
Modern Optical Engineering

The Design of Optical Systems

Warren J. Smith

Chief Scientist, Kaiser Electro-Optics Inc.

Carisbad, California

and Consultant in Optics and Design

Third Edition

McGraw-Hill

New York San Francisco Washington, D.C. Auckland Bogotá
Caracas Lisbon London Madrid Mexico City Milan
Montreal New Delhi San Juan Singapore
Sydney Tokyo Toronto

SDC EX. 1009 - 1/47

Library of Congress Cataloging-in-Publication Data

Smith, Warren J.

Modern optical engineering / Warren J. Smith—3rd ed.

p. cm.

Includes bibliographical references and index.

ISBN 0-07-136360-2

1. Optical instruments—Design and construction. I. Title.

TS513.S55 2000

621.36—dc21

00-032907

McGraw-Hill

A Division of The McGraw-Hill Companies



Copyright © 2000, 1990, 1966 by The McGraw-Hill Companies, Inc. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.

1 2 3 4 5 6 7 8 9 0 DOC/DOC 0 5 4 3 2 1 0

P/N 0-07-136379-3

PART OF

ISBN 0-07-136360-2

Kurt K. Wendt Library
University of Wisconsin-Madison
215 N. Randall Avenue
Madison, WI 53706-1688

The sponsoring editor of this book was Stephen S. Chapman. The editing supervisor was David E. Fogarty, and the production supervisor was Sherri Souffrance. It was set in New Century Schoolbook by Deirdre Sheean of McGraw-Hill's Professional Book Group Hightstown composition unit.

Printed and bound by R. R. Donnelley & Sons Company.



This book was printed on recycled, acid-free paper containing a minimum of 50% recycled, de-inked fiber.

McGraw-Hill books are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. For more information, please write to the Director of Special Sales, Professional Publishing, McGraw-Hill, Two Penn Plaza, New York, NY 10121-2298. Or contact your local bookstore.

Information contained in this work has been obtained by The McGraw-Hill Companies, Inc. ("McGraw-Hill") from sources believed to be reliable. However, neither McGraw-Hill nor its authors guarantee the accuracy or completeness of any information published herein, and neither McGraw-Hill nor its authors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that McGraw-Hill and its authors are supplying information but are not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought.

Optical Materials and Interference Coatings

7.1 Reflection, Absorption, Dispersion

To be useful as an optical material, a substance must meet certain basic requirements. It should be able to accept a smooth polish, be mechanically and chemically stable, have a homogeneous index of refraction, be free of undesirable artifacts, and of course transmit (or reflect) radiant energy in the wavelength region in which it is to be used.

The two characteristics of an optical material which are of primary interest to the optical engineer are its transmission and its index of refraction, both of which vary with wavelength. The transmission of an optical *element* must be considered as two separate effects. At the boundary surface between two optical media, a fraction of the incident light is reflected. For light normally incident on the boundary the fraction is given by

$$R = \frac{(n' - n)^2}{(n' + n)^2} \quad (7.1)$$

where n and n' are the indices of the two media (a more complete expression for Fresnel surface reflection is given in Sec. 7.9).

Within the optical element, some of the radiation may be absorbed by the material. Assume that a 1-mm thickness of a filter material transmits 25 percent of the incident radiation at a given wavelength (excluding surface reflections). Then 2 mm will transmit 25 percent of 25 percent and 3 mm will transmit $0.25 \times 0.25 \times 0.25 = 1.56$ percent.

Therefore, if t is the transmission of a unit thickness of material, the transmission through a thickness of x units will be given by

$$T = t^x \quad (7.2)$$

This relationship is often stated in the following form, where a is called the absorption coefficient and is equal to $-\log_e t$.

$$T = e^{-ax} \quad (7.3)$$

Thus, it can be seen that the total transmission through an optical element is a sort of product of its surface transmissions and its internal transmission. For a plane parallel plate in air, the transmission of the first surface is given (from Eq. 7.1) as

$$T = 1 - R = 1 - \frac{(n - 1)^2}{(n + 1)^2} = \frac{4n}{(n + 1)^2} \quad (7.4)$$

Now the light transmitted through the first surface is partially transmitted by the medium and goes on to the second surface, where it is partly reflected and partly transmitted. The reflected portion passes (back) through the medium and is partly reflected and partly transmitted by the first surface, and so on. The resulting transmission can be expressed as the infinite series

$$\begin{aligned} T_{1,2} &= T_1 T_2 (K + K^3 R_1 R_2 + K^5 (R_1 R_2)^2 + K^7 (R_1 R_2)^3 + \cdots) \\ &= \frac{T_1 T_2 K}{1 - K^2 R_1 R_2} \end{aligned} \quad (7.5)$$

where T_1 and T_2 are the transmissions of the two surfaces, R_2 and R_1 are the reflectances of the surfaces, and K is the transmittance of the block of material between them. (This equation can also be used to determine the transmission of two or more elements, e.g., flat plates, by finding first $T_{1,2}$ and $R_{1,2}$, then using $T_{1,2}$ and T_3 together, and so on.)

If we set $T_1 = T_2 = 4n/(n + 1)^2$ from Eq. 7.4 into Eq. 7.5, and assume that $K = 1$, we find that the transmission, including all internal reflections, of a completely nonabsorbing plate is given by

$$T = \frac{2n}{(n^2 + 1)} \quad (7.6)$$

This is obviously the maximum possible transmission of an uncoated plate of index n .

Similarly, the reflection is given by

$$R = 1 - T = \frac{(n - 1)^2}{(n^2 + 1)} \quad (7.7)$$

It should be emphasized that the transmission of a material, being wavelength-dependent, may not be treated as a simple number over any appreciable wavelength interval. For example, suppose that a filter is found to transmit 45 percent of the incident energy between 1 and 2 μm . It cannot be assumed that the transmission of two such filters in series will be $0.45 \times 0.45 = 20$ percent unless they have a uniform spectral transmission (neutral density). To take an extreme example, if the filter transmits nothing from 1 to 1.5 μm and 90 percent from 1.5 to 2 μm , its "average" transmission will be 45 percent within the 1- to 2- μm band. However, two such filters, when combined, will transmit zero from 1 to 1.5 μm , and about 81 percent from 1.5 to 2 μm , for an "average" transmission of about 40 percent, rather than the 20 percent which two neutral density filters would transmit.

The *photographic density* of a filter is the log of its opacity (the reciprocal of transmittance), thus

$$D = \log \frac{1}{T} = -\log T$$

where D is the density and T is the transmittance of the material. Note that transmittance does not account for surface reflection losses; thus, density is directly proportional to thickness. To a fair approximation, the density of a "stack" of neutral density absorption filters is the sum of the individual densities.

Equation 7.3 can be written to the base 10 if desired. This is done when the term "density" is used to describe the transmission of, for example, a photographic filter. The equation becomes

$$T = 10^{-\text{density}}$$

so that a density of 1.0 means a transmission of 10 percent, a density of 2.0 means a transmission of 1 percent, etc. Note that densities can be added. A neutral absorbing filter with a density of 1.0 combined with a filter of density 2.0 will yield a density of 3.0 and a transmission of $0.1 \times 0.01 = 0.001 = 10^{-3}$.

Index dispersion

The index of refraction of an optical material varies with wavelength as indicated in Fig. 7.1 where a very long spectral range is shown. The dashed portions of the curve represent absorption bands. Notice that the index rises markedly at each absorption band, and then begins to drop with increasing wavelength. As the wavelength continues to increase, the slope of the curve levels out until the next absorption band is approached, where the slope increases again. For optical

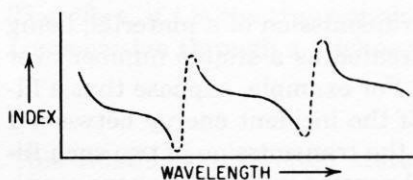


Figure 7.1 Dispersion curve of an optical material. The dashed lines indicate absorption bands. (Anomalous dispersion.)

materials we usually need concern ourselves with only one section of the curve, since most optical materials have an absorption band in the ultraviolet and another in the infrared and their useful spectral region lies between the two.

Many investigators have attacked the problem of devising an equation to describe "the irrational variation of index" with wavelength. Such expressions are of value in interpolating between, and smoothing the data of, measured points on the dispersion curve, and also in the study of the secondary spectrum characteristics of optical systems. Several of these dispersion equations are listed below.

$$\text{Cauchy} \quad n(\lambda) = a + \frac{b}{\lambda^2} + \frac{c}{\lambda^4} + \dots \quad (7.8)$$

$$\text{Hartmann} \quad n(\lambda) = a + \frac{b}{(c - \lambda)} + \frac{d}{(e - \lambda)} \quad (7.9)$$

$$\text{Conrady} \quad n(\lambda) = a + \frac{b}{\lambda} + \frac{c}{\lambda^{3.5}} \quad (7.10)$$

$$\text{Kettler-Drude} \quad n^2(\lambda) = a + \frac{b}{c - \lambda^2} + \frac{d}{e - \lambda^2} + \dots \quad (7.11)$$

$$\text{Sellmeier} \quad n^2(\lambda) = a + \frac{b\lambda^2}{c - \lambda^2} + \frac{d\lambda^2}{e - \lambda^2} + \frac{f\lambda^2}{g - \lambda^2} + \dots \quad (7.12)$$

$$\text{Herzberger} \quad n(\lambda) = a + b\lambda^2 + \frac{e}{(\lambda^2 - 0.035)} + \frac{d}{(\lambda^2 - 0.035)^2} \quad (7.13)$$

$$\text{Old Schott} \quad n^2(\lambda) = a + b\lambda^2 + \frac{c}{\lambda^2} + \frac{d}{\lambda^4} + \frac{e}{\lambda^6} + \frac{f}{\lambda^8} \quad (7.14)$$

The new Schott catalog uses the Sellmeier equation (Eq. 7.12).

The constants (a , b , c , etc.) are, of course, derived for each individual material by substituting known index and wavelength values and solving the resulting simultaneous equations for the constants. The Cauchy equation obviously allows for only one absorption band at zero wavelength. The Hartmann formula is an empirical one but does allow absorption bands to be located at wavelengths c and e . The Herzberger expression is an approximation of the Kettler-Drude equation and is reliable through the visible to about $1 \mu\text{m}$ in the near infrared. In his

later work, Herzberger used 0.028 as the denominator constant. The Conrady equation is empirical and designed for optical glass in the visible region. All these equations suffer from the drawback that the index approaches infinity as an absorption wavelength is approached. Since little use is made of any material close to an absorption band, this is usually of small consequence.

Equation 7.14 was used by Schott and other optical glass manufacturers as the dispersion equation for optical glass. It is accurate to about 3×10^{-6} between 0.4 and 0.7 μm , and to about 5×10^{-6} between 0.36 and 1.0 μm . The accuracy of Eq. 7.14 can be improved in the ultraviolet by adding a term in λ^4 , and in the infrared by adding a term in λ^{-10} . More recently, glass manufacturers have switched to Eq. 7.12, the Sellmeier equation, in order to improve the accuracy.

The dispersion of a material is the rate of change of index with respect to wavelength, that is, $dn/d\lambda$. From Figs. 7.1 and 7.2, it can be seen that the dispersion is large at short wavelengths and becomes less at longer wavelengths. At still longer wavelengths, the dispersion increases again as the long-wavelength absorption band is approached. Notice in Fig. 7.2 that the glasses have almost identical slopes for wavelengths beyond 1 μm .

For materials which are used in the visible spectrum, the refractive characteristics are conventionally specified by giving two numbers, the index of refraction for the helium d line (0.5876 μm) and the Abbe

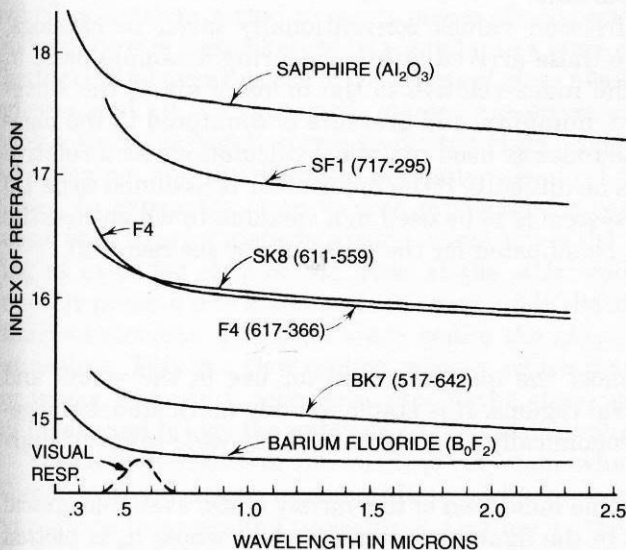


Figure 7.2 The dispersion curves for four optical glasses and two crystals.

V-number, or reciprocal relative dispersion. The V-number, or V-value, is defined as

$$V = \frac{n_d - 1}{n_F - n_C} \quad (7.15)$$

where n_d , n_F , and n_C are the indices of refraction for the helium d line, the hydrogen F line ($0.4861 \mu\text{m}$), and the hydrogen C line ($0.6563 \mu\text{m}$), respectively. Note that $\Delta n = n_F - n_C$ is a measure of the dispersion, and its ratio with $n_d - 1$ (which effectively indicates the basic refracting power of the material) gives the dispersion relative to the amount of bending that a light ray undergoes.

For optical glass, these two numbers describe the glass type and are conventionally written $(n_d - 1):V$ as a six-digit code. For example, a glass with an n_d of 1.517 and a V of 64.5 would be identified as 517:645.

For many purposes, the index and V-value are sufficient information about a material. For secondary spectrum work, however, it is necessary to know more, and the *relative partial dispersion*

$$P_C = \frac{n_d - n_C}{n_F - n_C} \quad (7.16)$$

is frequently used for this purpose. P_C is a measure of the rate of change of the slope of the index vs. wavelength curve (i.e., the curvature or second derivative). Note that a relative partial dispersion can be defined for any portion of the spectrum and that most glass catalogs list about a dozen partials.

The index of refraction values conventionally given in catalogs, handbooks, etc., are those arrived at by measuring a sample piece in air, and are thus the index relative to the index of air at the wavelength, temperature, humidity, and pressure encountered in the measurement. Since the index is used in optical calculations as a relative number, this causes no difficulty if the index of air is assumed to be 1.0 (unless the optical system is to be used in a vacuum, in which case the catalog index must be adjusted for the index of air; see Sec. 1.2).

7.2 Optical Glass

Optical glass is almost the ideal material for use in the visual and near-infrared spectral regions. It is stable, readily fabricated, homogeneous, clear, and economically available in a fairly wide range of characteristics.

Figure 7.3 gives some indication of the variety of the available optical glasses. Each point in the figure represents a glass whose n_d is plotted against its V-value; note that the V-values are conventionally plotted in reverse, i.e., descending, order. Glasses are somewhat arbitrarily divided

into two groups, the *crown* glasses and the *flint* glasses, crowns having a V-value of 55 or more if the index is below 1.60, and 50 or more for an index above 1.60; the flint glasses are characterized by V-values less than these limits. The "glass line" in Fig. 7.3 is the locus of the ordinary optical glasses made by adding lead oxide to crown glass. These glasses are relatively cheap, quite stable, and readily available.

The addition of lead oxide to crown glass causes its index to rise, and its V-value to decrease, along the *glass line*. Immediately above the glass line are the barium crowns and flints; these are produced by the addition of barium oxide to the glass mix. In Fig. 7.3 these are identified by the symbol Ba for barium. This has the effect of raising the index without markedly lowering the V-value. The rare earth glasses are a completely different family of glasses based on the rare earths instead of silicon dioxide (which is the major constituent of the other glasses). These are identified by the symbol La in Fig. 7.3, signifying the presence of lanthanum.

The table of Fig. 7.4 lists the characteristics of the most common optical glass types. Each glass type in the table is available from the major glass manufacturers, so that all types listed are readily obtainable. The index data given are taken from the Schott catalog; the equivalent glasses from other suppliers may have slightly different nominal characteristics.

Formerly, optical glass was made by heating the ingredients in a large clay pot, or crucible, stirring the molten mass for uniformity, and carefully cooling the melt. The hardened glass was broken into chunks which were then sorted to select pieces of good quality. Currently the molten glass is more likely to be poured into a large slab mold; this gives better control over the size of the pieces of glass available. Many barium glasses and all the rare earth glasses are processed in platinum crucibles, since the highly corrosive molten glass tends to attack the walls of a clay pot and the dissolved pot materials affect the glass characteristics. In extremely large volume production, a continuous process is used, with the raw materials going in one end of the furnace and emerging as extruded strip or rod glass at the other end. Raw glass is frequently pressed into blanks, which are roughly the size and shape of the finished element. The final stage before the glass is ready for use is annealing. This is a slow cooling process, which may take several days or weeks, and which relieves strains in the glass, assures homogeneity of index, and brings the index up to the catalog value.

The characteristics of optical glass vary somewhat from melt to melt (because of variations in composition and processing) and also due to variations in annealing procedures. Ordinarily the lower index glasses (to $n = 1.55$), are supplied to a tolerance of ± 0.001 on the catalog value of n_d , the higher index glasses may vary ± 0.0015 from the nom-

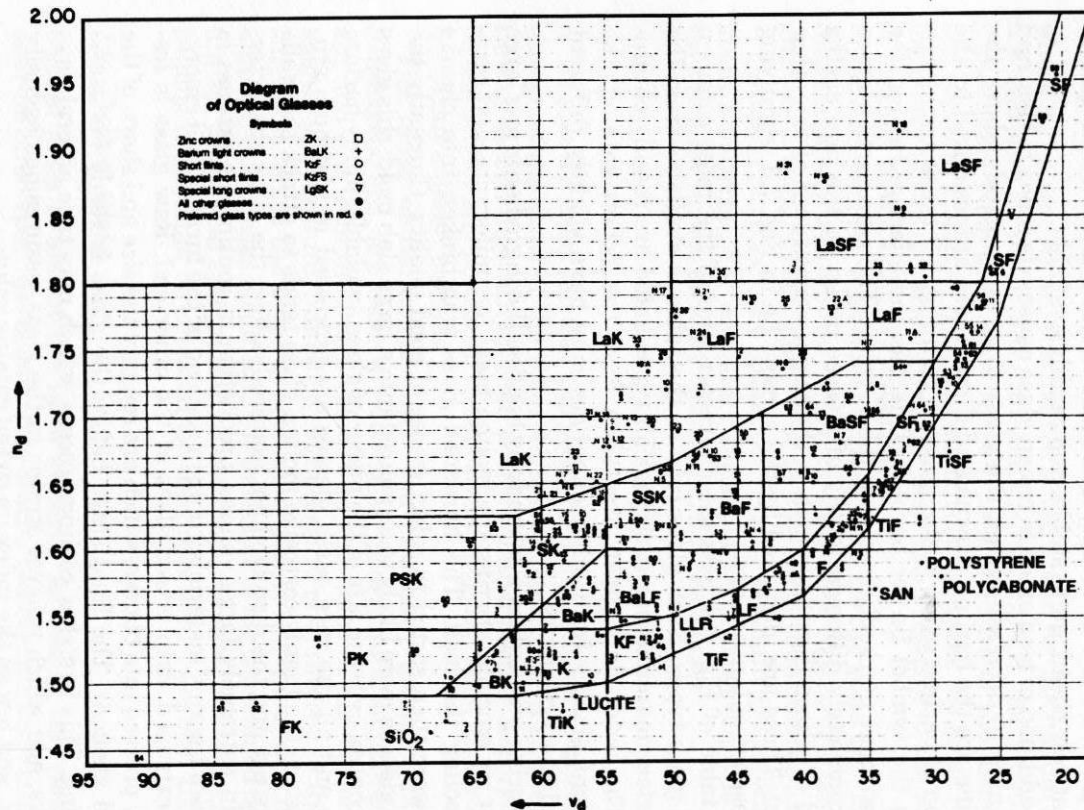


Figure 7.3 The “glass veil.” Index (n_d) plotted against the reciprocal relative dispersion (Abbe V-value). The glass types are indicated by the letters in each area. The “glass line” is made up of the glasses of types K, KF, LLF, LF, and SF which are strung along the bottom of the veil. (Note that K stands for *kron*, German for “crown,” S stands for *schwer*, or “heavy or dense.”) (Courtesy of Schott Glass Technologies, Inc., Duryea, Pa.)

Type	n_d	V_d	$n_F - n_C$	n_r	n_C	n_F	n_g	n_h	CR	FR	SR	AR	$\alpha_{-30/+70^\circ\text{C}}$ $10^{-6}/\text{K}$	T_g , $^\circ\text{C}$	D g/cm ³	HK	τ_i
BK7	1.51680	64.17	0.008054	1.51289	1.51432	1.52283	1.52669	1.53024	2	0	1	2.0	7.1	559	2.51	520	0.991
517642																	
K 5	1.52249	59.48	0.008784	1.51829	1.51982	1.52910	1.53338	1.53735	1	0	1	1.0	8.2	543	2.59	450	0.984
522595																	
BaK 1	1.57250	57.55	0.009948	1.56778	1.56949	1.58000	1.58488	1.58940	2	1	4	1.2	7.6	602	3.19	460	0.976
573575																	
BaK 2	1.53996	59.71	0.009043	1.53564	1.53721	1.54677	1.55117	1.55525	2	0	1	1.0	8.0	562	2.86	450	0.974
540597																	
SK 4	1.61272	58.63	0.010451	1.60774	1.60954	1.62059	1.62569	1.63042	3	2	51	2.0	6.4	643	3.57	500	0.973
613586																	
SK 16	1.62041	60.33	0.010284	1.61548	1.61727	1.62814	1.63312	1.63774	4(2.0)	4	52	3.0	6.3	638	3.58	490	0.970
620603																	
SK N 18	1.63854	55.42	0.011521	1.63308	1.63505	1.64724	1.65290	1.65819	3	4-5	52	2.2	6.4	643	3.64	470	0.93
639554																	
KF 6	1.51742	52.20	0.009913	1.51274	1.51443	1.52492	1.52984	1.53446	1	0	1	2.0	6.9	446	2.67	420	0.985
517522																	
SSK 4	1.61765	55.14	0.011201	1.61235	1.61427	1.62611	1.63163	1.63677	2	1	51	1.0	6.1	639	3.63	460	0.972
618551																	
SSK N5	1.65844	50.88	0.012940	1.65237	1.65456	1.66825	1.67471	1.68080	2	3	52	2.2	6.8	641	3.71	470	0.91
658509																	
LaK N 7	1.65160	58.52	0.011134	1.64628	1.64821	1.65998	1.66540	1.67042	4(2.3)	2	53(30)	4.2	7.1	618	3.84	460	0.960
652585																	
-LaK 8	1.71300	53.83	0.013245	1.70668	1.70898	1.72298	1.72944	1.73545	3	2	52	1.0	5.6	640	3.78	590	0.950
713538																	
LaK 9	1.69100	54.71	0.012631	1.68498	1.68716	1.70051	1.70667	1.71240	3	3	52	1.2	6.3	650	3.51	580	0.950
691547																	

Figure 7.4 Characteristics of a selection of optical glasses. CR, FR, SR, and AR are codes indicating the resistance of the glass to staining or hazing due to environmental attack; the higher the number, the lower the resistance; α is the thermal expansion coefficient, and T_g is the transformation temperature. D is the density, HK is the Knoop hardness, and τ_i is the internal transmittance at 0.4 μm for a thickness of 25 mm.

Type	n_d	V_d	$n_F - n_C$	n_r	n_C	n_F	n_g	n_h	CR	FR	SR	AR	$\alpha_{-30/+70^\circ\text{C}}$ $10^{-6}/\text{K}$	T _g , °C	D g/cm ³	HK	τ_i
LaK 10 720504	1.72000	50.41	0.014282	1.71323	1.71568	1.73079	1.73784	1.74444	2	2	52	1.2	5.7	620	3.81	580	0.91
BaF 4 606439	1.60562	43.93	0.013787	1.59925	1.60153	1.61613	1.62318	1.62990	2	0	2	1.0	7.9	521	3.50	400	0.970
BaF N 10 670471	1.67003	47.11	0.014222	1.66341	1.66579	1.68084	1.68803	1.69486	2	3	51	1.2	6.8	630	3.76	480	0.84
LF 1 573426	1.57309	42.58	0.013458	1.56687	1.56910	1.58335	1.59025	1.59684	1	0	1	2.0	8.5	435	3.16	390	0.990
LF 5 581409	1.58144	40.85	0.014233	1.57489	1.57723	1.59230	1.59964	1.60667	2	0	1-2	2.3	9.1	419	3.22	410	0.992
F 1 626357	1.62588	35.70	0.017530	1.61790	1.62074	1.63932	1.64851	1.65741	1	0	2	2.3	8.7	432	3.65	350	0.975
F 2 620364	1.62004	36.37	0.017050	1.61227	1.61503	1.63310	1.64202	1.65063	1	0	1	2.3	8.2	432	3.61	370	0.990
F 5 603380	1.60342	38.03	0.015868	1.59615	1.59874	1.61556	1.62380	1.63174	1	0	1	2.3	8.0	438	3.47	380	0.984
SF 1 717295	1.71736	29.51	0.024307	1.70647	1.71032	1.73610	1.74916	1.76199	2	1	3	2.3	8.1	417	4.46	340	0.89
SF 2 648339	1.64769	33.85	0.019135	1.63902	1.64210	1.66238	1.67249	1.68233	1	0	2	2.3	8.4	441	3.86	350	0.970
SF 5 673322	1.67270	32.21	0.020884	1.66328	1.66661	1.68876	1.69985	1.71068	1	1	2	2.3	8.2	425	4.07	340	0.950
SF 8 689312	1.68893	31.18	0.022098	1.67899	1.68250	1.70594	1.71772	1.72926	1	1	3	2.3	8.2	423	4.22	340	0.89

Figure 7.4 *Continued*

inal index. Similarly the V-value will vary from the catalog value. Typical tolerances on V-value are ± 0.3 for V-values below 46; ± 0.4 from 46 to 58; ± 0.5 for V-values above 58. Most glass manufacturers will select glass to closer tolerances at an increased price.

Optical glass may be obtained in hundreds of different types; complete information is best obtained from the manufacturer's catalog.

Figure 7.5 gives an indication of the spectral transmission of optical glasses. In general, most optical glasses transmit well from 0.4 to 2.0 μm . The heavy flints tend to absorb more at the short wavelengths and transmit more at the long wavelengths. The rare earth glasses also absorb in the blue region. Since the transmission of a glass is affected greatly by minute impurities, the exact characteristics of any given glass may vary significantly from batch to batch, even when made by the same manufacturer.

Most optical glasses turn brown (or black) when exposed to nuclear radiation because of increased absorption of the short (blue) wavelengths. To provide glasses which can be used in a radiation environment, the glass manufacturers have developed "protected" or "nonbrowning" glasses containing cerium. These glasses will tolerate radiation doses to the order of a million roentgens. Fused quartz glass, which is discussed in the next section, is almost pure SiO_2 and is extremely resistant to radiation browning.

Although not strictly "optical glass," ordinary window glass and plate glass are frequently used when cost is an important factor. The index of window glass ranges from about 1.514 to about 1.52, depending on the manufacturer. Ordinary window glass is slightly greenish, due primarily to modest amounts of absorption in the red and blue wavelengths; the red absorption continues to about 1.5 μm . Window glass is also available in "water white" quality, without the greenish tint. For elements with one or two plane surfaces and with modest precision requirements, window glass can often be used without further processing; the accuracy of the plane surfaces is surprisingly good. By special selection, plane parallels can be obtained which meet fairly rigorous requirements. The secret here is to avoid pieces cut from the edge of the large sheets in which this type of glass is made; the center sections are usually far more uniform in surface and thickness. Note that the surface of "float glass" is significantly less smooth by a factor of 3 or 4, although recent process improvements have brought the surfaces up to that of window and plate glass.

7.3 Special Glasses

Several glasses are available which differ sufficiently from the standard optical glasses to deserve special mention.

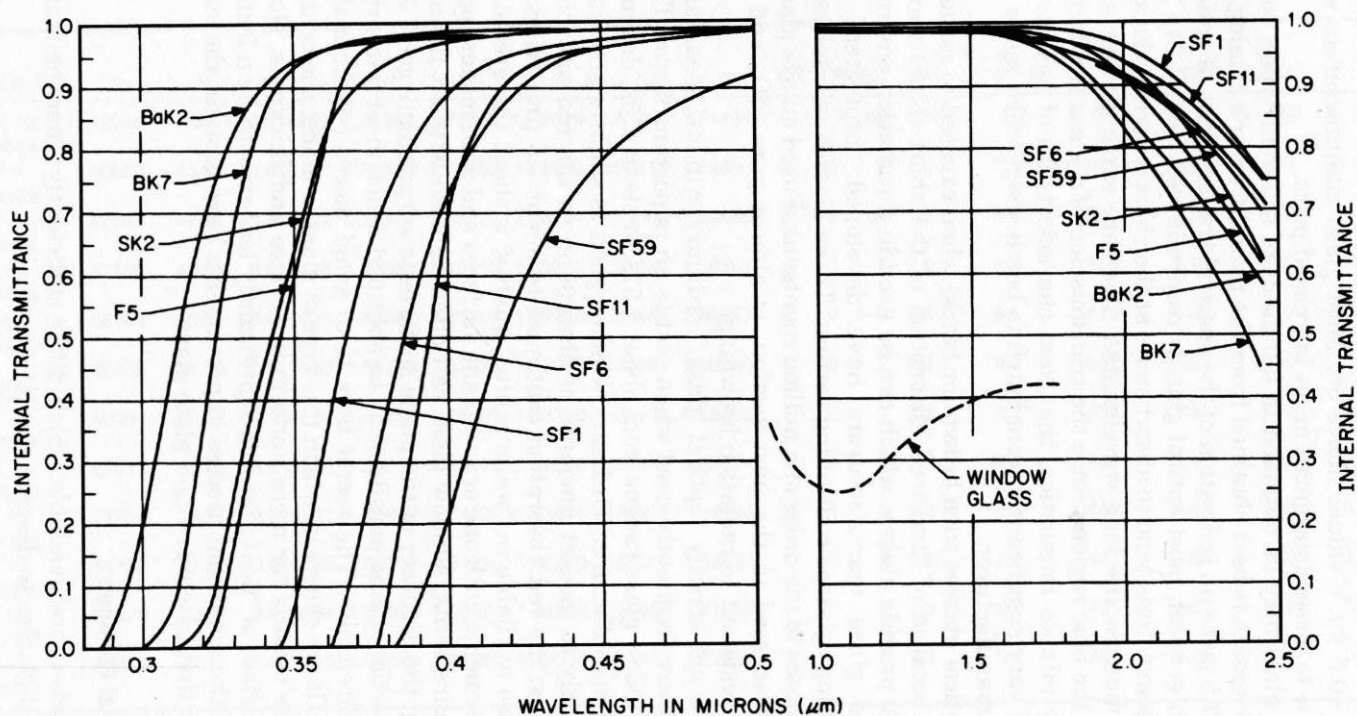


Figure 7.5 Internal transmittance of several representative optical glasses plus window glass, all for a thickness of 25 mm.

Low-expansion glasses. In applications where the elements of an optical system are subject to strong thermal shocks (as in projection condensers) or where extreme stability in the presence of temperature variations is necessary (such as astronomical telescope reflectors or laboratory instruments), it is desirable to use a material with a low thermal coefficient of expansion.

A number of borosilicate glasses are made with expansion coefficients which are less than half that of ordinary glass. Corning's Pyrex #7740 and #7760 have expansion coefficients between 30 and $40 \times 10^{-7}/^{\circ}\text{C}$. The index of refraction of these glasses is about 1.474 with a V -value of about 60 , and their density is about 2.2 . Unfortunately they are usually afflicted with veins and striations so that they are suitable only for applications such as condensing systems when used as refracting elements. They are widely used for test plates and for mirrors. Some of these materials are yellowish or brownish, but others are available in a clear white grade.

Another low-expansion glass is fused quartz, which is also called fused silica glass. This material is essentially pure (more or less, depending on the grade and manufacturer) silicon dioxide (SiO_2) and has an extremely low expansion coefficient of $5.5 \times 10^{-7}/^{\circ}\text{C}$. It was originally made by fusing powdered crystalline quartz. Fused quartz can be obtained in grades with homogeneity equal to that of optical glass. Fused glass is a completely different material than crystalline quartz. Its index is 1.46 versus 1.55 ; it is amorphous (glassy) without crystalline structure; and it is not birefringent, as is quartz. Fused quartz has excellent spectral transmission characteristics, extending further into both the ultraviolet and infrared than ordinary optical glass. For this reason it is frequently used in spectrophotometers, infrared equipment, and ultraviolet devices. The excellent thermal stability of fused quartz is responsible for its use where extremely precise reflecting surfaces are required. Large mirrors and test plates are frequently made from fused quartz for this reason. As previously mentioned, pure fused quartz is highly resistant to radiation browning. The index of refraction and transmission of fused quartz are given in Fig. 7.6. Note that the absorption bands indicated are not of the type indicated in Fig. 7.1, but are due to impurities and are thus subject to elimination, as indicated by the range of transmissions given.

A new class of materials, which are partially crystallized glasses, is available for use as extremely thermally stable mirror substrates, since they can be fabricated with a zero thermal expansion coefficient. Owens-Illinois CER-VIT was the original material; Corning ULE and Schott ZERODUR have similar properties. These materials can be tailored to have a zero thermal expansion coefficient (plus or minus about 1×10^{-7}) at a given temperature. The zero thermal expansion coefficient

Wavelength, μm	Index at 24°C	Transmission 10 mm Thick (Incl. Refl. Losses)
0.17		0.0–0.56 (depending on purity)
0.1855	1.5746*	0.0–0.78
0.2026	1.54725*	0.3–0.84
0.2573	1.50384*	0.58–0.90
0.2749	1.49624*	0.88–0.92
0.35	1.47701	0.93
0.40	1.47021	0.93
0.45	1.46564	0.93
0.4861 (F)	1.46320	0.93
0.5	1.46239	0.93
0.55	1.45997	0.93
0.5893 (D)	1.45846	0.93
0.60	1.45810	0.93
0.6563 (C)	1.45642	0.93
0.70	1.45535	0.93
0.80	1.45337	0.93
1.0	1.45047	0.93
1.35	Absorption band	0.76–0.93
1.5	1.44469	0.93
2.0	1.43817	0.93
2.2	Absorption band	0.50–0.93
2.5	1.42991	0.93
2.7	Absorption band	0–0.8
3.0	1.41937	0.45–0.85
3.5	1.40601	0.6–0.7
4.0		0.1–0.15

* n at "room temperature" $V = 67.6$ $P_c = 0.301$

$\Delta n = 10^{-6} \Delta t$ (°C) visible, to $0.4 \times 10^{-6} \Delta t$ at 3.5 μm

Dispersion equation $n^2 = 2.978645 + \frac{0.008777808}{\lambda^2 - 0.010609} + \frac{84.06224}{\lambda^2 - 96.0}$

yields values about 0.00042 less than table.

Figure 7.6 Optical characteristics of fused quartz.

cient results from the mixture of crystals (with a negative coefficient) and amorphous glass with a positive coefficient. These materials tend to be brittle, yellow or brown, and to scatter light, so they are not suitable for refracting optics.

Infrared transmitting glasses. A number of special "infrared" glasses are available. Some of these are much like extremely dense flint glasses, with index values of 1.8 to 1.9 and transmitting to 4 or 5 μm . The arsenic glasses transmit even further into the infrared. Arsenic-modified selenium glass transmits from 0.8 to 18 μm , but will soften and flow at 70°C. It has the following index values: 2.578 at 1.014 μm ; 2.481 at 5 μm ; 2.476 at 10 μm ; 2.474 at 19 μm . Arsenic trisulfide glass transmits from 0.6 to 13 μm and is somewhat brittle and soft. Index values: 2.6365 at 0.6 μm ; 2.4262 at 2 μm ; 2.4073 at 5 μm ; 2.3645 at 12 μm .

Gradient index glass. As indicated in Chap. 1, if the index of refraction is not uniform, light rays travel in curved paths rather than in straight lines. In visualizing this, it often helps to remember that the light rays curve toward the region of higher index. If the index varies in a controlled way, this property may be advantageously utilized. Glass can be doped by infusion with other materials, typically by the immersion of the glass into a bath of molten salts to effect an ion exchange which produces a changed index. A gradient also can be produced by fusing together layers of glasses with differing indexes. Several types of index gradient are useful in optical systems. A *radial gradient* has an index which varies with the radial distance from the optical axis. An *axial gradient* varies the index with the distance along the axis. A *spherical gradient* varies the index as a function of the radial distance from an axial point. An axial gradient at a spherical surface has an effect on the aberrations which is quite analogous to that of an aspheric surface. A radial gradient can produce lens power in a plano-plano element. For example, a plano element whose index varies as a function of the radial distance r according to

$$n(r) = n_0(1 - Kr^2)$$

and has a length L will have a focal length given by

$$f = \frac{1}{n_0 \sqrt{2K} \sin(L \sqrt{2K})}$$

and a back focal length of

$$\text{bfl} = \frac{1}{n_0 \sqrt{2K} \tan(L \sqrt{2K})}$$

This effect is the basis of the GRIN rod lens and the SELFOC lens.

7.4 Crystalline Materials

The valuable optical properties of certain natural crystals have been recognized for years, but in the past the usefulness of these materials was severely limited by the scarcity of pieces of the size and quality required for optical applications. However, many crystals are now available in synthetic form. They are grown under carefully controlled conditions to a size and clarity otherwise unavailable.

The table of Fig. 7.7 lists the salient characteristics of a number of useful crystals. The transmission range is indicated in micrometers for a 2-mm-thick sample; the wavelengths given are the 10 percent transmission points. Indices are given for several wavelengths in the transmission band.

Crystal quartz and calcite are infrequently used because of their birefringence, which limits their usefulness almost entirely to polarizing prisms and the like. Sapphire is extremely hard and must be processed with diamond powder. It is used for windows, interference filter substrates, and occasionally for lens elements. It is slightly birefringent, which limits the angular field over which it can be used. The halogen salts have good transmission and refraction characteristics, but their physical properties often leave much to be desired, since they tend to be soft, fragile, and occasionally hygroscopic.

Germanium and especially silicon are widely used for refracting elements in infrared devices. They are much like glass in their physical characteristics, and can be processed with ordinary glass-working techniques. Both are metallic in appearance, being completely opaque in the visible. Their extremely high index of refraction is a joy to the lens designer since the weak curvatures which result from the high index tend to produce designs of a quality which cannot be duplicated in comparable glass systems. Special low-reflection coatings are necessary since the surface reflection (per Eq. 7.1 et seq.) is very high, for example, 36 percent per uncoated germanium surface. Zinc sulfide, zinc selenide, and AMTIR are also widely used in infrared systems.

Worthy of special mention is calcium fluoride, or fluorite. This material has excellent transmission characteristics in both ultraviolet and infrared, which make it valuable for instrumentation purposes. In addition, its partial dispersion characteristics are such that it can be combined with optical glass to form a lens system which is free of secondary spectrum. Its physical properties are not outstanding since it is soft, fragile, resists weathering poorly, and has a crystal structure which sometimes makes polishing difficult. In exposed applications, the fluorite element can sometimes be sandwiched between glass elements to protect its surfaces. The table of Fig. 7.8 lists selected index and transmission values for fluorite. Natural fluorite has been used in microscope objectives for many, many years. The FK glasses, especially FK51, FK52, and FK54, share many of fluorite's characteristics and are very useful in correcting secondary spectrum.

7.5 Plastic Optical Materials

Plastics are rarely used for high precision optical elements. A great deal of effort was made to develop plastics for optical systems during the Second World War, and a few systems incorporating plastics were produced. Since then, the technology of fabrication of plastic optics has advanced significantly, and today, in addition to novelty items such as toys and magnifying glasses, plastic lenses can be found in a multitude of optical applications, including inexpensive, disposable camera lens-

Material	Transmission Range, μm	Index	Remarks
Crystal quartz (SiO_2)	0.12–4.5	$n_o = 1.544, n_e = 1.553$	Birefringent
Calcite (CaCO_3)	0.2–5.5	$n_o = 1.658, n_e = 1.486$	Birefringent
Rutile (TiO_2)	0.43–6.2	$n_o = 2.62, n_e = 2.92$	Birefringent
Sapphire (Al_2O_3)	0.14–6.5	1.834 @ 0.265, 1.755 @ 1.01, 1.586 @ 5.58	Hard, slightly birefringent
Strontium titanate (SrTiO_3)	0.4–6.8	2.490 @ 0.486, 2.292 @ 1.36, 2.100 @ 5.3	IR immersion lenses
Magnesium fluoride (MgF_2)	0.11–7.5	$n_o = 1.378, n_e = 1.390$	IR optics, low reflection coatings
Lithium fluoride (LiF)	0.12–9	1.439 @ 0.203, 1.38 @ 1.5, 1.109 @ 9.8	Prisms, windows, apochromatic lenses
Calcium fluoride (CaF_2)	0.13–12	See Fig. 7.10	Same as LiF
Barium fluoride (BaF_2)	0.25–15	1.512 @ 0.254, 1.468 @ 1.01, 1.414 @ 11.0	Windows
Sodium chloride (NaCl)	0.2–26	1.791 @ 0.2, 1.528 @ 1.6, 1.175 @ 27.3	Prisms, windows, hygroscopic
Silver chloride (AgCl)	0.4–28	2.096 @ 0.5, 2.002 @ 3., 1.907 @ 20.	Ductile, corrosive, darkens
Potassium bromide (KBr)	0.25–40	1.590 @ 0.404, 1.536 @ 3.4, 1.463 @ 25.1	Prisms, windows, soft, hygroscopic
Potassium iodide (KI)	0.25–45	1.922 @ 0.27, 1.630 @ 2.36, 1.557 @ 29	Soft, hygroscopic
Cesium bromide (CsBr)	0.3–55	1.709 @ 0.5, 1.667 @ 5, 1.562 @ 39	Hygroscopic, prisms and windows
Cesium iodide (CsI)	0.25–80	1.806 @ 0.5, 1.742 @ 5, 1.637 @ 50	Prisms and windows
Silicon (Si)	1.2–15	3.498 @ 1.36, 3.432 @ 3, 3.418 @ 10	IR optics
Germanium (Ge)	1.8–23	4.102 @ 2.06, 4.033 @ 3.42, 4.002 @ 13	IR optics, absorbs at higher temp., subject to thermal runaway @ 40°C
Zinc Selenide (ZnSe)	0.5–22	2.489 @ 1, 2.430 @ 5, 2.406 @ 10, 2.366 @ 15	
Zinc Sulfide (ZnS)	0.5–14	2.292 @ 1, 2.246 @ 5, 2.200 @ 10, 2.106 @ 15	
AMTIR (Ge/As/Se)	0.7–14	2.606 @ 1, 2.511 @ 5, 2.497 @ 10, 2.482 @ 14	
Gallium Arsenide (GaAs)	1–15	3.317 @ 3, 3.301 @ 5, 3.278 @ 10, 3.251 @ 14	
Cadmium Telluride (CdTe)	0.2–30	2.307 @ 3, 2.692 @ 5, 2.680 @ 10, 2.675 @ 12	
Magnesium Oxide (MgO)	0.25–9	1.722 @ 1, 1.636 @ 5, 1.482 @ 8	

Figure 7.7 Characteristics of optical crystals.

Wavelength, μm	Index	Absorption Coefficient, cm^{-1}
0.2	1.49531	—
0.3	1.45400	—
0.4	1.44186	—
0.4861 (F)	1.43704	—
0.5893 (D)	1.43384	—
0.6563 (C)	1.43249	—
1.014	1.42884	—
2.058	1.42360	—
3.050	1.41750	—
4.0	1.40963	—
5.0	1.39908	—
7	—	0.02
8	—	0.16
8.84	1.33075	—
9	—	0.64
10	—	1.8

$$V = 95.3 \quad P_c = 0.297$$

$$\Delta n = -10^{-5} \Delta T (^{\circ}\text{C})$$

Figure 7.8 Index and transmission of calcium fluoride (CaF_2) for various wavelengths.

es, many zoom lenses, projection TV lenses, and even some high-quality camera lenses. The low cost of mass-produced plastic optics is one important factor in this popularity; another is the ease of production of aspheric surfaces. Once the aspheric mold has been fabricated, an aspheric surface is as easy to make as is a spherical surface (in marked contrast to glass optics). The rule of thumb that the introduction of an aspheric surface allows the elimination of an element from the system attests to the value of optical plastic materials. This aspheric capability largely offsets the unfortunate fact that the number of suitable optical plastics is very small and that there are only relatively low index materials in that number.

In considering a venture into the plastic optics arena, one is well advised to seek out a specialist in making plastic optics. Not only is the typical injection molder incapable of making good optics, but he or she also has no conception of what is required to do so. The successful fabricators have developed good, reliable sources of consistently high-quality raw materials and material handling techniques, and they have molding machines which have been adapted to the special requirements of optical work. Temperature control is extremely critical, and a longer cycle time is necessary to achieve an optical level of precision. I encountered an extreme case a few years ago. I had designed a visual system for a client who insisted (against my advice) not only on patronizing an inexperienced (in optics) injection molder but also on

using an unusual material. The result was a system which you literally could not see through.

In addition to the general, smooth aspheric capability, plastics are widely used to make Fresnel lenses, where fine steps are necessary. The condenser system in overhead projectors and the field lenses in the viewfinders of single-lens reflex cameras are examples of plastic Fresnel lenses (see Sec. 9.6). Another currently popular application is in diffractive optics (discussed at greater length in Chaps. 9 and 13), where the diffractive surface is basically a Fresnel surface whose step height is on the order of a half wavelength.

Another advantage in mass production is the ability to mold both the lens element and its mounting cell in one shot. The cells of an assembly can in fact be designed so that the lens assembly simply snaps together, and a drop of a suitable solvent can make the assembly permanent.

The obvious advantages of plastic—that it is light and relatively shatterproof—are offset by a number of disadvantages. It is soft and scratches easily. Except by molding, it is difficult to fabricate. Styrene plastic is frequently hazy, scatters light, and is occasionally yellowish. Plastics tend to soften at 60 to 80°C. In some plastics the index is unstable and will change as much as 0.0005 over a period of time. Most plastics will absorb water and change dimensionally; almost all are subject to cold flow under pressure. The thermal expansion coefficient is almost 10 times that of glass, being 7 or $8 \times 10^{-5}/^{\circ}\text{C}$.

The change of index with temperature for plastics is very large (about twenty times that of glass) and negative. Thus, maintaining focus over a range of temperature is a significant problem for plastic optics. Often they must be athermalized as well as achromatized. The density of plastics is low, usually to the order of 1.0 to 1.2. The characteristics of some of the most widely used optical plastics are summarized in Fig. 7.9.

Another optical application for plastics is in *replication*. In this process a precisely made master mold is vacuum-coated with a release, or parting layer, plus any required high- or low-reflection coatings. (The nature of the release layer is usually considered proprietary, but very thin layers of silver, salt, silicone, or plastic have been publicly mentioned.) Next, a few drops of low-shrinkage epoxy are pressed out into a thin (ideally about 0.001 or 0.002 in thick) layer between the master and a closely matching substrate. The substrate may be Pyrex, ceramic, or very stable aluminum (for reflector optics), or glass (for refracting optics). When the epoxy has cured, the master is removed and a reasonably precise (negative) replica is left on the substrate. This process has several advantages. For example, any surface (including aspherics) for which a master can be made can be replicat-

Wavelength, μm	Acrylic (Lucite)	Polystyrene	Polycarbonate	Copolymer Styrene- Acrylonitrile (SAN)
	492:574	590:309	585:299	567:348
1.01398 <i>t</i>	1.483115	1.572553	1.567248	1.551870
0.85211 <i>s</i>	1.484965	1.576196	1.570981	1.555108
0.70652 <i>r</i>	1.487552	1.581954	1.576831	1.560119
0.65627 <i>C</i>	1.489201	1.584949	1.579864	1.562700
0.64385 <i>C'</i>	1.489603	1.585808	1.580734	1.563438
0.58929 <i>D</i>	1.491681	1.590315	1.585302	1.567298
0.58756 <i>d</i>	1.491757	1.590481	1.585470	1.567440
0.54607 <i>e</i>	1.493795	1.595010	1.590081	1.571300
0.48613 <i>F</i>	1.497760	1.604079	1.599439	1.579000
0.47999 <i>F'</i>	1.498258	1.605241	1.600654	1.579985
0.43584 <i>g</i>	1.502557	1.615446	1.611519	1.588640
0.40466 <i>h</i>	1.506607	1.625341	1.622447	1.597075
0.36501 <i>i</i>	1.513613	1.643126	1.643231	1.612490
Thermal expansion coefficient $^{\circ}\text{C}^{-1}$	68×10^{-6}	70×10^{-6}	66×10^{-6}	65×10^{-6}
$dn/dt, ^{\circ}\text{C}^{-1}$	-105×10^{-6}	-140×10^{-6}	-107×10^{-6}	-110×10^{-6}
Service temperature $^{\circ}\text{C}$	83°	75	120	90
Density	1.19	1.06	1.20	1.09

Figure 7.9 Properties of several optical plastics. (From *Lytel and Altman*.) Note that index values may vary significantly from one manufacturer to another.

ed relatively inexpensively, since the master can be used over and over. Other advantages are that a mirror can be made an integral part of its mount, the bottom of a blind hole can have an optical polish and figure, and extremely thin and lightweight parts can be produced. In many cases these things are effectively impossible with standard optical fabrication techniques. The limitations to replicated parts are the inherent softness of the epoxy and the change in the surface figure from that of the mold.

7.6 Absorption Filters

Absorption filters are composed of materials which transmit light selectively; that is, they transmit certain wavelengths more than others. A small percentage of the incident light is reflected, but the major portion of the energy which is not transmitted through the filter is absorbed by the filter material. Obviously, every material discussed in the preceding sections of this chapter is, in the broadest sense, an absorption filter, and occasionally these materials are introduced into optical systems as filters. However, most filters are made by the addition of metallic salts

to clear glass or by dyeing a thin gelatin film to produce a more selective absorption than is available in "natural" materials.

The prime source of dyed gelatin filters is the Eastman Kodak Company, whose line of Wratten filters is widely used for applications where the versatility of dyed gelatin is required and the environmental requirements are not too severe. Gelatin filters are usually mounted between glass to protect the soft gelatin from damage.

The number of coloring materials which are suitable for use in optical filter glass is limited, and the types of filter glass available are thus not as extensive as one might desire. In the visible region, there are several main types. The red, orange, and yellow glasses all transmit the red and near-infrared and have a fairly sharp cutoff, as indicated in Fig. 7.10. The position of this cutoff determines the apparent color of the filter. Green filters tend to absorb both the red and blue portions of the spectrum. Their transmission curves often resemble the spectral sensitivity curve of the eye. Blue optical glass filters can be a disappointment, since they occasionally transmit not only blue light, but some green, yellow, orange, and frequently a sizable amount of red light as well. The purple filters transmit both the red and blue ends of the spectrum, with fair suppression of the yellow and green spectral regions. Filter glass is manufactured by most optical glass companies

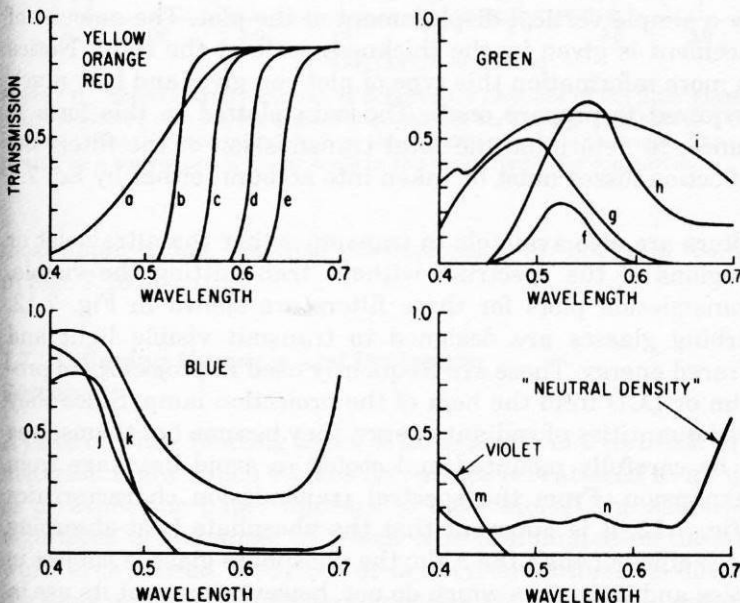


Figure 7.10 Spectral transmission curves for several optical glass filters.

as well as a number of establishments which make commercial colored glass (as opposed to "optical" glass, which is more carefully controlled).

The transmission characteristics of glass filters vary from melt to melt for any given type. If a filter application requires that the transmission be accurately controlled, it is frequently necessary to adjust the finished thickness of the filter to compensate for these variations. The red filters are probably the most variable; since they are sensitive to heat, some red glasses cannot be re-pressed into blanks. Spectral transmission data for filters is usually given for a specific thickness and includes the losses due to Fresnel surface reflections. To determine the transmission for thicknesses other than the nominal value, the transmittance, that is, the "internal" transmission of the piece without the reflection losses, must be determined. In most cases, it is sufficient to divide the transmission by Eq. 7.4 to get the transmittance. Then Eq. 7.2 or 7.3 can be used to determine the transmittance of the new thickness. This transmittance times the T of Eq. 7.4 will then give the total transmission for the filter to a reasonable accuracy.

This process is greatly simplified by the use of a log-log plot of the transmittance. The Schott catalog of filter glass makes use of this type of scale. A transparent overlay makes it possible to evaluate instantly the effect of a thickness change. A study of Fig. 7.11 will indicate the utility of this type of a transmittance plot; the same filter is shown in two thicknesses on a log-log scale in the upper figure and on a linear scale in the lower. Against the log-log scale, the thickness change is effected by a simple vertical displacement of the plot. The amount of the displacement is given by the thickness scale at the right. Notice how much more information this type of plot can give (and how much more is required to prepare one!). The data plotted in this form is transmittance; to determine the total transmission of the filter, the surface reflection losses must be taken into account, either by Eq. 7.4 or 7.5.

Glass filters are also available to transmit either the ultraviolet or infrared regions of the spectrum without transmitting the visible. Typical transmission plots for these filters are shown in Fig. 7.12. Heat-absorbing glasses are designed to transmit visible light and absorb infrared energy. These are frequently used in projectors to protect the film or LCD from the heat of the projection lamp. Since they absorb large quantities of radiant energy, they become hot themselves and must be carefully mounted and cooled to avoid breakage from thermal expansion. From the spectral transmission characteristics given in Fig. 7.12, it is apparent that the phosphate heat-absorbing glass is more efficient than the Aklo; the phosphate glass is subject to large bubbles and inclusions which do not, however, prevent its use in

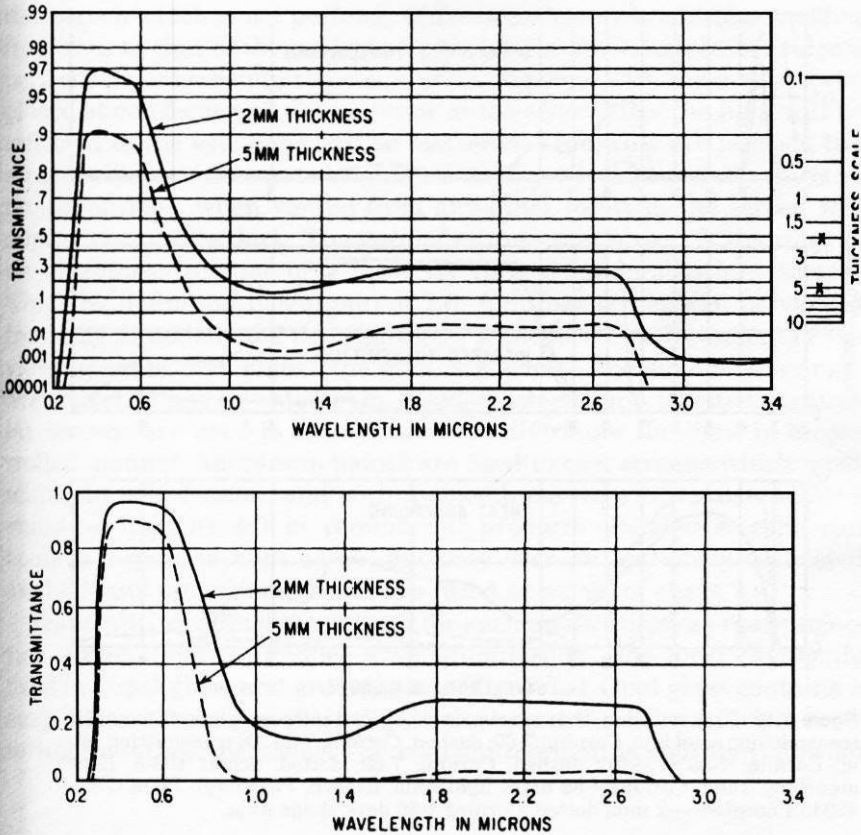


Figure 7.11 Spectral transmittance of Schott KG2 heat-absorbing filter glass. The upper graph is plotted on a log-log scale. Note that the vertical spacing between the two plots is equal to the distance from 2 to 5 on the thickness scale at the right. The same data is plotted on a conventional linear scale in the lower figure for comparison.

most applications. See also the discussion of “hot” and “cold” mirrors in Sec. 7.10.

7.7 Diffusing Materials and Projection Screens

A piece of white blotting paper is an example of a (reflecting) diffusing material. Light which strikes its surface is scattered in all directions; as a result, the paper appears to have almost the same brightness regardless of the angle at which it is illuminated or the angle from which it is viewed. A perfect, or lambertian, diffuser is one which has the same apparent brightness from any angle; thus the radiation emitted per unit area in the surface is given by $I_0 \cos \theta$, where θ is the angle

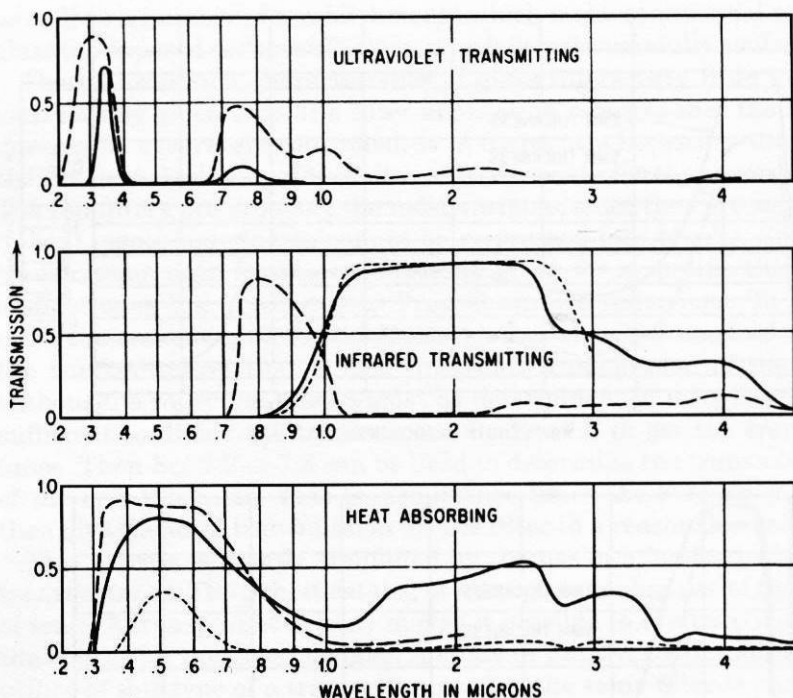


Figure 7.12 Transmission characteristics of special-purpose glass filters. UV transmitting: solid line, Corning 7-60; dashed, Corning 7-39. IR transmitting solid, Corning 7-56 (#2540); dashed, Corning 7-69; dotted, Schott UG-8. Heat absorbing: solid, Corning I-59 extra light Aklo; dashed, Pittsburgh Plate Glass #2043 Phosphate—2 mm; dotted, Corning I-56 dark shade Aklo.

to the surface normal and I_0 is the intensity of an element of area in a direction perpendicular to the surface.

There are a number of quite good reflecting diffusers with relatively high efficiencies. Matte white paper is a very convenient one and reflects 70 to 80 percent of the incident visible light. Magnesium oxide and magnesium carbonate are frequently used in photometric work since their efficiencies are high, to the order of 97 or 98 percent.

The brightness (luminance) of a perfectly diffuse reflector is proportional to the illumination falling on it and to its reflectivity. If the illumination is measured in footcandles, multiplication by the reflectivity yields the brightness in foot-lamberts. The brightness in lamberts is given by the illumination in lumens per cm^2 times the reflectivity, and if this product is divided by π , the result is the brightness in candles per cm^2 , or in lumens per steradian per cm^2 . (See Chap. 8 for more material on photometric considerations.)

As indicated above, a perfectly diffuse surface appears to have the same brightness regardless of the angle at which it is viewed. A projec-

tion screen which is not perfectly diffuse can have a brightness ranging from zero to that of the projector light source. For example, consider a perfect mirror screen in the shape of an ellipsoid, with the viewer's eye placed at one focus and the projector at the other. All of the light will be reflected to the eye; none will be scattered. From this eye position the screen will have the same brightness as if one looked directly into the projection lens; when viewed from any other location, the screen will appear completely dark. The *gain* of a projection screen is the ratio of its brightness to that of a perfectly diffuse (or lambertian) screen, which by definition has a gain of 1.0. A diffuse screen can be viewed from any direction, and its brightness, while low, is independent of the viewing angle. The higher the gain of a screen, the smaller the angle over which it has its rated gain. Beaded screens and faceted, lenticular screens are used to concentrate and distribute the light in a controlled manner. Aluminum paints are used to coat screens which must maintain polarization, and with a smooth curved surface can achieve gains as high as 4.0 in commercial products. Beaded screens can achieve a gain as high as 10, but only over an extremely restricted angle. Many projection screens are rated at a gain of about 2.0.

Transmitting diffusers are used for such applications as rear projection screens and to produce even illumination. The most commonly used are opal glass and ground glass (Fig. 7.13). Opal glass contains a suspension of minute colloidal particles and diffuses by multiple scattering from these particles. The transmitted light is slightly yellowish

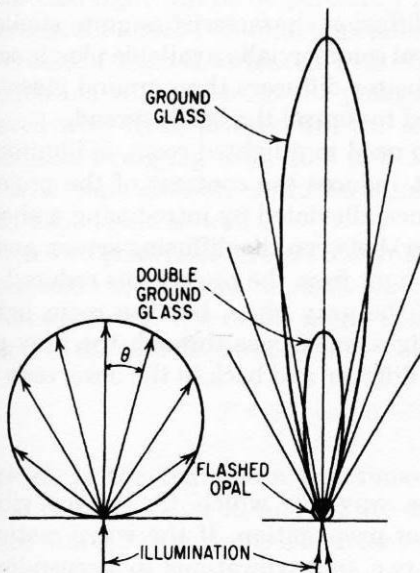


Figure 7.13 Polar intensity plots of diffusing materials. (Left) For a "perfect diffuser, the intensity of a unit area of the surface varies with $\cos \theta$. (Right) The relative intensities of single- and double-ground glass and flashed opal glass.

since the shorter wavelengths are scattered more than the longer. Opal glass is ordinarily used as *flashed opal*, which is a thin layer of opal glass fused to a supporting sheet of clear glass. The diffusion of flashed opal is quite good. When illuminated normally, the brightness at 45° from the normal is about 90 percent of what one would expect from a perfect diffuser. Its total transmission is quite low, about 35 or 40 percent. It should be noted that, since good diffusion means that the incident light is scattered into 2π steradians, the axial brightness of a rear-illuminated screen of good diffusion is very low when compared with a poor diffuser.

Ground glass is produced by fine grinding (or etching) the surface of a glass plate to produce a large number of very small facets which refract the incident light more or less randomly. The total transmission of ground glass is about 75 percent. This transmission is quite strongly directional, and ground glass is far from a perfect diffuser. Its characteristics vary somewhat, depending on the coarseness of the surface. Typically, for a normally illuminated surface, the brightness at 10° from the normal is about 50 percent of the normal brightness; at 30° , the brightness is about 2.5 percent of the brightness at the normal. This characteristic is of course quite useful when partial diffusion is desired. By combining two sheets of ground glass (with the ground faces in contact), the transmission is lowered about 10 percent but the diffusion is improved; at 20° to the normal, the brightness is about 20 percent; at 30° , about 7 percent. With two sheets, the diffusion can be increased by spacing them apart, although this will destroy their utility as a projection screen.

A sheet of tracing paper has diffusion characteristics quite similar to ground glass, and there are several commercially available plastic screen materials which are somewhat better diffusers than ground glass. The plastic surface also can be shaped to control the beam spread.

A rear projection screen, when used in a lighted room, is illuminated from both sides. The room light reduces the contrast of the projected image. This situation is sometimes alleviated by introducing a sheet of gray glass (that is, a neutral filter) between the diffusing screen and the observer. When this is done, the light from the projector is reduced by a factor of T , the transmission of the gray glass, but the room light is reduced by T^2 , since the room light must pass through the gray glass twice to go from the room to the diffuser and back to the observer's eye.

7.8 Polarizing Materials

Light behaves as a transverse wave in which the waves vibrate perpendicular to the direction of propagation. If the wave motion is considered as a vector sum of two such vibrations in perpendicular planes, then plane polarized light results when one of the two compo-

nents is removed from a light beam. Plane polarized light can be produced by passing the radiation from an ordinary source through a polarizing prism, several types of which are available. These prisms depend on the birefringent characteristic of calcite (CaCO_3), which has a different index of refraction for the two planes of polarization. Since light of one polarization is refracted more strongly than the other, it is possible to separate them either by total internal reflection (as in the Nicol and Glan-Thompson prisms) or by deviation in different directions (as in the Rochon and Wollaston prisms).

Such prisms are large, heavy, and expensive. Sheet polarizers, which are made by aligning microscopic crystals in a suitable base, are thin, light, relatively inexpensive, useful over a wide field of view, and simple to fabricate into an almost unlimited range of sizes and shapes. Thus, despite the fact that they are not quite as efficient as a good prism polarizer and are not effective over as large a wavelength range, they have largely supplanted prisms for the great majority of applications where polarization is required. The Polaroid Corporation of Cambridge, Massachusetts, produces a number of types of sheet polarizers. For work in the visible region, several types are available, depending on whether optimum transmission or optimum extinction (through crossed polarizers) is desired. Special types are available for use at high temperatures and also for use in the near-infrared (0.7 to 2.2 μm). Polaroid also produces circular (as opposed to plane) polarizers in sheet form.

Since a plane polarizer will eliminate half the energy, it is obvious that the maximum transmission of a "perfect" polarizer in a beam of unpolarized light will be 50 percent. Practical values range from 25 to 40 percent for sheet Polaroid, depending on the type. If two polarizers are "crossed," that is, oriented with their polarizing axes at 90° , the transmission will be zero if the polarization is complete. This can be achieved with Nicol prisms, but the sheet polarizers have a residual transmission ranging from 10^{-6} to 5×10^{-4} , again dependent on the type. The transmission characteristics of sheet polarizers are wavelength-dependent as well.

When two polarizers are placed in a beam of unpolarized light, the transmission of the pair depends on the relative orientation of their polarization axes. If θ is the angle between the axes, then the transmission of the pair is given by:

$$T = K_0 \cos^2 \theta + K_{90} \sin^2 \theta \quad (7.17)$$

where K_0 is the maximum transmission and K_{90} is the minimum. Typical value pairs for K_0 and K_{90} are 42 percent and 1 or 2 percent; 32 percent and 0.005 percent; 22 percent and 0.0005 percent.

Reflection from the surface of a glass plate may also be used to produce plane polarized light. When light is incident on a plane surface at

Brewster's angle, one plane of polarization is completely transmitted (if the glass is perfectly clean) and about 15 percent of the other is reflected. This occurs when the reflected and refracted rays are at 90° to each other; thus, *Brewster's angle* is given by

$$I = \arctan \frac{n'}{n} \quad (7.18)$$

The reflected beam is thus completely polarized and the transmitted beam partially so. The percentage of polarized light in the transmitted beam can be increased by using a stack of thin plates all tilted to Brewster's angle. For an index of 1.52, Brewster's angle is 56.7° . Note that Brewster's angle is the angle at which the tangent term in Eq. 7.19 goes to zero.

The subject of polarized light is treated at greater length in texts devoted to physical optics, to which the reader is referred. Two additional points are worth noting: one, interference filters (Sec. 7.9) are usually polarizing and are occasionally used as polarizers; and two, opal glass and other diffusers are excellent depolarizers, as are integrating spheres.

7.9 Dielectric Reflection and Interference Filters

The portion of the light reflected (*Fresnel reflection*) from the surface of an ordinary dielectric material (such as glass) is given by

$$R = \frac{1}{2} \left[\frac{\sin^2(I - I')}{\sin^2(I + I')} + \frac{\tan^2(I - I')}{\tan^2(I + I')} \right] \quad (7.19)$$

where I and I' are the angles of incidence and refraction, respectively. The first term of Eq. 7.19 gives the reflection of the light which is polarized normal to the plane of incidence (*s*-polarized), and the second term the reflection for the other plane of polarization (*p*-polarized). As indicated in Sec. 7.1, at normal incidence Eq. 7.19 reduces to

$$R = \frac{(n' - n)^2}{(n' + n)^2} \quad (7.20)$$

The variation of reflection from an air-glass interface as a function of the angle of incidence (I) is shown in Fig. 7.14, where the solid line is R , the dashed line is the sine term, and the dotted line is the tangent term. Notice that the dotted line drops to zero reflectivity at Brewster's angle (Eq. 7.18).

The reflection from more than one surface can be treated as indicated by Eq. 7.5 when the separation between the surfaces is large compared to the wavelength of light. However, when the surface-to-surface

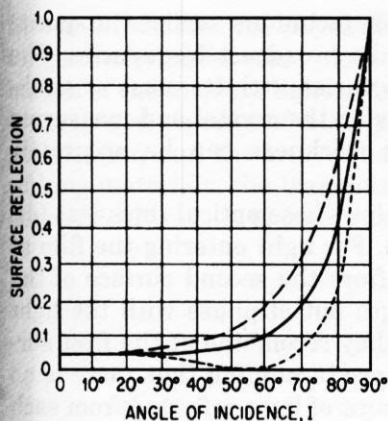


Figure 7.14 The reflection from a single air-glass interface (for an index of 1.523). Solid line is the reflection of unpolarized light. The fine dashed line is the reflection of *p*-polarized light, with the electric field vector parallel to the plane of incidence. The heavier dashed line is for the *s*-polarization. (Note that the "plane of polarization" was originally defined to be at right angles to what we now call the plane of polarization/vibration.)

separation is small, then interference between the light reflected from the various surfaces will occur and the reflectivity of the stack of surfaces will differ markedly from that given by Eq. 7.5. (At this point the reader may wish to refer to the discussion of interference effects contained in the first chapter.)

Optical coatings are thin films of various substances, notably magnesium fluoride (MgF_2 , $n = 1.38$), zinc sulfide (ZnS , $n = 2.3$), silicon monoxide (SiO , $n = 1.86$), tantalum pentoxide (Ta_2O_5 , $n = 2.15$), thorium fluoride (ThF_4), lanthanum trifluoride (LaF_3 , $n = 1.57$), cerium fluoride (CeF_3 , $n = 1.60$), hafnium oxide (HfO_2 , $n = 2.05$), neodymium fluoride (NdF_3) and yttrium oxide (Y_2O_3 , $n = 1.85$), among others, which are deposited in layers on an optical surface for the purpose of controlling or modifying the reflection and transmission characteristics of the surface. Such films have an optical thickness (index times mechanical thickness) which is a fraction of a wavelength, usually one-quarter or one-half wavelength. The deposition of thin films is carried out in a vacuum and is done by heating the material to be deposited to its evaporation temperature and allowing it to condense on the surface to be coated. The thickness of the film is determined by the rate of evaporation (or more precisely, condensation) and the length of time the process is allowed to continue. Since interference effects produce colors in the light reflected from thin films, just as in oil films on wet pavements, it is possible to judge the thickness of a film by the apparent color of light reflected from it. Simple coatings can be controlled visually by utilizing this effect, but coatings consisting of several layers are often monitored photoelectrically, using monochromatic light, so that the sinusoidal rise and fall of the reflectivity can be accurately assessed and the thickness of each layer controlled. By using two different wavelengths (often from lasers), this technique can achieve high

precision. Another popular monitoring technique utilizes a quartz crystal of the type used to control radio broadcast frequencies. The oscillation frequency of such a crystal varies with its mass or thickness. By depositing the coating directly on the crystal and measuring its oscillation frequency, the coating thickness can be accurately monitored.

Let us first consider a single-layer film whose optical thickness (nt) is exactly one-quarter of a wavelength. For light entering the film at normal incidence, the wave reflected from the second surface of the film will be exactly one-half wavelength out of phase with the light reflected from the first surface when they recombine at the first surface, resulting in destructive interference (assuming that there is no phase change by reflection). If the amount of light reflected from each surface is the same, a complete cancellation will occur and no light will be reflected. Thus, if the materials involved are nonabsorbing, all the energy incident on the surface will be transmitted. This is the basis of the "quarter-wave" low-reflection coating which is almost universally used to increase the transmission of optical systems. Since low-reflection coatings reduce reflections, they tend to eliminate ghost images as well as the stray reflected light which reduces contrast in the final image. Before the invention of low-reflection coatings, optical systems which consisted of many separate elements were impractical because of the transmission losses incurred in surface reflections and the frequent ghost images. Even complex lenses were usually limited to only four air-glass surfaces. A magnesium fluoride coating has an additional benefit in that it is actually (when properly applied) a protective coating; the chemical stability of many glasses is enhanced by coating.

The reflectivity of a surface coated with one thin film is given by the equation

$$R = \frac{r_1^2 + r_2^2 + 2r_1r_2 \cos X}{1 + r_1^2 r_2^2 + 2r_1r_2 \cos X} \quad (7.21)$$

where

$$X = \frac{4\pi n_1 t_1 \cos I_1}{\lambda} \quad (7.22)$$

$$r_1 = \frac{-\sin(I_0 - I_1)}{\sin(I_0 + I_1)} \quad \text{or} \quad \frac{\tan(I_0 - I_1)}{\tan(I_0 + I_1)} \quad (7.23)$$

$$r_2 = \frac{-\sin(I_1 - I_2)}{\sin(I_1 + I_2)} \quad \text{or} \quad \frac{\tan(I_1 - I_2)}{\tan(I_1 + I_2)} \quad (7.24)$$

and λ is the wavelength of light; t is the thickness of the film; n_0 , n_1 , and n_2 are the refractive indices of the media; and I_0 , I_1 , and I_2 are the angles of incidence and refraction. Figure 7.15 shows a sketch of the

film and indicates the physical meanings of the symbols. The sine or tangent expressions for r_1 and r_2 are chosen depending on the polarization of the incident light as in Eq. 7.19; for unpolarized light, which is composed equally of both polarizations, R is computed for each polarization and the two values are averaged. If we assume nonabsorbing materials, the transmission T equals $(1 - R)$. At normal incidence $I_0 = I_1 = I_2 = 0$, and r_1 and r_2 reduce to

$$r_1 = \frac{n_0 - n_1}{n_0 + n_1} \quad (7.25)$$

$$r_2 = \frac{n_1 - n_2}{n_1 + n_2} \quad (7.26)$$

Using Eqs. 7.25 and 7.26 for r_1 and r_2 , Eq. 7.21 can be solved for the thickness which yields a minimum reflectance. As the preceding discussion would lead one to expect, this occurs when the optical thickness of the film is one-quarter wavelength, that is,

$$n_1 t_1 = \frac{\lambda}{4} \quad (7.27)$$

At normal incidence the reflectivity of a quarter-wave film is thus equal to

$$\left[\frac{(n_0 n_2 - n_1^2)}{(n_0 n_2 + n_1^2)} \right]^2 \quad (7.28a)$$

and the film index which will produce a zero reflectance is

$$n_1 = \sqrt{n_0 n_2} \quad (7.28b)$$

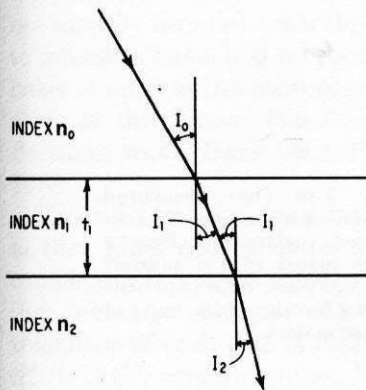


Figure 7.15 Passage of light ray through a thin film, indicating the terms used in Eq. 7.21.

Thus, to produce a coating which will completely eliminate reflections at an air-glass surface, a quarter-wave coating of a material whose index is the square root of the index of the glass is required. Magnesium fluoride (MgF_2) with an index of 1.38 is used for this purpose; its ability to form a hard durable film which will withstand weathering and frequently cleaning is the prime reason for its use, despite the fact that its index is higher than the optimum value for almost all optical glasses. Equation 7.28b indicates that the magnesium fluoride, with its index of 1.38, would be an ideal low-reflection coating material for a substrate with an index of $1.38^2 = 1.904$. Thus it is a much more efficient low-reflection coating for high-index glass than for ordinary glass of a lower index. The measured white light reflection of a low-reflection coating on various index materials is shown in Fig. 7.16.

From Eq. 7.21 it is apparent that the reflectivity of a coated surface will vary with wavelength. Obviously a quarter-wave coating for one wavelength will be either more or less than a quarter-wave thick for other wavelengths, and the interference effects will be modified accordingly. Thus a low-reflection coating designed for use in the visible region of the spectrum will have a minimum reflectance for yellow light, and the reflectance for red and blue light will be appreciably higher. This is the cause of the characteristic purple color of single-layer low-reflection coatings. Figure 7.17 indicates this variation.

With more than one layer, more effective antireflection coatings can be constructed. Theoretically, two layers allow the reduction of the reflection to zero, provided that materials of suitable index are available; frequently, three layers are used for this purpose. Such a coating achieves a zero reflectivity at a single wavelength at the

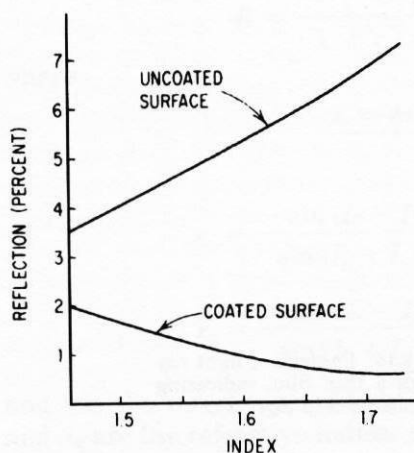


Figure 7.16 The measured reflection of white light from an uncoated surface and from a surface coated with a quarter-wave MgF_2 low-reflection coating, as a function of the index of the base material.

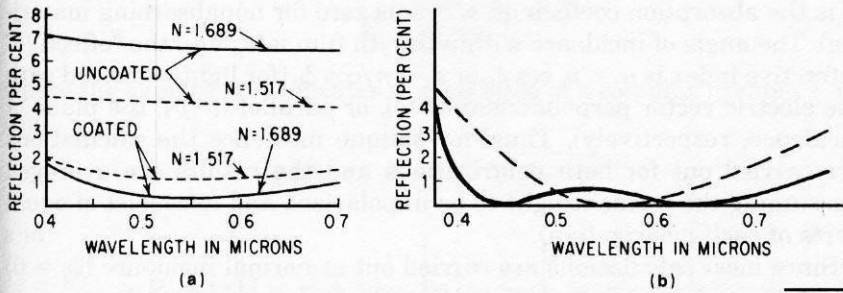


Figure 7.17 (a) The spectral reflectivity of a single-layer quarter-wave MgF_2 coating, compared with the reflectivity of uncoated glass. The solid curves are for a glass of index 1.69 and the dashed curves are for an index of 1.52. (b) Multilayer coatings. The solid line is a broadband multilayer low-reflection coating. The dashed curve is for a "V-coating," which can have zero reflectivity at a single wavelength.

expense of a much higher reflectivity on either side. Because of the shape of the reflectivity curve, this is called a V-coating. It is widely used for monochromatic systems, such as those utilizing lasers as light sources.

With three or more layers, a broad-band, higher-efficiency, low-reflection coating may be achieved as shown in Fig. 7.17. Such a coating may have two minima as shown, or three, depending on the complexity of the coating design. A typical reflection over the visual spectrum is to the order of 0.25 percent, sometimes with another 0.25 percent lost to scattering and absorption.

Thin-film computations

The following equations can be used to calculate the reflection and transmission of an interference coating of any number of layers. The equations can be used at oblique angles and will accommodate absorbing materials. They do require a knowledge of complex arithmetic; if not already familiar with the subject, the interested reader may wish to consult a basic text on complex arithmetic. These equations are the basis of most of the computer programs used in the design and evaluation of thin films. The formulas given here are taken from Peter Berning, in G. Hass (ed.), *Physics of Thin Films*, vol. 1, Academic, 1963.

The reflection and transmission characteristics of a "stack" of several thin films can be expressed in explicit equations; however, their complexity increases rapidly with the number of films, and the following recursion expressions are usually preferable. The physical thickness of each film is represented by t_j and the index by $n_j = N_j - iK_j$ (n is the complex index, N is the ordinary index of refraction, and

K is the absorption coefficient, which is zero for nonabsorbing materials). The angle of incidence within the j th film is ϕ_j ; and the "effective" refractive index is $u_j = n_j \cos \phi_j$ or $u_j = n_j / \cos \phi_j$ (for light polarized with the electric vector perpendicular to $[s]$, or parallel to $[p]$, the plane of incidence, respectively). Thus, for oblique incidence the calculations are carried out for both polarizations and the results are averaged (assuming the incident light to be unpolarized and to consist of equal parts of each polarization).

Since most calculations are carried out at normal incidence ($\phi_j = 0$) and for nonabsorbing materials ($K_j = 0$), one may ordinarily use $u_j = n_j = N_j$.

The subscript notation is $j = 0$ for the substrate, $j = 1$ for the first film, $j = 2$ for the second, etc., $j = p - 1$ for the last film and $j = p$ for the final medium, which is usually air. For each film g_j , the effective optical thickness, in radians, is computed from

$$g_j = \frac{2\pi n_j t_j \cos \phi_j}{\lambda} \quad (7.29)$$

where λ is the wavelength of light for which the calculation is made.

Starting with $E_1 = E_0^+ = 1.0$ and $H_1 = u_0 E_0^+ = u_0$, the following equations are applied iteratively at each surface, with the subscript j advancing from $j = 1$ to $j = p - 1$.

$$E_{j+1} = E_j \cos g_j + \frac{iH_j}{u_j} \sin g_j \quad (7.30)$$

$$H_{j+1} = iu_j E_j \sin g_j + H_j \cos g_j \quad (7.31)$$

where $i = \sqrt{-1}$ and the other terms have been defined above. Readers familiar with matrix notation may prefer to manipulate the equivalent matrix form

$$\begin{pmatrix} E_{j+1} \\ H_{j+1} \end{pmatrix} = \begin{pmatrix} \cos g_j & \sin g_j \\ iu_j \sin g_j & \frac{i}{u_j} \cos g_j \end{pmatrix} \begin{pmatrix} E_j \\ H_j \end{pmatrix} \quad (7.32)$$

When Eqs. 7.30 and 7.31 (or 7.32) have been applied to the entire stack, we have the values of E_p and H_p , which will generally be complex numbers of the form $z = x + iy$. These are substituted into

$$E_p^+ = \frac{1}{2} \left(E_p + \frac{H_p}{u_p} \right) = x_2 + iy_2 \quad (7.33)$$

$$E_p^- = \frac{1}{2} \left(E_p - \frac{H_p}{u_p} \right) = x_1 + iy_1 \quad (7.34)$$

and the reflectance of the thin-film system is found from

$$R = \left| \frac{E_p^-}{E_p^+} \right|^2 \quad (7.35)$$

where the symbol $|z|$ indicates the modulus of a complex number z , so that

$$|z| = |x + iy| = \sqrt{x^2 + y^2}$$

and

$$R = |z|^2 = x^2 + y^2 = \left| \frac{x_1 + iy_1}{x_2 + iy_2} \right|^2 = \frac{x_1^2 + y_1^2}{x_2^2 + y_2^2}$$

If the computation has been for normal incidence through nonabsorbing materials, the transmission is given by

$$T = 1 - R \quad (7.36)$$

Otherwise, the transmission is given by

$$T = \frac{n_0 \cos \phi_0}{n_p \cos \phi_p} \left| \frac{E_0^+}{E_p^+} \right|^2 \quad (7.37a)$$

or

$$T = \frac{n_0 \cos \phi_p}{n_p \cos \phi_0} \left| \frac{E_0^+}{E_p^+} \right|^2 \quad (7.37b)$$

where Eq. 7.37a is used for light polarized with the electric vector perpendicular to $[s]$ and Eq. 7.3b for the electric vector parallel to $[p]$ the plane of incidence.

A discussion of the design of multilayer coatings is beyond the scope of this volume; the interested reader may pursue the subject in the references listed at the end of this chapter. By suitable combinations of thin films of different indices and thicknesses a tremendous number of transmission and reflection effects can be created. Among the types of interference coatings which are readily available are long- or short-pass transmission filters, bandpass filters, narrow bandpass (spike filters), achromatic extra-low-reflection coatings as well as the reflection coatings described in the next section. An extremely valuable property of thin-film coatings is their spectral versatility. Once a combination of films has been designed to produce a desired characteristic, the wavelength region can be shifted at will by simply increasing or decreasing all the film thicknesses in proportion. For example, a spike filter designed to transmit a very narrow spectral band at $1 \mu\text{m}$ can be shifted to $2 \mu\text{m}$ by doubling the thickness of each film in the coating. This, of course, is limited by the absorption characteristics of the substrate and the film materials.

The characteristics of a number of typical interference coatings are shown in Fig. 7.18. Note that the wavelength scale is plotted in arbitrary units, with a central wavelength of 1, since (within quite broad limits) the characteristics can be shifted up or down the spectrum as described in the preceding paragraph. Most interference filters are very nearly 100 percent efficient, so that the reflection for a film is equal to one minus the transmission (except in regions where the materials used become absorbing). Since the characteristics of an interference filter depend on the thickness of the films, the characteristics will change when the angle of incidence is changed. This is in great measure due to the fact that the optical path through a film is increased when the light passes through obliquely. For *moderate* angles the effect is usually to shift the spectral characteristics to a slightly *shorter* wavelength. The wavelength shift with obliquity is approximated by

$$\lambda_{\theta} = \frac{\lambda_0}{n} \sqrt{n^2 - \sin^2 \theta}$$

where λ_{θ} is the shifted wavelength at an angle of incidence of θ , λ_0 is the wavelength for normal incidence, and n is the "effective index" for the coating stack (n is typically in the range of 1.5 to 1.9 for most coatings).

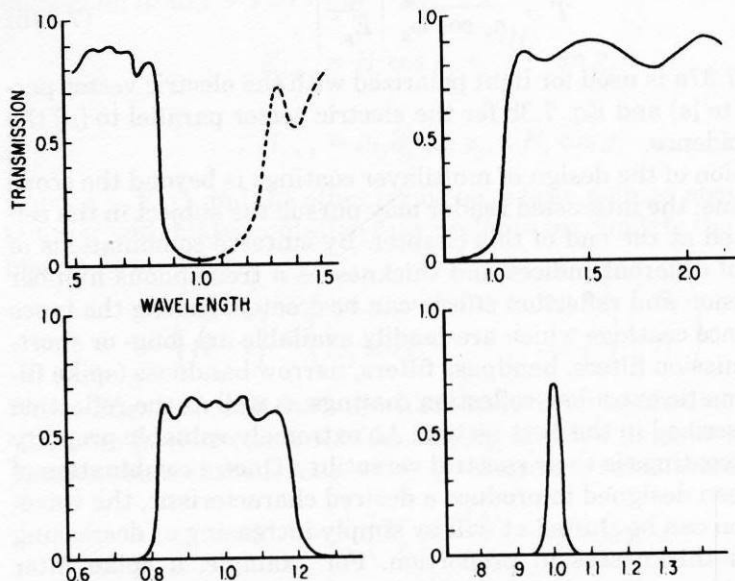


Figure 7.18 Transmission of typical evaporated interference filters plotted against wavelength in arbitrary units. (Upper left) Short-pass filter (note that dashed portion of curve must be blocked by another filter if low long wavelength transmission is necessary). (Upper right) Long-pass filter. (Lower left) Bandpass filter. (Lower right) Narrow bandpass (spike) filter.

Coatings also shift wavelength effects with temperature; this shift is to the order of one- or two-tenths of an angstrom per degree Celsius.

Coatings consisting of a few layers are for the most part reasonably durable and can withstand careful cleaning. However, coatings consisting of a great number of layers (and coatings consisting of 50 or more layers are occasionally used) tend toward delicacy, and must be handled with due respect.

Some multilayer coatings are quite effective polarizers when used obliquely (and as such, are occasionally responsible for "mysterious" happenings). This is notably true in systems using linearly polarized laser beams. One must also exercise care in photometric or radiometric applications (e.g., spectrophotometers), since polarization effects can introduce significant errors.

7.10 Reflectors

Although polished bulk metals are occasionally used for mirror surfaces, most optical reflectors are fabricated by evaporating one or more thin films on a polished surface, which is usually glass. Obviously the interference filters described in the preceding section can be used as special-purpose reflectors in instances where their spectral characteristics are suitable. However, the workhorse reflector material for the great majority of applications is an aluminum film deposited on a substrate by evaporation in vacuum. Aluminum has a broad spectral band of quite high reflectivity and is reasonably durable when properly applied. Almost all aluminum mirrors are "overcoated" with a thin protective layer of either silicon monoxide or magnesium fluoride. This combination produces a first-surface mirror which is rugged enough to withstand ordinary handling and cleaning without undue scratching or other signs of wear.

The spectral reflectance characteristics of several evaporated metal films are shown in Fig. 7.19. With the exception of the curve for rhodium, the reflectivities given here can seldom be attained for practical purposes; the silver coating will tarnish and the aluminum film will oxidize, so that the reflectances tend to decrease with age, especially at shorter wavelengths. The high reflectivity of silver is only useful when the coating can be properly protected.

Figure 7.20 indicates the variety of characteristics which are available in commercial aluminum mirrors. A run-of-the-mill protected aluminum mirror can be expected to have an average visual reflectance of about 88 percent. Two, four, or more interference films may be added to improve the reflectance where the additional cost can be accepted. This enhanced reflectivity within the bandpass of the mirror is obtained at the expense of a lowered reflectivity on either side, as can be seen from the dashed curve in Fig. 7.20.

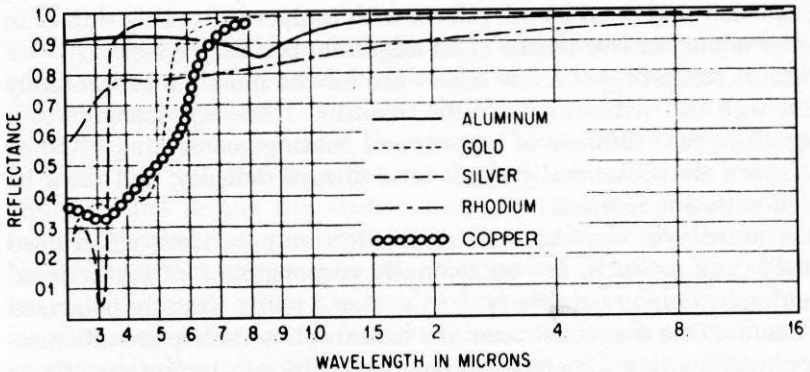


Figure 7.19 Spectral reflectance for evaporated metal films on glass. Data represents new coatings, under ideal conditions.

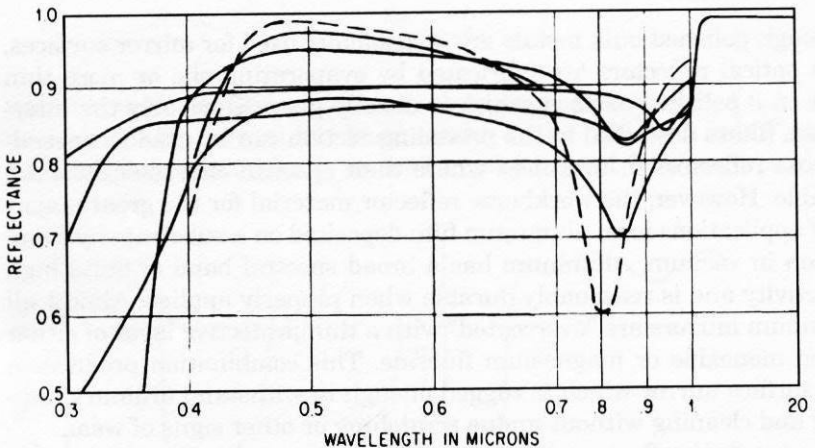


Figure 7.20 Spectral reflectance of aluminum mirrors. The solid curves are for aluminum films with various types of thin film overcoatings—either for protection or for increased reflectivity. The dashed line is an extra-high-reflectance multilayer coating. All coatings shown are commercially available.

Dichroics and semireflecting mirrors constitute another class of reflector. Both are used to split a beam of light into two parts. A dichroic reflector splits the light beam spectrally, in that it transmits certain wavelengths and reflects others. A dichroic reflector is often used for heat control in projectors and other illuminating devices. A *hot mirror* is a dichroic which transmits the visible region of the spectrum and reflects the near infrared. A *cold mirror* does just the reverse, in that it transmits the infrared and reflects the visible. For example, a cold mirror introduced into the optical path will allow undesired heat in the form of infrared radiation to be removed from

the beam by transmitting it to a heat dump. These mirrors have the advantage over heat-absorbing filter glass in that they do not themselves get hot and thus do not require a fan for cooling. A semireflecting mirror is, nominally at least, spectrally neutral; its function is to divide a beam into two portions, each with similar spectral characteristics. Figure 7.21 shows the characteristics of a variety of these partial reflectors.

7.11 Reticles

A reticle is a pattern used at or near the focus of an optical system, such as the cross hairs in a telescope. For a simple cross-hair pattern, fine wire or spider (web) hair is occasionally used, stretched across an open frame. However, a pattern which is supported on a glass (or other material) substrate offers considerably more versatility, and most reticles, scales, divided circles, and patterns are of this type.

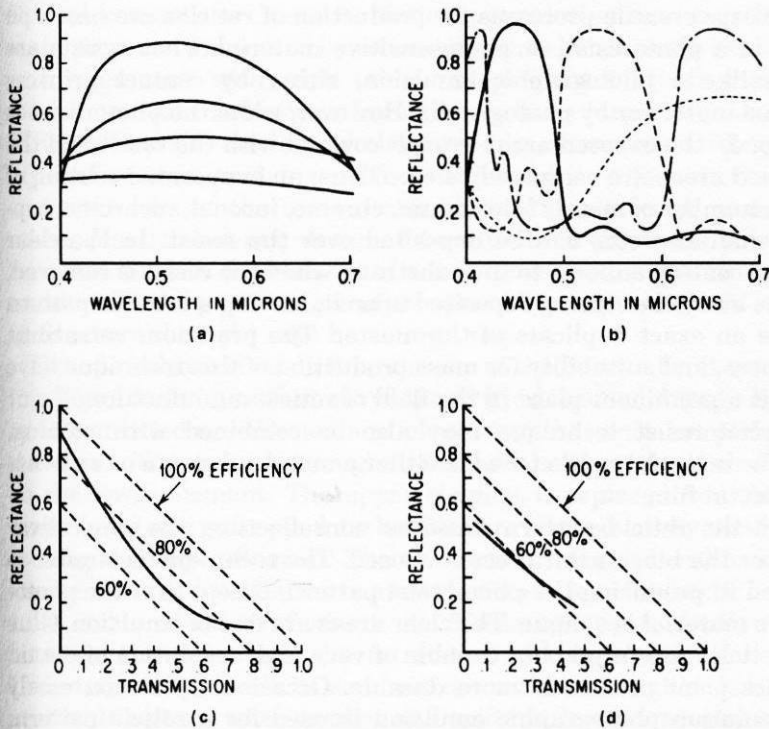


Figure 7.21 Characteristics of partial reflectors. (a) Multilayer "neutral" semireflectors (efficiency better than 99 percent). (b) Dichroic multilayer reflectors—blue, green, red, and yellow reflection. (c) Visual efficiency of aluminum semireflectors. (d) Visual efficiency of chrome semireflectors.

The simplest type of reticle is produced by scribing, or scoring, the glass surface with a diamond tool. A line produced this way, while not opaque, modifies the glass sufficiently so that under the proper type of illumination the line will appear dark. Where clear lines in an opaque background are desired, the glass can be coated with an opaque coating, such as evaporated aluminum, and the lines scribed through the coating with a diamond or hardened steel tool, depending on the type of line desired. Scribing produces very fine lines.

Another old technique is to etch the substrate material. A waxy resist is coated on the substrate and the desired pattern cut through the resist. The exposed portion of the substrate is then etched (with hydrofluoric acid in the case of glass) to produce a groove in the material. The groove can be filled with titanium dioxide (white), or lamp black in a waterglass medium, or evaporated metal. Etched reticles are durable and have the advantage that they can be edge-lighted if illumination is necessary. Any substrate that is readily etched can be used. This process is used for many military reticles and also for accurate metrology scales on steel.

The most versatile processes for production of reticles are based on the use of a photoresist, or photosensitive material. Photoresists are exposed like a photographic emulsion, either by contact printing through a master or by photography. However, when the photoresist is "developed," the exposed areas are left covered with the resist and the unexposed areas are completely clear. Thus, an evaporated coating of any of a number of metals (aluminum, chrome, inconel, nichrome, copper, germanium, etc.) can be deposited over the resist. In the clear areas the coating adheres to the substrate; when the resist is removed, it carries away the coating deposited upon it, leaving a durable pattern which is an exact duplicate of the master. The precision, versatility, ruggedness, and suitability for mass production of this technique have earned it a prominent place in the field of reticle manufacture.

The photoresist technique may also be combined with etching, where the material to be etched is either a metal substrate or an evaporated metal film.

Where the reticle pattern must be nonreflecting, the glue silver process or the black-print process is used. The technique is similar to that used in producing the photoresist pattern, except that the photosensitive material is opaque. The clear areas are free of emulsion. Glue silver reticles are fragile but capable of very high resolution of detail. The black-print process is more durable. Occasionally an extremely high resolution photographic emulsion is used for a reticle pattern; however, the presence of emulsion in the clear areas of the pattern is ordinarily a drawback.

The following tabulation indicates the resolution and accuracy possible with these techniques. These figures represent the highest level of quality that reticle manufacturers are capable of at the present time; if cost is a factor, one is well advised to lower one's requirements an order of magnitude or so below the levels indicated here.

Method	Finest line width, in	Dimensional repeatability, in	Minimum figure height, in
Scribing	0.00001	± 0.00001	
Etch (and fill)	0.0002–0.0004	± 0.0001	0.004
Photo-resist			
(evaporated metal)	0.001–0.002	± 0.00005	0.002
Glue silver	0.00003–0.0002	± 0.00005 – 0.0005	0.002
Black print	0.001	± 0.0001	0.005
Emulsion	0.00005–0.0001	± 0.00005	0.001

7.12 Cements and Liquids

Optical cements are used to fasten optical elements together. Two main purposes are served by cementing: the elements are held in accurate alignment with each other independent of their mechanical mount, and the reflections from the surfaces (especially those from TIR; see Sec. 4.6) are largely eliminated by cementing. Ordinarily the layer of cement used is extremely thin and its effect on the optical characteristics of the system can be totally neglected; some of the newer plastic cements, designed to withstand extremes of temperature, are used in thicknesses of a few thousandths of an inch (which could affect the performance of an optical system under critical conditions where the light rays have large slopes).

Canada balsam is made from the sap of the balsam fir. It is available in a liquid form (dissolved in xylol) and in stick or solid form. Elements to be cemented are cleaned and placed together on a hot plate. When the elements are warm enough to melt the balsam, the stick is rubbed on the lower element. The upper element is replaced and the excess cement and any entrapped air bubbles are worked out by oscillating or rocking the upper element. The elements are then placed in an alignment fixture to cool. Balsam cement has an index of refraction of about 1.54 and a V-value of about 42. These are conveniently midway between the refractive characteristics of crown and flint glasses. Unfortunately, Canada balsam will not withstand high or low temperatures. It softens when heated and splits at low temperatures and is thus unsuited for rigorous thermal environments. Balsam is rarely used today.

A great number of plastic cements have been developed to withstand extremes of both temperature and shock. For the most part, these are thermosetting (heat-curing) or ultraviolet light-curing plastics, although a few thermoplastic (heat-softening) materials are used. Cements are available which will withstand temperatures from 82°C down to -65°C without failure when properly used. In general the thermosetting cements are supplied in two containers (sometimes refrigerated), one of which contains a catalyst which is mixed into the cement prior to use. A drop of cement is placed between the elements to be cemented, the excess cement and air bubbles are worked out, and the elements are placed in a fixture or jig for a heating cycle which cures the cement. Once the cement has set, it is exceedingly difficult to separate the components; the customary technique is to shock them apart by immersion in hot (150 to 200°C) castor oil. The index of refraction of plastic cements ranges from 1.47 to 1.61, depending on the type, with most cements falling between 1.53 and 1.58 with a V-value between 35 and 45. Epoxies and methacrylates are widely used. Because of the variety of types and characteristics which are available, one should consult the manufacturer's literature for specific details regarding any given cement.

A rarely used method of fastening optical elements together is by what is called *optical contact*. Both pieces must be scrupulously cleaned (often the final cleaning is with a cloth slightly stained with polishing rouge) and laid together. If the surface shapes match well enough, as the air is pressed out from between the pieces, a molecular attraction will cause them to adhere in a surprisingly strong bond, which will withstand a force of about 95 lb/in². Usually the only way properly contacted surfaces can be separated is by heating one of them and allowing thermal expansion to break the contact (it often breaks the glass as well). Occasionally, soaking in water will separate the pieces.

Optical liquids are used primarily for microscope immersion fluids and for use in index measurement (in critical-angle refractometers). For microscopy, water ($n_d = 1.33$), cedar oil ($n_d = 1.515$), and glycerin (ultraviolet $n = 1.45$) are frequently utilized. For refractometers alpha-bromonaphthalene ($n = 1.66$) is the most commonly used liquid. Methylene iodide ($n = 1.74$) is used for high index measurement (since the liquid index must be larger than that of the sample to avoid total internal reflection back into the sample).

Bibliography

Note: Titles preceded by an asterisk (*) are out of print.
American Institute of Physics Handbook, 3d ed., New York, McGraw-Hill, 1972.

- Ballard, S., K. McCarthy, and W. Wolfe, *Optical Materials for Infrared Instrumentation*, Univ. of Michigan, 1959 (Supplement, 1961).
- Barnes, W., in Shannon and Wyant (eds.), *Applied Optics and Optical Engineering*, vol. 7, New York, Academic, 1979 (reflective materials).
- Baumeister, P., in Kingslake (ed.), *Applied Optics and Optical Engineering*, vol. 1, New York, Academic, 1965 (coatings).
- Bennett, J. M., "Polarization," in *Handbook of Optics*, vol. 1, New York, McGraw-Hill, 1995, Chap. 5.
- Bennett, J. M., "Polarizers," in *Handbook of Optics*, vol. 2, New York, McGraw-Hill, 1995, Chap. 3.
- Berning, P., in Hass (ed.), *Physics of Thin Films*, vol. 1, New York, Academic, 1963 (calculations).
- *Conrady, A., *Applied Optics and Optical Design*, Oxford, 1929. (This and vol. 2 were also published by Dover, New York.)
- Dobrowolski, J., "Optical Properties of Films and Coatings," in *Handbook of Optics*, vol. 1, New York, McGraw-Hill, 1995, Chap. 42.
- Dobrowolski, J., in W. Driscoll (ed.), *Handbook of Optics*, New York, McGraw-Hill, 1978 (coatings).
- Driscoll, W. (ed.), *Handbook of Optics*, New York, McGraw-Hill, 1978.
- *Hackforth, H., *Infrared Radiation*, New York, McGraw-Hill, 1960.
- Handbook of Chemistry and Physics*, Chemical Rubber Publishing Co., published annually.
- *Hardy, A., and F. Perrin, *The Principles of Optics*, New York, McGraw-Hill, 1932.
- Hass, G., in Kingslake (ed.), *Applied Optics and Optical Engineering*, vol. 3, New York, Academic, 1975 (mirror coatings).
- *Heavens, O., *Optical Properties of Thin Films*, London, Butterworth's, 1955.
- Herzberger, M., *Modern Geometrical Optics*, New York, Interscience, 1958.
- *Holland, L., *Vacuum Deposition of Thin Films*, New York, Wiley, 1956.
- Jacobs, S., in Shannon and Wyant (eds.), *Applied Optics and Optical Engineering*, vol. 10, San Diego, Academic, 1987 (dimensional stability).
- *Jacobs, D., *Fundamentals of Optical Engineering*, New York, McGraw-Hill, 1943.
- Jacobson, R., in Kingslake (ed.), *Applied Optics and Optical Engineering*, vol. 1, New York, Academic, 1965 (projection screens).
- *Jamieson, J., et al., *Infrared Physics and Engineering*, New York, McGraw-Hill, 1963.
- Jenkins, F., and H. White, *Fundamentals of Optics*, 4th ed., New York, McGraw-Hill, 1976.
- Kreidl, N., and J. Rood, in Kingslake (ed.), *Applied Optics and Optical Engineering*, vol. 1, New York, Academic, 1965 (materials).

- Lytle, J. D., "Polymetric Optics," in *Handbook of Optics*, vol. 2, New York, McGraw-Hill, 1995, Chap. 34.
- Macleod, H., in Shannon and Wyant (eds.), *Applied Optics and Optical Engineering*, vol. 10, San Diego, Academic, 1987 (coatings).
- Macleod, H., *Thin Film Optical Filters*, 2d ed., New York, McGraw-Hill, 1988.
- Meltzer, R., in Kingslake (ed.), *Applied Optics and Optical Engineering*, vol. 1, New York, Academic, 1965 (polarization).
- Moore, D. T., "Gradient Index Optics," in *Handbook of Optics*, vol. 2, New York, McGraw-Hill, 1995, Chap. 9.
- Palmer, J. M., "The Measurement of Transmission, Absorption, Emission and Reflection," in *Handbook of Optics*, vol. 2, New York, McGraw-Hill, 1995, Chap. 25.
- Paquin, R. A., "Properties of Metals," in *Handbook of Optics*, vol. 2, New York, McGraw-Hill, 1995, Chap. 35.
- Parker, C., in Shannon and Wyant (eds.), *Applied Optics and Optical Engineering*, vol. 7, New York, Academic, 1979 (refractive materials).
- Photonics Buyers Guide*, Optical Industry Directory, Laurin Publishers, Pittsfield, MA (published annually).
- Pompea, S. M., and R. P. Breault, "Black Surfaces for Optical Systems," in *Handbook of Optics*, vol. 2, New York, McGraw-Hill, 1995, Chap. 37.
- Rancourt, J., *Optical Thin Films*, New York, McGraw-Hill, 1987.
- Scharf, P., in Kingslake (ed.), *Applied Optics and Optical Engineering*, vol. 1, New York, Academic, 1965 (filters).
- *Strong, J., *Concepts of Classical Optics*, New York, Freeman, 1958.
- Thelen, A., *Design of Optical Interference Coatings*, New York, McGraw-Hill, 1988.
- Tropf, W. J., M. Thomas, and T. J. Harris, "Properties of Crystals and Glasses," in *Handbook of Optics*, vol. 2, New York, McGraw-Hill, 1995, Chap. 33.
- *Vasicek, A., *Optics of Thin Films*, Amsterdam, North Holland, 1960.
- Welham, B., in Shannon and Wyant (eds.), *Applied Optics and Optical Engineering*, vol. 7, New York, Academic, 1979 (plastics).
- Wolfe, W., in W. Driscoll (ed.), *Handbook of Optics*, New York, McGraw-Hill, 1978 (materials).
- Wolfe, W., in Wolfe and Zissis (eds.), *The Infrared Handbook*, Washington, D.C., Office of Naval Research, 1985 (materials).

Exercises

- 1 (a) What is the transmission of a stack of three thin plane parallel plates of glass ($n = 1.5$) at normal incidence?

(b) What percentage of the incident light is transmitted directly (i.e., without any intervening reflections)?

ANSWER: (a) 80 percent, (b) $(0.96)^6 = 78$ percent

2 If a 1-cm thickness of a material transmits 85 percent and 2-cm thickness transmits 80 percent, (a) what percentage will a 3-cm thickness transmit? (b) What is the absorption coefficient of the material? (Neglect all *multiple* reflections.)

ANSWER: (a) 75.3 percent; (b) 0.06062 cm^{-1}

3 Determine the coefficients for the dispersion equations given in Section 7.1 for one of the optical glasses listed in Fig. 7.4. Evaluate the accuracy of the equations by comparing the index values given by the equations with those listed in the table (for wavelengths not used in determining the constants).

4 Using the spectral transmission curves of Fig. 7.10, plot the spectral transmission which would result from a combination of filters (c) and (f).

5 Plot, in the manner of Fig. 7.14, the curve of reflection against angle of incidence for a single surface of glass ($n = 1.52$) coated with a quarter wavelength thickness of magnesium fluoride ($n = 1.38$).