Chapter 1
Introduction

Thin-film optical systems have evolved over the past several decades from simple metallic coatings to multilayer stacks of dielectric materials that are used to control the reflection, transmission, and absorption of light. Most interestingly, the optical performance of both the simple metallic and multilayer thin-film systems are described by the same optical interference principles. Many of our current commercial optical systems rely on thin-film coatings to optimize their performance and in some cases could not operate without them. Thin-film interference filters are responsible for the high-reflectance, antireflective, and band-control coatings that define the performance of optical elements used in high-power laser systems, high-quality binoculars, telescopes, cameras, displays, and many other applications. The thin-film coating industry is fast becoming a multibillion dollar market, which has created considerable interest and motivation for engineers and scientists to improve their understanding of thin-film optical coating design and synthesis.

Many applications of thin-film interference coatings are currently in use to improve the performance of reflection and transmission optics. The field of optical coatings is broad and encompasses far more than can be presented here, and continues to grow and expand. However, there is considerable overlap and commonality in the many specific applications of thin-film coatings. Bandpass optical interference filters, especially induced-transmission filters, incorporate many of the features and components of other thin-film system designs so are an ideal starting point to develop our understanding of thin-film optical coatings. Induced-transmission filters are interesting, as they include absorbing layers, i.e., metallic layers, so involve working with the complex index of refraction. As such, bandpass optical interference filters demonstrate many advanced thin-film concepts, including how several separate structures can be combined to obtain a desired transmission profile.

Many outstanding publications on thin-film optical systems written for engineers, scientists, technicians, and students are available, a few of which are listed in the reference section of this chapter[1–8] and in the bibliography. The foundations for describing and analyzing thin-film optics are summarized by Heavens[1] in his 1955 book *Optical Properties of Thin Solid Films*, and these fundamentals are expanded on by MacLeod[2] in his book *Thin-Film Optical Filters*, whose popularity is underscored by being in its Fifth Edition. Baumeister's work *Optical Coating Technology*[3] provides details on thin-film coatings from classes he taught and his work on the analysis of metallic filters using unique methods. Cushing's *Enhanced Optical Filter Design* builds on the fundamental concepts of thin films and adds an intuitive approach to improving filter performance. These books also include many references to the research associated with the fundamental developments in the field and are important resources for anyone in thin-film work. Additionally, many excellent online freeware and commercial software programs are available that can be used to perform nearly any thin-film calculation that may be required. A list of commonly used software packages is provided in the Appendix, and an Internet search provides an ever-growing list of thin-film calculation programs. Interested readers are encouraged to explore these calculators and decide if they are appropriate for their use.

One of the challenges for many scientists and engineers is that, no matter how well a book or a program is written, there is always the desire to be able to generate one's own results. This approach often serves two purposes. First, of course, is to be able to solve a specific problem at hand; however, it can be argued that this can be accomplished more effectively by using already existing programs. The second purpose lies in the do-it-yourself (DIY) approach, which not only can be used to solve a particular problem, but can also provide a means of developing an enhanced understanding of the topical area and the underlying subtleties in the mathematics. It is this second approach that drives this book, and it is hoped that the DIY approach of integrating the optical concepts and supporting mathematics into programs will lead the reader to a better and deeper understanding of the topic. Essentially, this is a foundation for a programming-based learning style applied to thin-film optical coatings.

This book is intended to provide a bridge between the physics concepts of optical thin-films and the mathematics used in designing and modeling the performance of thin-film optical systems. Its aim is to provide a guide to simulating the performance of optical interference filters using custom-built MATLAB® programs. The ability to generate custom programs and tune them to explore specific features of optical interference filters is anticipated to enhance the designer's understanding and appreciation of the subtleties in filter design. Many practicing scientists, engineers, and engineering colleges have adopted MATLAB as their standard scientific computing tool, and MATLAB works well for developing the numerical calculations for thin-film simulations. MATLAB's calculation power and visualization tools provide the needed functionality to see and interpret filter performance, and study the effects of refining the design of these optical filters. MATLAB is available through The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098 United States, www.mathworks.com. The availability and low cost of high-performance computing allows almost all users the ability to perform high-fidelity calculations of optical filters. The programs included in this book are meant to serve as a starting point for those interested in developing their own routines and are not designed to compete with commercial programs.

This chapter provides an overview of the topics explored in this book and introduces some of the key concepts that are expanded on in later chapters. The bibliography at the end of the book contains a list of works that were useful in developing the material included here. While it is not an exhaustive list of authors and their work, the included publications should be useful to those interested in understanding, modelling, and designing optical interference filters.

1.1 Optical Filters

Optical filters operate on one of two basic principles—absorption and the interference of light—thus, these filters are often identified as either absorptive or interference filters.[2–4] Both of these filter types are actively used and can be combined to produce a desired overall filter response. The filter type we will explore in detail is the bandpass transmission filter, including the induced-transmission filter, which is unique in that it is a transmission interference filter with absorption as a fundamental part of its design. In all cases, an optical filter is completely specified by the wavelengths, magnitude, and phase of the light output from the filter compared to the incident light, neglecting secondary losses and nonlinear effects.

Absorption filters, sometimes called gel filters,[8] operate by absorbing specific wavelengths of light within the filter while passing other wavelengths, so are commonly used as transmission filters. In general, the light transmitted by the filter has had the intensity of some wavelengths reduced from the spectrum of the incident light. The absorption filter is illustrated in the upper portion of Fig. 1.1. These filters are widely used in photography as well as in more-demanding applications in scientific instrumentation, ranging from microscopy to telescopy and from astronomy to zoology. These absorbing filters incorporate various compounds, typically metal salts,[7,8] that are added to glass or plastic to act as absorbers, and the filters are often identified by having a distinctive color. It is important to note that many liquids can also serve as filters and are valuable when nonstandard surface shapes are involved.

A wide variety of absorption optical filters are available and have been a mainstay for use in photography for many decades. More recently, these filters have become popular for many industrial uses, including computer vision applications. One of the more common photographic filters is the Eastman Kodak Wratten filter,[8] which incorporates a numbering system that is familiar

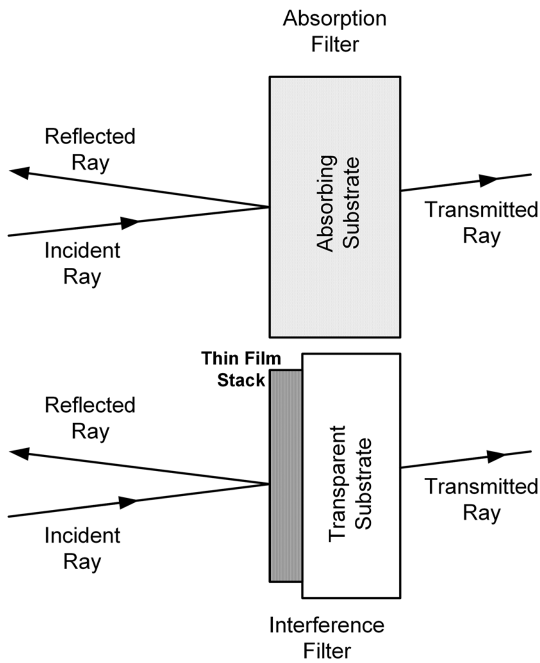

Figure 1.1 Comparison of an absorption filter (top) and an interference filter (bottom) showing the incident, reflected, and transmitted ray. Absorbing filters are rarely used in reflection.

to many. The filters are identified by a number and sometimes by a letter in the codes, e.g., the 80B filter, which transmits blue light. The numbering system, while common, does not contain any wavelength information. The numbering system, while in common use, does not infer wavelength information for the filter. The numbers do indicate color information for the filter, but there is no obvious correlation in the number sequence. That is, numbers close together do not indicate similar colors. For example, consecutive filters numbered 81 and 82 indicate orange and blue filters, respectively, and while their numbers are close, their colors are well separated in wavelength. In use, these absorbing filters are commonly placed over the front of a camera lens, allowing only specific wavelengths to pass through to the light-sensitive imager. Such filters can be constructed to pass specific wave bands such as blue, green, or red light and so are known as bandpass filters. Many imaging applications do not require narrow band passes or precise band widths to make a good image, as has been demonstrated by the creative work of many photographers, making these filters ideal. However, many scientific applications require very precise and narrow bandpass regions. For such applications, optical interference bandpass filters can be constructed using stacks of alternating high– and low–index-of-refraction thin-film layers that use interference principles to generate the output.

Interference or dichroic filters (lower image of Fig 1.1) make use of multiple thin layers of optical materials and operate using constructive and destructive interference of light to control wavelengths that are transmitted or reflected. As with absorption filters, interference filters have wide application. Interference filters are ideally suited to scientific instrumentation as their transmission and reflection curves can be highly controlled, and very sharp transitions and narrow bandpass regions are possible. The thin-film coatings are supported on an optical substrate, which for visible light is often a glass plate or window.[2–4] One drawback to the interference filter is that it is designed to work with collimated light and operate within specific entrance angles, typically at normal incidence. Light not entering at the defined entrance angle follows different paths and therefore encounters different path lengths through the layers of the filter, which shift the wavelength response from the designed wavelength.[1–4]

Optical filters can be designed to provide many output profiles in both transmission and reflection based on the input illumination. These filter profiles include: long-wavelength-pass filters, which pass light above a certain turn-on wavelength; short-wavelength-pass filters, which have a turn-off wavelength above which the filter blocks the light; neutral density filters, which have a constant attenuation over a broad wavelength range; and broadband filters such as ultraviolet and infrared filters, which can block or pass specific bands.

1.2 Interference Filters

Optical interference filters are constructed by depositing materials in thin, uniform layers onto a suitable substrate. Many materials can be used as substrates, e.g., glasses, plastics, metals, and semiconductors to name a few possible choices.[2–4] Many of these materials can also be deposited onto other substrates as thin films as well. Numerous techniques can be used for depositing the thin-film layers, including chemical vapor deposition, electron beam deposition, magnetron sputtering, ion beam sputtering, and physical thermal vapor deposition.[1–4,7] Each of these approaches has its merits, and selection of one approach for use in deposition is typically determined by the material to be deposited, as not all techniques work well for all materials.

A deposition technique often used in manufacturing interference filters is physical vapor deposition.[2–4,8] Physical vapor deposition typically uses resistive heating of metal elements or ceramic crucibles to melt the deposition material in a vacuum chamber at pressures typically below 10^{-6} Torr. Materials such as silver, gold, and aluminum can be deposited using metal boats that are heated until the material evaporates and radiates away to be deposited on target that is often a rotating glass surface positioned above the source. When different materials are to be deposited onto a surface, a plate is moved over the source to physically block the flow of material to the plate, and the deposition process continues using the next source.

The performance of an interference filter is controlled by the organization of the thin-film layers, of which there can be many in a filter. Under uniform broadband illumination, these layers—or (more specifically) the interfaces between the thin-film layers—act as reflectors, and the light reflected from the layers combines destructively or constructively, depending on the wavelength. The result is that the output intensity from the filter varies with wavelength. The filter's output profile can be controlled by varying the number of layers and the layer order. Many interference filters are designed using nonabsorbing dielectric materials, which has the advantage of minimizing light loss in the thin-film stack due to absorption and allows a large number of layers to be used to create filters.

The simplest strategy for bandpass interference filters makes use of layer thicknesses that are on the order of one-quarter of the wavelength of the light at the center of the band. This introduces the common thin-film thickness unit known as the quarter-wave optical thickness (QWOT). As such, even when many layers or layer pairs are used in a particular design, the thin-film stack that defines the filter is not very thick. A filter composed of one hundred layers can be constructed with an overall optical thickness of 100 QWOT or 25 wavelengths of light. The physical thickness of the thin-film stack will be slightly less than if we convert 25 wavelengths to the actual thickness in meters, as a correction is required to account for the index of refraction of the materials in each layer. For a single layer, the relationship between these parameters is given as

$$\mathrm{QWOT} = nd = \frac{\lambda_0}{4}, \tag{1.1}$$

where λ_0 is the design or central wavelength of the bandpass, d is the physical thickness, and n is the index of refraction of the layer.

1.3 Bandpass Filters

The focus of this book is on bandpass filters; however, the topics of interest by necessity stray from this single topic. As an example, narrow-bandpass filters can be constructed by combining a high-pass filter and a low-pass filter. The effect is that the overlapping low- and high-pass filters allow the wavelengths in common to both filters to be passed, as shown in Fig. 1.2. Mathematically, the output is the product of the transmission profiles of the two filters, provided they are constructed as separate optical elements.

An alternative approach is to use a Fabry–Pérot cavity, which can be constructed from dielectric thin-film materials.[1–8] The bandpass filters are

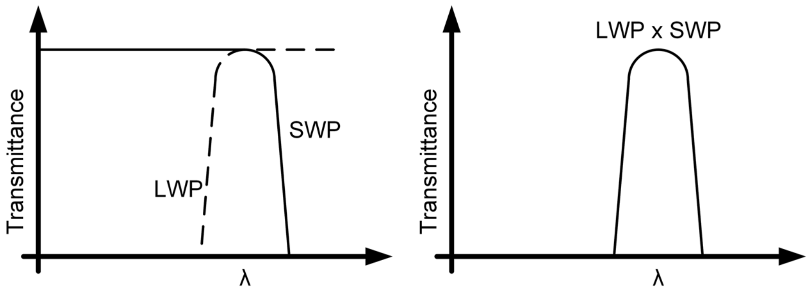

Figure 1.2 A bandpass filter constructed from overlapping long-wavelength-pass (LWP) and short-wavelength-pass (SWP) filters. This approach is often used for filters designed to pass a broad range of wavelengths.

constructed by including a half-wavelength optical thickness, or 2 QWOT, of one of the thin-film materials to form a Fabry–Pérot cavity. It is also possible to construct these filters using many of these cavities, which has a net effect of narrowing the width of the bandpass peak. Optical interference filters are designed to operate at a specific entrance angle of the incident light. One drawback to the interference filters is that, if it is used at an angle other than the designed operating angle, there will be a shift in the wavelength of the output profile.[2,3] A basic bandpass filter structure with a single half-wavelength-thick layer cavity is shown in Fig. 1.3.

The thin-film layers of an interference stack are typically designated by the relationship between the indices of refraction [such as low (L) and high (H) in Fig. 1.3] with respect to each other. LL indicates two L layers in sequence and is the structure of the Fabry–Pérot cavity used to generate the bandpass, which will appear as a narrow spike in the transmission profile of the filter. The glue layer in Fig 1.3 represents an epoxy whose refractive index is matched to the refractive index of the substrate. Index matching is required because the thin-film layers are deposited on one substrate, and the second substrate must be attached to protect the more delicate thin-film

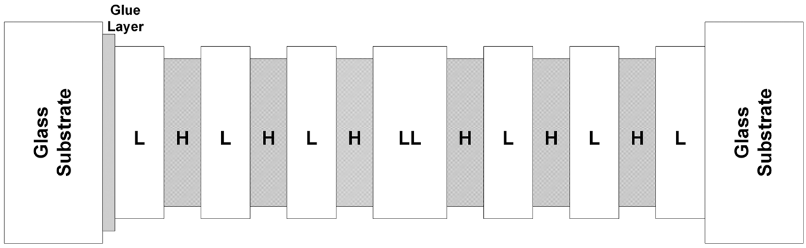

Figure 1.3 Structure of a single-cavity bandpass filter made up of high– and low–refractive-index layers. Notice the glue layer on the left hand side to attach the second substrate.

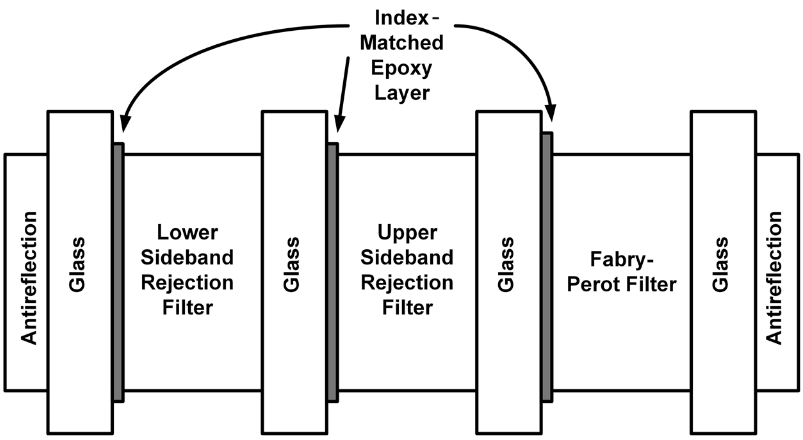

Figure 1.4 Block diagram of a complete bandpass interference filter that incorporates additional filters to control light leaks. Notice that this is a composite structure with thin-film filters on their own substrates.

layers. This offers the advantage of having a glass material on either side of the thin-film structure, which provides excellent scratch resistance for the thin-film layers.

The transmission profile of a Fabry–Pérot-based filter like the one shown in Fig. 1.3 is not optimal. While the bandpass or spike feature of the transmission curve is well defined, there is typically significant unwanted light transmission above and below the bandpass. The unwanted transmission is controlled by adding in blocking filters that will allow the light in the bandpass through, but will block the unwanted light. Thus, a complete filter comprises several specific thin-film structures or filters stacked together to make a single filter. A complete bandpass filter made up of three individual filters is shown in Fig. 1.4. Notice the glass windows at the entrance and exit of the filter. The performance of a complete bandpass filter can be obtained from the product of the transmission profiles of each of the individual filters. In this way, the individual filters can be designed separately using different central wavelengths, simplifying the design process.

1.4 Induced-Transmission Filters

Many dielectric optical materials, including many glasses, do not appreciably absorb visible light, but may absorb light in the ultraviolet region at the short-wavelength end of the spectrum. The index of refraction is a function of wavelength and is actually a complex number.[1–4] The first term of the complex index of refraction relates to the ratio of the speed of light in vacuum to that in a medium, and the second term relates to absorption in the material.

In a dielectric material, which is nonabsorbing, this latter term is zero. Interestingly, metals are absorbing materials, and the complex index of refraction N is written as

$$N = n - jk, \tag{1.2}$$

where $j = \sqrt{-1}$, and k is the extinction coefficient.

Normally, absorption is not desirable in the layers that make up an interference filter; however, the induced-transmission filter embeds an absorptive layer in a dielectric stack that can be used to great advantage. Typically, the absorptive layer is a thin metal layer some tens of nanometers thick, as shown in Fig. 1.5. It is also possible to use multiple metal layers in the filter and thereby tune the performance of the filter. The advantage of these multiple-cavity filters often takes the form of extremely effective long-wavelength rejection. The challenge is that considerable design effort is needed to impedance match the metal layer to the substrate. Impedance matching is a major consideration in designing these filters.

Induced-transmission and multiple-metal-layer filters combine many of the design elements common to dielectric thin-film filters, but the introduction of absorption also introduces some dramatic new properties that must be taken into account. In many cases, simple design tools are not sufficient to properly incorporate the absorbing layers, and new visualization tools are needed to both create and understand these filters.[2–4]

The idea has been introduced that bandpass filters made from Fabry–Pérot cavities may require additional filters to remove unwanted light. This can be accomplished by adding other filters, a gel-type absorption filter, or a multi-cavity filter. However, one of the uses of the induced-transmission filter, whose function centers on the desired bandpass, is to provide significant suppression of wavelengths on the long-wavelength side of the filter.[2–4] This suppression can result in a reduction of throughput in the bandpass, but it greatly improves the

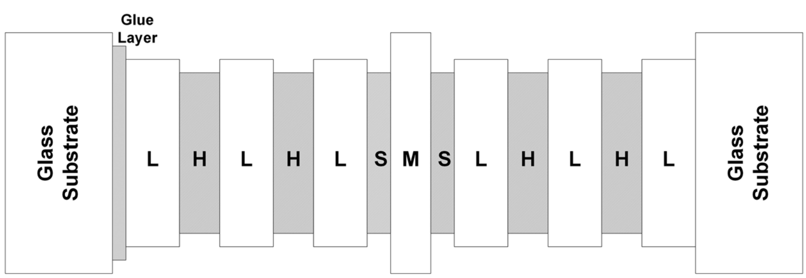

Figure 1.5 Structure of an induced-transmission filter showing the position of the metal layer (M) and adjacent spacer layers (S). The induced-transmission filter can be used to suppress the long-wavelength-light leaks in a bandpass filter.

removal of the unwanted sideband, i.e., wavelengths transmitted outside of the desired bandpass on the long-wavelength side. Developing models for the design of such bandpass filters is a large component of this book.

1.5 MATLAB®

Computer simulation of interference filters is almost a requirement as there can be tens to many hundreds of layers in a single filter. As such, most texts on interference filters include computer codes to assist in understanding the material. However, the programming language used in these texts has not always been accessible to the reader who has not spent considerable time working in that language, and the visualization tools for these languages have not always been the best. Understanding interference filters is much simpler when working with a computer language that has excellent visualization tools and allows for easy manipulation of matrices.

The strength of MATLAB for use in optical interference calculation is its combination of visualization and matrix manipulation capabilities. The calculations to be performed include large numbers of matrix multiplications. While the matrices are not particularly large, the number of matrix multiplications can be significant, and this is where MATLAB provides many advantages.[9] Additionally, many of the concepts required to understand interference calculations are more readily accessible when the visualization tools in MATLAB are used.

As we develop our optical interference filter calculators and analysis tools, much of the mathematics will be in the form of matrices and vectors. MATLAB was designed to work easily with these elements and therefore streamlines code writing so that the code is easy to both follow and maintain.

MATLAB features many different plotting functions and can easily represent data in multiple dimensions, and can even make movies to provide time evolution of the data. It is not necessary to be a MATLAB expert to develop your own simulation code in conjunction with this book. Numerous MATLAB examples are included to develop the plots shown throughout the text, and these examples can be expanded to provide even more details on the simulations.

MATLAB is more than just a programming environment and is constantly evolving, with capability changes from version to versions. The current implementation is MATLAB 2018b. The examples used in this book were built and evaluated using MATLAB 2016a through MATLAB 2018b, although the majority of the code will run on any modern version and most of the older versions. An advantage to using MATLAB 2016a (and higher versions) is a feature that is used here, which is the ability to include functions within a MATLAB script. If you are using an older version, this ability may require separating the functions into their own files.

1.6 Summaries of the Chapters

Each of the chapters that follow introduces concepts related to interference filters and, as appropriate, develops the MATLAB code to demonstrate the particular mathematics that drives the topic. The results of the calculations are presented using MATLAB visualization tools to support understanding the various topics. A short overview of the topics in each of the subsequent chapters is provided here.

Chapter 2—Light: Reflection and Transmission introduces the fundamental properties of light that are of interest in optical filters and describes the mathematics used in the calculations. This discussion leads to the fundamental mathematical form we will use for the calculations, the characteristic matrix, and demonstrates how this matrix results in the ability to calculate the transmission, reflection, and absorption of light.

Chapter 3—Complex Index of Refraction in Optical Materials introduces the complex index of refraction and its importance in working with metals. Metals are examples of materials that absorb light, and absorption is important in calculating the characteristics of metals.

Optical admittance is the focus of Chapter 4—Optical Admittance Matching and is calculated as a function of the film thickness. The optical admittance diagram is used to show the importance of quarter-wavelength layers and the effects of thickness changes to thin films.

Chapter 5—Dielectric Thin-Film Structures introduces different dielectric filter structures assembled from thin optical films. Most important to this work is the spike structure, which is used to define the bandpass. Other filters are used to remove unwanted sidebands and light leaks in the filter.

Chapter 6—Maximum Potential Transmittance for Induced-Transmission Filters introduces the induced-transmission filter or metal bandpass filter. In these filters, absorbing metal layers are used to generate spike structures that have very strong long-wavelength-rejection properties. A technique is introduced for matching the metal layer to a substrate by controlling the admittance of the structure.

Chapter 7—Offband Effects in Induced-Transmission Filters introduces the properties of three different metals that are used as the absorbing material in induced-transmission filters. The peak shape and long-wavelength suppression of these metal filters are explored.

The design of spike structures is explored in Chapter 8—Enhancing Bandpass Filters, including increasing the number of cavities and changing the reflector design to improve the overall peak shape.

Several applications for interference filters are introduced and discussed in Chapter 9—Interference Filter Applications using the simulation tools that are developed throughout the book.

The final chapter, From Simulations to Functional Filters, provides a summary of topics needed to go beyond *simulating* filters and actually start constructing them. Chapter 10 also identifies some useful references to consult.

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