, does not have a "flat" spectral rsponse; that is, it does not respond with equal sensitivity at all wavelengths. If three sources of light of equal radiant power but radiating blue, yellow, and red light, respectively, are observed visually, the yellow source will appear to be far brighter than the others. When we use photometric quantities, then, we are measuring the properties of visible radiation as they appear to the normal eye, rather than as they appear to an "unbiased" detector. Since not all human eyes are identical, a standard response has been determined by the International Commission on Illumination (CIE) and is reproduced in Figure 2-7. The relative response or sensation of brightness for the eye is plotted versus wavelength, showing that peak sensitivity occurs at the "yellow-green" wavelength of 555 nm. Actually the curve shown is the luminous efficiency of the eye for *photopic vision*, that is, when adapted for day vision. For lower levels of illumination, when adapted for night or *scotopic vision*, the curve shifts toward the green, peaking at 510 nm. It is interesting to note that human color sensation is a function of illumi-

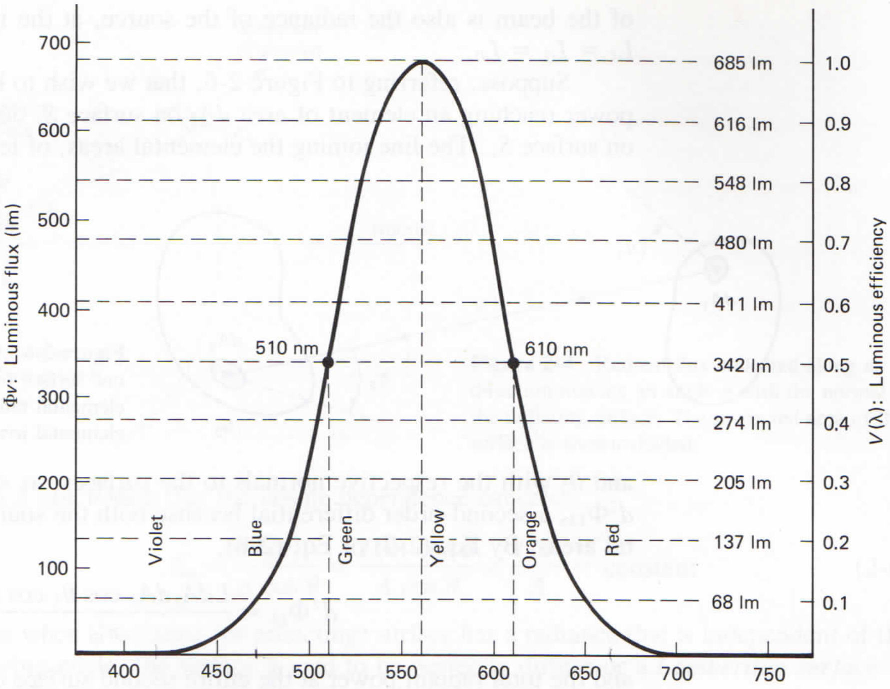


Figure 2-7 CIE luminous efficiency curve. The luminous flux corresponding to 1 W of radiant power at any wavelength is given by the product of 685 lm and the luminous efficiency at the same wavelength: $\Phi_v(\lambda) = 685V(\lambda)$ for each watt of radiant power.

nation and is almost totally absent at lower levels of illumination. One way to confirm this is to compare the color of stars, as they appear visually, to their photographic images made on color film using a suitable time exposure. Another, very dramatic way to demonstrate human color dependence on illumination is to project a 35-mm color slide of a scene onto a screen with a low current in the projector bulb. At sufficiently low currents, the scene appears black and white. As the current is increased, the full colors in the scene gradually emerge. On the other hand, very intense radiation may be visible beyond the limits of the CIE curve. The reflection of an intense laser beam of wavelength 694.3 nm from a ruby laser is easily seen. Even the infrared radiation around 900 nm from a gallium-arsenide semiconductor laser can be seen as a deep red.

Radiometric quantities are now related to photometric quantities through the luminous efficiency curve of Figure 2-7 in the following way: Corresponding to a radiant flux of 1 W at the peak wavelength of 555 nm, where the luminous efficiency is maximum, the *luminous flux* is defined to be 685 lm. Then, for example, at $\lambda = 610$ nm, in the range where the luminous efficiency is 0.5 or 50%, 1 W of radiant flux would produce only 0.5×685 or 342 lm of luminous flux. The curve shows that again at $\lambda = 510$ nm, in the blue-green, the brightness has dropped to 50%.

Photometric units, in terms of their definitions, parallel radiometric units. This is amply demonstrated in the summary and comparison provided in Table 2-1. In general, analogous units are related by the following equation:

$$\text{photometric unit} = K(\lambda) \times \text{radiometric unit} \qquad (2\text{-}10)$$

where $K(\lambda)$ is called the *luminous efficacy*. If $V(\lambda)$ is the *luminous efficiency*, as given on the CIE curve, then