SERIES IN OPTICS AND OPTOELECTRONICS

Thin-Film Optical Filters

Fourth Edition

H. Angus Macleod

CRC Press
Taylor & Francis Group
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Thin Film Center Inc.
Tucson, Arizona, USA

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
A TAYLOR & FRANCIS BOOK

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number: 978-1-4200-7302-7 (Hardback)

Library of Congress Cataloging-in-Publication Data

Macleod, H. A. (Hugh Angus)
Thin-film optical filters / H. Angus Macleod. -- 4th ed.
p. cm. -- (Series in optics and optoelectronics)
Includes bibliographical references and index.
ISBN 978-1-4200-7302-7 (hardcover : alk. paper)
1. Light filters. 2. Thin films--Optical properties. I. Title. II. Series.

QC373.L5.M34 2010
681'.42--dc21 2009052758

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Preface to the Fourth Edition

In some ways first editions are easier, or perhaps I should say, less difficult, to prepare than subsequent editions. By the time a fourth edition is required, there is a strong expectation among readers of the character and content of the book. Thus, the author must somehow try to maintain the style at the same time as bringing the book up to date. What to omit and what to include are very difficult questions. Modern optical coating design is virtually entirely performed by computer, frequently using automatic techniques. However, computers do not remove the need for understanding, and I think it is understanding that readers look for in the book. Also, I am conscious that a reader, having perhaps rejected an earlier edition in favor of a later and remembering something important in the earlier, might well expect to find it in the later. I made the decision, therefore, to retain most of the descriptions of the earlier design techniques because of their importance in understanding how designs work. Then, although some of the applications that I describe are rather old, nevertheless they do illustrate how optical coatings are incorporated into a system, and so I retained them. I have tried to incorporate a reasonable amount of new material throughout the book. I added a chapter on color because it is increasing in importance in optical coatings, and, although it is of largely academic interest, I could not resist a section on the effects of gain in optical coatings, because I find it a fascinating topic. Then I struggled with coatings for the soft x-ray region and, with some regret, decided not to include them at this time. It is the old design synthesis problem: one has to stop somewhere.

I am fortunate in my friends and colleagues who have helped me immeasurably with suggestions, advice, and, I have to admit it, corrections. The field of optical thin films has been very good to me. I cannot imagine a more friendly, supportive, and open group of people than the international optical thin-film community. It sets an example the rest of the world would do well to follow.

Thank you, all of you, my readers, publishers, friends, colleagues, family, and especially my wife, Ann.

H. Angus Macleod

Symbols and Abbreviations

The following list gives those more important symbols that have been used in at least several places in the text. We have tried as far as possible to create a consistent set of symbols, but there are several well-known and accepted symbols that are universally used in the field for certain quantities and changing them would probably lead to even greater confusion than would retaining them. This has meant that in some cases the same symbol is used in different places for different quantities. We hope the list will make it clear. Less important symbols, defined and used only in very short sections, have been omitted.

A — Absorptance; ratio of the power absorbed in the structure to the power incident on it.

$\mathcal{A}$ — Potential absorptance; quantity used in the calculation of the absorptance of coatings. It is equivalent to $(1 - \psi)$ where ψ is the potential transmittance.

B — Normalized total tangential electric field at an interface, usually the front interface of an assembly of layers. It is also used very briefly at the beginning of Chapter 2 as the magnetic induction.

C — Normalized total tangential magnetic field at an interface, usually the front interface of an assembly of layers.

d_q — Physical thickness of the qth layer in a thin film coating.

E — Electric vector in the electromagnetic field.

$\mathcal{E}$ — Total tangential electric field amplitude, that is, the field parallel to the thin film boundaries.

$\mathscr{E}$ — Electric field amplitude.

E — Equivalent admittance of a symmetrical arrangement of layers.

F — Function used in the theory of the Fabry–Perot interferometer.

$\mathcal{F}$ — Finesse. The ratio of the separation of adjacent fringes to the half-width of the fringe in the Fabry–Perot interferometer.

g — $g = \lambda_0/\lambda = \nu/\nu_0$ sometimes called the relative wavelength, or the relative wave number, or the wavelength ratio. λ_0 and ν_0 are the reference wavelength and reference wave number, respectively. The optical thicknesses of the layers in a coating are defined with respect to these quantities that are usually chosen to make the more important layers in the coating as close to quarter-waves as possible.

H — Magnetic vector in the electromagnetic field.

$\mathcal{H}$	Total tangential magnetic field amplitude, that is, the field parallel to the thin-film boundaries.
$\mathscr{H}$	Magnetic field amplitude.
H	Represents a quarter-wave of high index in shorthand notation.
I	Irradiance of the wave, that is power per unit area. Unfortunately, the standard SI symbol for irradiance is *E* but to use *E* would cause great confusion between irradiance and electric field. It is even more unfortunate that *I* is the SI symbol for intensity that is the power per unit solid angle from a point source. Doubly unfortunate is that the older definition of intensity is identical to the current definition of irradiance.
k	Extinction coefficient. The extinction coefficient denotes the presence of absorption. The complex refractive index, *N*, is given by $N = n - ik$.
L	Represents a quarter-wave of low index in shorthand notation.
M	Represents a quarter-wave of intermediate index in shorthand notation. Also used for a matrix element, or to indicate an array of matrix elements.
N	Denotes the complex refractive index, $n - ik$.
n	Refractive index or, sometimes, the real part of refractive index.
n^*	Effective index of a narrowband filter, that is, the index of an equivalent layer that yields a shift of its fringes in wavelength, by the same amount as the peak of the narrowband filter, when tilted with respect to the direction of incidence.
p	Packing density, that is the ratio of the solid volume of a film to its total volume.
p	*p*-Polarization, that is the polarization where the electric field direction is in the plane of incidence. It is sometimes known as TM for transverse magnetic.
R	Reflectance. The ratio at a boundary of the normal components of reflected and incident irradiance or, alternatively, the ratio of the total reflected beam power to the total incident beam power.
s	*s*-Polarization, that is the polarization where the electric field direction is normal to the plane of incidence. It is sometimes known as TE for transverse electric.
T	Transmittance. The ratio of the normal components of transmitted and incident irradiance or, alternatively, the ratio of the total transmitted beam power to the total incident beam power.
TE	See *s* for *s*-polarization.
TM	See *p* for *p*-polarization.

x, y, z	Coordinate axes. In the case of a thin film or surface the z-axis is usually taken positive into the surface in the direction of incidence. The x-axis is usually arranged in the plane of incidence and the x-, y-, and z-axes, in that order, make a right-handed set.
$\bar{x}, \bar{y}, \bar{z}$	Three color-matching functions that define the CIE 1931 Standard Colorimetric Observer.
X, Y, Z	Tristimulus values. They are the three basic responses defining a color.
x, y, z	Chromaticity coordinates, $X/(X + Y + Z)$, $Y/(X + Y + Z)$, $Z/(X + Y + Z)$. Usually z is omitted because they are normalized to add to unity.
$X + iZ$	Complex surface admittance.
y	Characteristic admittance of a material given in SI units (siemens) by $N\mathcal{Y}$, that is $(n - ik)\mathcal{Y}$ and in units of the admittance of free space, $\mathcal{Y}$, by N or $n - ik$.
Y	Surface admittance, that is the ratio of the total tangential components of magnetic and electric field at any surface parallel to the film boundaries. $Y = C/B$.
$\mathcal{Y}$	Admittance of free space (2.6544×10^{-3} S).
y_0	Characteristic admittance of the incident medium.
y_m or y_{sub}	Characteristic admittance of the emergent medium, or substrate.
α	Absorption coefficient, given by $4\pi k/\lambda$ usually in units of cm^{-1}.
α, β, γ	Three direction cosines, that is, the cosines of the angle the direction makes with the three coordinate axes.
β	Symbol for $2\pi kd/\lambda$ usually with reference to a metal.
γ	Equivalent phase thickness of a symmetrical arrangement of layers.
Δ	Relative retardation. It is given by $\varphi_p - \varphi_s \pm 180°$ in reflection and $\varphi_p - \varphi_s$ in transmission, where the normal thin-film sign convention for φ_p is used.
Δ	η_p/η_s where η is the modified tilted admittance. The quantity is used in the design of polarization-free coatings.
δ	Phase thickness of a coating, given by $2\pi(n - ik)d/\lambda$.
ε	Indicates a small error in the discussion of tolerances, etc.
ε	Permittivity of a medium.
η	Tilted optical admittance.
ϑ	Angle of incidence.

κ	Sometimes called the wave number, κ is given by $2\pi(n - ik)/\lambda$ where λ is the free space wavelength. Note the confusing use of the term wave number. It is also applied to ν.
λ	Wavelength of light. In the book, except at the very beginning of Chapter 2, it always indicates the wavelength in free space.
λ_0	Reference wavelength. The optical thicknesses of the layers in a coating are defined with respect to the reference wavelength that is usually chosen to make the more important layers in the coating as close to quarter-waves as possible.
ν	Wave number. $\nu = 1/\lambda$ and is frequently expressed in units of cm^{-1} (also sometimes known as kayser. The SI unit is, strictly, inverse meters or m^{-1}).
ν_0	Reference wave number, $1/\lambda_0$.
μ	Permeability. Used in early part of Chapter 2.
ρ	Amplitude reflection coefficient. Used also as electric charge density in early Chapter 2.
τ	Amplitude transmission coefficient.
φ	Phase difference, often in reflection or transmission.
ψ	Potential transmittance, $T/(1 - R)$ or the ratio of the quantities $\mathrm{Re}(BC^*)$ evaluated at two different interfaces. It represents the power emerging from a system divided by the power entering and is unity if there is no loss.

Contents