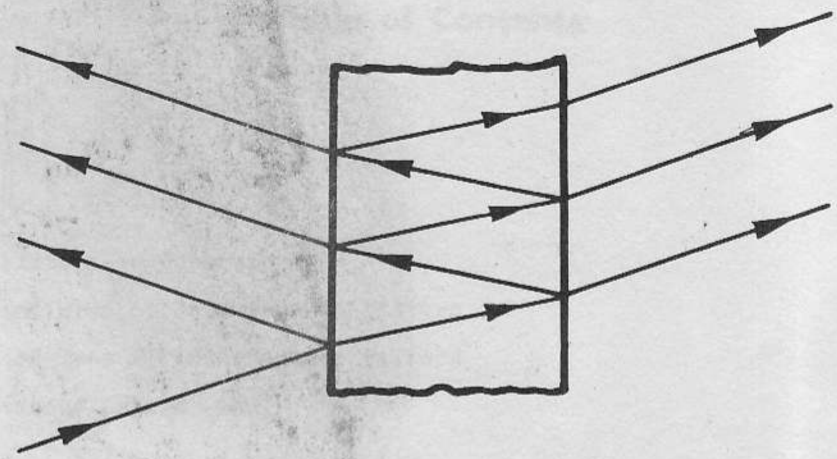
Monochromatic Transmission-Type
INTERFERENCE FILTERS



for efficient isolation of narrow spectral bands in

Colorimetry
Fluorimetry
Flame Photometry
Color Densitometry,

also in reflectometry, microscopy, photomicrography, polarimetry, retractometry, light-scattering measurements, and in many other fields wherever high-purity monochromatic light is required in the visible, near-ultraviolet, and near-infrared range.

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INTRODUCTION

Color Filters in General

Color filters, generally speaking, are plates of clear transparent materials such as glass, plastics, or gelatin which transmit light selectively in the sense that they transmit more light in some parts of the visible spectrum than in other parts. The region of higher transmission determines the color appearance. A red glass appears red because it transmits a comparatively large part of the red light and absorbs a comparatively large part of the blue and green light.

Color filters are said to "isolate" a spectral wave band if they transmit light exclusively in one limited band of the spectrum and absorb all the light outside of this band. Such filters are usually called broad-band filters if the isolated band has a spectral width of approximately 50 millimicrons or more. They are called narrow-band filters, if the band width is appreciably less than 50 millimicrons, and they are designated as "monochromatic" if the isolated band is so narrow that, when viewed in transmitted white light, they give a color appearance which is close to a pure spectrum color.

Up till a few years ago, all color filters consisted of colored glass (or gelatin or plastics) which owed its color effect to coloring agents dissolved or suspended in the glass. Such colored glass, however, mostly transmits light over a wide spectral range. Therefore, in order to make up narrow-band color filters from colored glass, it is necessary to use combinations of at least two glasses, one to cut off towards the long-wavelength side, the other towards the short-wavelength side. In this way, it is possible, with the aid of the available colored glasses, to make up monochromatic filters of 30 millimicrons width or less in most parts of the visible spectrum, and filters of this kind are widely used. However, the luminous efficiency of such filters is comparatively low inasmuch as they mostly do not transmit more than 10% of the light even at the wavelength at which they have their maximum transmission.

Completely new methods of producing color filters have been developed during the last fifteen years. The isolation of wave bands is achieved by interference of light waves in passing through very thin layers of suitable materials, rather than by combining glasses that contain coloring agents. The principle, of course, is old and widely encountered in nature. The color of the wings of a butterfly, for instance, is partly produced by a thin film on an opaque background. Color effects without pigmentation or coloring agents can also be observed in soap bubbles and in thin films of oil on water.

Color filters consisting of colored glass or gelatin absorb the light which they do not transmit. A filter of this kind, if it transmits, for instance, between 420 and 480 millimicrons, will appear blue no matter in which relative position to the light source it is being viewed. Interference filters reflect most of the light which they do not transmit. In fact, the luminous effect of the reflected light is much stronger than that of the transmitted light, the latter comprising only the narrow isolated band, the former comprising all the other visible light. Therefore, under most viewing conditions, an interference filter will have the appearance of an almost colorless mirror. Its color effect can only be observed if it is viewed exclusively by transmitted light. This can be achieved best by observing a source of white light with the filter held close to the eye.

The Principles of Interference Filters

There are two ways in which interference of light waves can be made use of to produce color filters. The most widely used method is based on the principle of the Fabry-Perot Interferometer. The interference effect is obtained as a result of multiple reflection on two highly reflecting but partially transparent parallel metallic layers. In this way, the isolation of a narrow wave band is achieved as explained in further detail below. Interference filters made on the basis of the Fabry-Perot principle will here be designated as FP filters.

In the other method, the metallic layers are replaced by alternating layers of high and low indices of refraction. The multilayer method results in a sharp cut-off towards the one or the other side of the spectrum, and multilayer interference filters are sometimes employed just for cut-off purposes (dichroic filters). However, by combining two multilayer components, one cutting off towards the long-wavelength side, the other towards the short-wavelength side, one can produce filters isolating extremely narrow spectral bands and also broad bands of any desired width. Multilayer filters will be designated here as ML filters.

All interference filters offered in accordance with this bulletin are of the FP type. However, some of the filters are equipped with ML components which act as auxiliary filters to suppress "side bands" and "stray light" as explained in further detail on page 184.

Theory of Type FP Interference Filters

The Interferometer of Fabry-Perot serves for the measurement of length. It operates with strictly monochromatic light. The metallic layers are at a considerable distance from each other, and there is air between them.

While based on the same principle, the interference filters are designed to be acted upon by white light and to isolate certain spectral bands by transmitting light only within this band. This makes it necessary to work with an extremely short distance between the metallic layers. To maintain such short distance with the required degree of accuracy, a spacer layer of transparent material is deposited on the first metallic layer, and the second metallic layer is then deposited on the transparent layer. The transparent layer is made of material of low refractive index and is, by way of analogy with similar phenomena in the field of electricity, sometimes referred to as "dielectric".

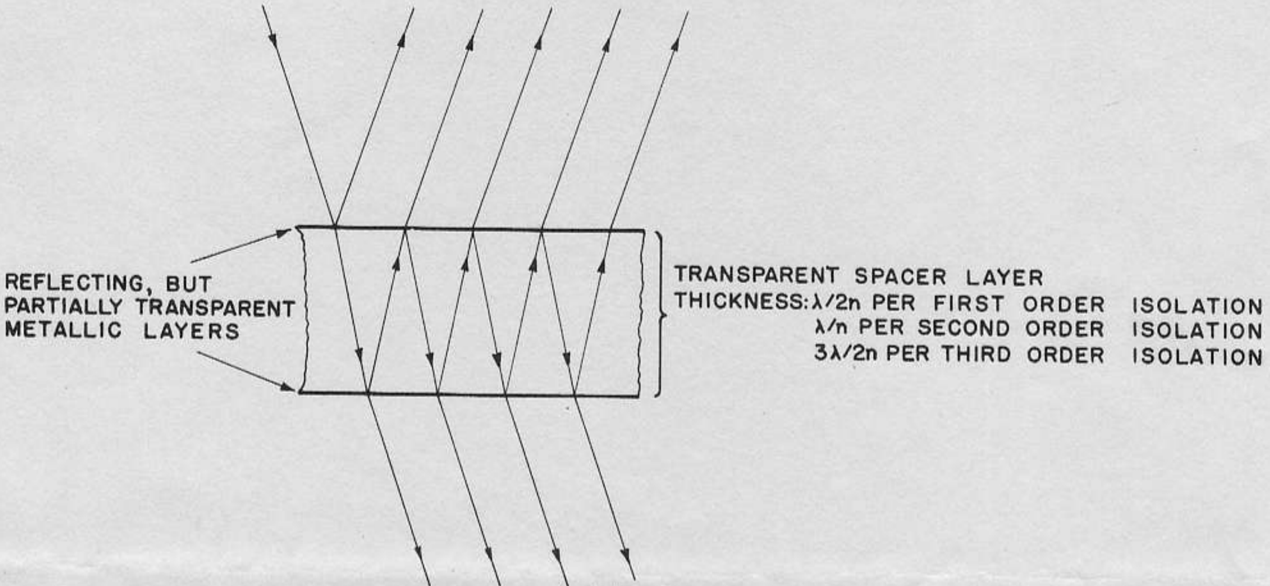


Fig. 1

Part of a ray of light which has passed the first metallic layer will pass also through the second metallic layer, but another part will be reflected back to the first layer. A part of this backward-reflected light will pass through the first layer in the backward direction, but another part will be reflected forward again. Striking the second layer, a part of this twice-reflected light will pass the second layer, and another part will be reflected back, etc.

The diagram in Fig. 1, in which the light ray is shown at a slight angle from normal, is mostly used to illustrate this multiple reflection of a single ray. The angularity serves solely for the purpose of making it possible to illustrate the light path. If the incident light ray strikes the filter in the normal direction, all the drawn lines merge into one, and the various portions passing the second layer become components of a single ray. However, since these components have gone through different path lengths, they will differ in their phase. As a result of these phase differences, rays of some wavelengths will be almost extinguished, while rays of other wavelengths will pass the filter with a minimum of loss. Computing the transmitted light intensity i for light of the wavelength λ, by totalling the various components in consideration of their phase, leads to the following equation of the Fabry-Perot system:

$$i = \frac{T^2}{(1-R)^2 + 4R\sin^2 \pi \frac{\lambda_1}{\lambda}} I \qquad (1)$$

where T and R are, respectively, the transmission and reflection of a single metallic layer, I the intensity of the incident light, and λ_1 the wavelength at which the filter has maximum transmission. (λ_1 is determined by the thickness and the refractive index of the dielectric layer as explained in further detail on page 185.) The equation shows that the maximum light, obtained for $\lambda = \lambda_1$, amounts to

$$i_{max} = \frac{T^2}{(1-R)^2} I \qquad (2)$$

while minimum light is obtained for $\lambda = 2\lambda_1$ and for $\lambda = 2/3\lambda_1$ and amounts to

$$i_{min} = \frac{T^2}{(1+R)^2} I \qquad (3)$$

In Fig. 2, the ratio of i/I according to Equ. (1), i.e. the transmission of the complete filter for light of each wavelength, is plotted against wavelength λ for an assumed value of λ_1 = 700 millimicrons. In curve (a), the assumption is made that T=0.10 and R=0.90, while in curve (b) T=0.25 and R=0.75. It will be seen that the higher reflection gives narrower transmission bands and lower transmission between the peaks. Both curves show a maximum transmission of 1.0, because the unrealistic assumption has been made that R+T=1.0, which means that the metallic layers have been assumed to have no absorption whatsoever. More realistic values are R=0.83 and T=0.12, indicating 5% absorption in the metallic layers. These values are assumed in curve (c) which shows a maximum of approximately 0.50.

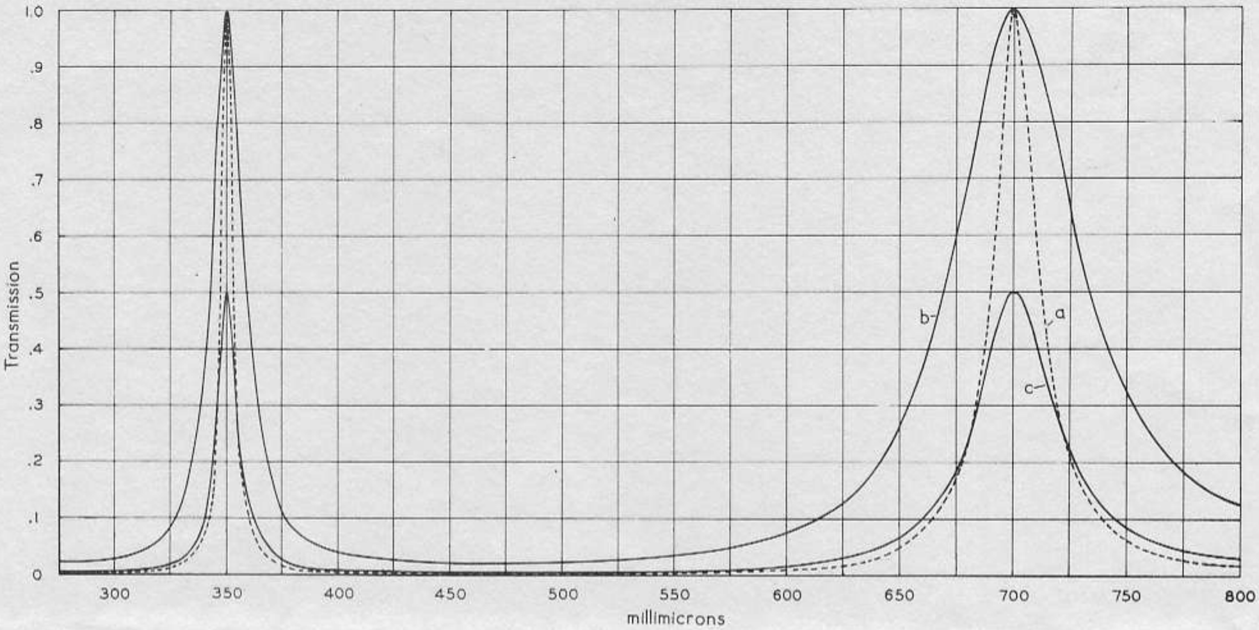


Fig. 2

As one can compute from Equ. (1) and as shown in Fig. 2, an FP interference filter isolates more than one wave band. Maxima of the same height as at λ_1 occur also at $1/2\lambda_1$, $1/3\lambda_1$, etc. For instance, if the longest wavelength at which maximum intensity occurs (first-order band λ_1) is at 700 millimicrons, maxima will also occur at 350 millimicrons (second-order band λ_2), at 233 millimicrons (third-order band λ_3), etc. If, in a given filter, the first-order band is made use of for the isolation of the desired wavelength, all undesired maxima appear on the short-wavelength side. However, if one of the higher-order bands is utilized, unwanted maxima will be on both sides. Second-order filters, for instance, have side bands at $2\lambda_2$ and at $2/3\lambda_2$, and their nearest transmission minima are at $4/3\lambda_2$ and $4/5\lambda_2$.

The use of higher orders offers the advantage of furnishing narrower bands and steeper curves, but the undesired bands, aside from being on both sides rather than on one side only, are closer to the desired band. For instance, if the 500 millimicron band is isolated in the first order, there is no band on the long side, and the nearest band on the short side is at 250. In isolating the 500 band in the second order, the nearest side bands are at 1000 and 333; in the third order, they are at 750 and 375; in the fourth order at 666 and 400; etc. This increasing proximity of the side bands acts as a limitation regarding the order of interference that can be made use of for practical purposes.

Some of the undesired bands may not require any special precautions. For instance, on the short-wavelength side, bands below 330 millimicrons will be absorbed automatically by the glass that is used to carry the metallic layers. Undesired transmission bands in the infrared can frequently be disregarded, for instance, if the filters are to be used in conjunction with photocells that have no sensitivity in that part of the infrared. In some special instances, it may even be permissible to disregard side bands which are in the visible range and comparatively close to the desired band. This applies if the filter is to be used in conjunction with a gas-discharge light source, that has no emission in the range of the side bands. However, the filter will then not isolate the desired band effectively, except when used with that particular light source. Where the elimination of undesired side bands is necessary, additional elements are required as discussed in further detail on page 186.

The efficiency of a filter can be expressed by the percentage transmission at the peak. For its effectiveness in isolating the band, it is customary to indicate the width of the spectral transmission curve at a height which is 50% of the peak transmission value (half-peak width). In addition, in order to indicate the width near the base of the transmission curve, it is sometimes useful to know the band width at 10% of the peak (one-tenth-peak width) or even at 1% of the peak (one-hundredth-peak width).

In some applications, the "rejection" of undesired bands and of any light outside the isolated band is of even greater importance than the height and the width of the isolated band itself. The degree of rejection is expressed by the low transmission values, such as 0.5 or 0.2%, which the filters show outside the isolated band. It may also be useful to know, in some instances, at which spectral distance on each side from the center of the band the indicated low transmission value is reached.

The analysis above refers to light passing the filter in the normal direction. At a deviation from normal, the transmission band shifts towards the short-wavelength side, and the band increases in width. A green interference filter will thus shift towards the blue when viewed through at an angle. However, the shift also applies to the side bands. Therefore, if the filter is of second or higher order, a longer wave band, lying in the infrared at normal light, may, upon tilting, shift into the visible range, making the filter appear red.

Thickness of Layers

Referring again to Fig. 1, one can conclude that the various components of a single ray passing through the second layer will add up to a maximum if the phase difference between each two subsequent components is 2π, because they can then be added numerically. The thinnest dielectric spacer layer, to cause a phase difference of 2π must have a thickness of $d = \lambda_1/2n$ where n is the index of refraction and λ_1 is the longest wavelength of the of the first-order transmission maximum. For instance, for n=1.3 and for first-order isolation of the 520 millimicron band, the required thickness is thus 200 millimicrons or 0.0002 mm or less than 1/100,000th of an inch. The same dielectric layer will isolate the 260 millimicron wave band in the second order of interference. In order to isolate 520 millimicrons in the second order, the thickness of the layer must be 0.0004 mm. The metallic layers, in order to have a minimum absorption, must necessarily also be extremely thin.

To form such thin layers, the materials are thermally evaporated and deposited in high vacuum. In principle, an interference filter of the FP type thus comprises the following elements: A glass as a carrier, a first metallic layer deposited on the glass, a deposited transparent spacer layer, and a second deposited metallic layer. A second glass is then added for protection. The layers must, of course, be absolutely uniform and must have exactly the correct thickness. It will be seen from the foregoing that the production of interference filters is thus essentially a problem of thin-layer and high-vacuum technique.

PROPERTIES OF AVAILABLE INTERFERENCE FILTERS

All the available interference filters described in this bulletin are of the Fabry-Perot type and isolate the specific spectral band in the second order of interference. They cover the range from 340 to 900 millimicrons. Within this range, any filter is available either immediately from stock or for delivery in 4-6 weeks, depending to a certain extent upon the specified tolerance for the peak wavelength. Filters above 900 millimicrons can usually be furnished on order with longer delivery.

Fig. 3 shows a typical transmission curve of a filter. The transmission peak is usually around 40 and the half-peak width 8-12 millimicrons. At one-tenth of the peak transmission, the width is 20-32 millimicrons.

The high reflection of the metallic layers employed in the filters results in a high spectral purity, i.e. in a high degree of rejection and extremely low transmission outside the isolated band. Less than 0.5% transmission is reached at 30 millimicrons on each side of the isolated principal band. However, since the second-order interference is made use of for the isolation of the principal band, there is a first-order band at

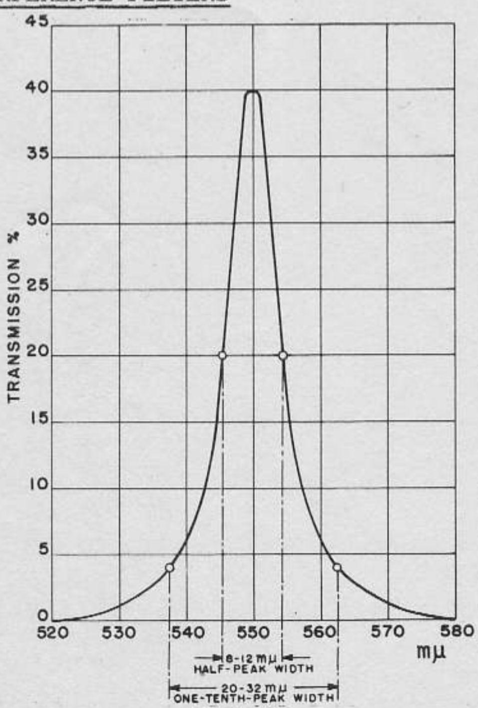


Fig. 3

twice the wavelength and a third-order band at 2/3 of the wavelength (also a fourth-order band at 1/2 the wavelength, etc.) of the band to be isolated. This makes it necessary to use auxiliary cut-off filters.

Second-order filters below 500 millimicrons do not require any special provision for eliminating the third-order or higher-order side bands because these side bands are in the ultraviolet below 340 millimicrons and are thus absorbed by the glass. Filters above 425 do not necessarily require provisions for cut-off of the first-order band inasmuch as this band is sufficiently far in the infrared to be disregarded in the use of the filters for most applications. Just the same, for best rejection of all unwanted light, practically all filters are provided with auxiliary cut-off components. As a result, the spectral purity of the filters is such that the average transmission outside the principal band is less than 0.2%. In fact, in the range of the interference minima, i.e. at 4/3 and 4/5 of the wavelength of the principal band, the transmission is less than 0.1%.

The additional cut-off towards the short-wavelength side is mostly achieved in a simple manner by the use of a colored glass having a sharp-cutting spectral transmission curve. However, there are not many colored glasses available with the required sharp cut-off towards the long-wavelength side. Therefore, the cut-off towards the long side is, in some instances, achieved by an additional multilayer component of the dichroic type.

The layers constituting the dichroic component can mostly be deposited directly on the second metallic layer of the FP filter. The complete filter thus comprises the following combination: A colorless glass as a carrier, the FP component (consisting of two metallic layers with a transparent spacer layer between them), an ML component (consisting of a number of non-metallic layers), and a colored or colorless covering glass. In some instances, however, the ML component is carried by a third glass.

The filters are available in the 2" x 2" size only. The exact dimensions of the glasses are 50 x 50 mm, the combined thickness being 3 to 5 mm. The filter layers have an area of only 45 x 45 mm. For sealing purposes, a strip of 2.5 mm width on all four edges is left uncovered by the filtering layer in the production process. This strip is thus colorless or, if a colored covering glass is employed, the strip appears transparent blue, yellow, red, or purple. In some applications such as, for instance, in the use of the filters in the LUMETRON Colorimeter Mod. 402-E, special provisions are necessary to cover up the strip so as to keep unfiltered light from being registered by the photocell.

The filters are safe for temperatures up to 180° F. When exposed mainly to radiant heat, they are not likely to become excessively warm, because practically all of the radiation which is not transmitted is reflected, the absorption being very small.

Since the isolated wave band is determined by the thickness of the transparent spacer layer, the interference filters can, in principle, not fade or change their transmission characteristics in any other way. If anything, deterioration of interference filters can only be the result of separation of layers or penetration of atmospheric moistures and chemical vapors. In the interference filters offered, this is prevented by suitable choice of the cementing material and by the sealing strip along the four edges. Since the outside of the filters is glass, they can be cleaned in the ordinary way.

Each filter furnished is identified by a serial number, and the characteristics of each filter are registered. In addition, the filters can be ordered with individual spectral transmission curves at an additional price of $15.00.

APPLICATIONS

Colorimetric Analysis

It has become customary to refer to photoelectric transmission-measuring instruments as "spectrophotometers" if the wave band is isolated by a prism or a grating, and to call them "colorimeters" if the isolation is achieved by color filters. In the majority of instances, the two types of instruments serve for the same purpose, namely for chemical analysis by way of transmission measurements of solutions in selected wave bands. This analysis mostly serves the purpose of determining the concentration of a certain constituent in a solution.

When the above distinction between the two types of instruments came into general use, it was tacitly assumed that the wave band isolated by a spectrophotometer is never more than a few millimicrons or even a fraction of a millimicron wide and that colorimeters work with filters that do not isolate wave bands of less than about 30 millimicrons width. By now, interference filters make it possible to isolate wave bands of 5-15 millimicrons with a high degree of optical purity while, at the same time, spectrophotometers have come into use some of which operate with wave bands of 30 millimicrons or more.

It thus becomes necessary to revise some concepts in the field of colorimetric analysis. With solutions having a smooth spectral transmission curve without pronounced absorption bands, measurements on a colorimeter have always been practically equivalent to measurements on a spectrophotometer, inasmuch as the width of the spectral band is not critical. There are, however, other cases where the existence of a sharp absorption band in the spectral transmission curve of the solution makes it advisable to carry out transmission tests in this very band. Even in such instances, the interference filter isolating this very band now frequently permits to obtain, with a colorimeter, results of equal or even higher accuracy than with a spectrophotometer.

The graph on page 193 shows 12 interference filters offered for use in the LUMETRON Colorimeter Mod. 402-E as described in Bulletin #420. The set of these 12 filters permits transmission and reflection measurements in 12 well-defined points of the visible spectrum, making it possible to plot close approximations of spectral transmission and reflection curves. It is understood that filters for the isolation of intermediate bands are also available for this colorimeter. The filters fit the removable filter holder of the instrument but require the Adapter Mask Cat.-No. 4178 (price $3.00) to cover up the transparent strip along the edge of the filter.

Photoelectric Color Grading

In the preceding paragraphs, the assumption was made that the transmission measurements on liquids are carried out for analytical purposes. There are many other instances where the transmission tests serve for grading of liquids according to their color appearance rather than for analysis. This applies, for instance, to the color of mineral and vegetable oils, of solvents, of liquid food products, of beverages such as beer, wine, fruit juices, etc.

Color grading of these and similar materials is widely carried out with the aid of visual standards, but the visual grading method depends on individual judgement and on light conditions. There is, therefore, a growing tendency to replace visual grading methods by photoelectric measurements in order to achieve full reproducibility from one operator to another and under all light conditions. However, photoelectric tests for color grading require rigid standardization of the wave band employed. Such standardization cannot be accomplished by filters made up of combinations of colored glasses, but is now made possible by interference filters.

Flame Photometry

The term "flame photometry" is employed for the method, developed during the last 15 years, of quantitative analysis, including trace analysis, of substances such as sodium and potassium in solutions by atomizing the solutions within a burning flame and measuring the light in the characteristic emission bands. The procedure permits accurate determinations within a minimum of time even in the presence of other elements, but makes it necessary to isolate reliably the emission bands of the various substances to be determined.

For sodium and potassium, the interference filters 590 and 767 are used. An Interference filter 670 serves for isolating the emission band of lithium which is mostly employed as an internal standard. A filter 620 will suitably isolate the calcium band. Other filters will serve for the determination of additional substances such as magnesium, strontium, barium, chromium, manganese, etc. by flame photometry.

Isolation of wave bands by prisms or gratings requires a concentrated light source for high efficiency. The area of radiation of a flame is, of course, comparatively large. Therefore, the use of interference filters is a much more efficient system of isolation of wave bands in flame photometry. It furnishes higher sensitivity for the measurement of low concentrations and makes it possible to get along with less expensive equipment for the registration of the resulting light.

Fluorimetry

In the determination of the concentration of fluorescent constituents in solutions, the fluorescent light to be measured is always very weak. Also, it is in no way concentrated but emerges from a rather wide area. Therefore, just as in flame photometry, spectral resolution of the light with prisms or gratings is difficult to achieve except by extremely complicated and expensive equipment. Colored-glass color filters are widely used for isolating spectral bands of the fluorescent light, but must be made to transmit over a wide spectral range, otherwise they cause too much loss of light. Interference filters permit the passage of a beam of light of large cross-section and do not require a concentrated light source. Also, they isolate narrow wave bands with a comparatively small light loss. Therefore, they represent the most efficient means to increase the specificity of analysis by fluorescence. A set of interference filters, spaced to cover the fluorescent spectrum, permits plotting of spectral curves of the fluorescent light. A suitable instrument for the use of interference filters in fluorescence measurements is the PHOTOVOLT Multiplier Fluorescence Meter Model 540 described in Bulletin #392.

Microscopy, Photomicrography, Microcolorimetry

The use of monochromatic light as obtainable with the interference filters increases the contrast between the stained parts and the background of microscopic slides. For the usually employed blue and red stains, a green interference filter isolating a wave band of 550 millimicrons will give good results in most instances.

Even more can be accomplished by taking advantage of the fact that the transmission band of the interference filter shifts with changing angle of incidence as pointed out on page 185. By simply tilting the filter, the wave band can be adjusted so as to make the important details stand out clearly by illuminating them with the complementary color. Or one may extinguish unwanted portions by illuminating them with light of their own color. A set of two or three interference filters will permit going through the whole visible spectrum so as to find the band that is most suitable for the specimen being observed.

An interference filter of 550 millimicrons will also be found useful to limit the light to that wavelength range for which the spherical correction of achromatic objectives is best. Furthermore, since the resolving power increases as the wavelength of light decreases, a blue interference filter serves to increase the resolving power of the microscope, particularly when apochromats are employed.

Light of longer wavelength is less subject to scattering than light of shorter wavelength and has thus more penetrating power. Therefore, interference filters in the red and near-infrared can be used advantageously, in photomicrography, to penetrate cloudy masses of debris in slides and to locate organisms such as bacteria.

The term "microcolorimetry" is used here to cover the procedures, developed during the last few years by Pollister, Holter, and others, of measuring absorption in selected wave bands through a microscope for the purpose of quantitative histochemistry and cytochemistry. In these methods, the interference filters will improve the accuracy and specificity of the results obtained.

Other Applications

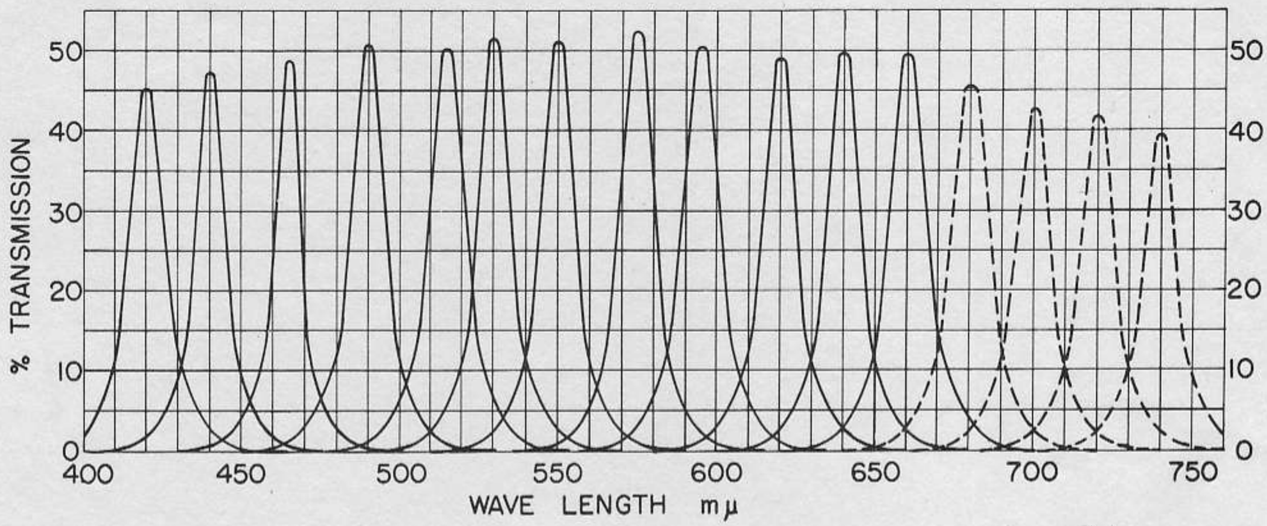
Interference filters in combination with incandescent light frequently make it possible to replace gas-discharge lamps in refractometry and polarimetry. They also permit determining the refractive index and the optical rotation as a function of wavelength. Other fields of application of interference filters are studies involving diffraction and interference phenomena. In studies involving photo-elasticity, observation through interference filters improves contrast and definition.

Monochromatic light is mostly employed in the measurement of the angular distribution of light scattering effects for the purpose of determination of particle size and molecular weight. In this field, too, interference filters employed in combination with incandescent lamps can frequently be substituted for gas-discharge lamps and permit refinements by investigation of the scattering effect in various selected spectral wave bands.

Color densitometry in the processing of still and motion picture film is another important field of application of interference filters. They are particularly suitable for this application on account of their sharp cut-off characteristics and of their high degree of rejection of light outside the isolated band.

PRICE LIST

on Interference Filters



Typical Set of Interference Filters Series MM for
LUMETRON Photoelectric Colorimeter Model 402-E
for the isolation of the following wave bands:

420	440	465	490	515	530
550	575	595	620	640	660

with additional filters for 680 700 720 740

Filters 2" x 2":

Range	340	to	389 millimicrons	ea.	$40.00
Range	390	to	705 millimicrons	"	32.00
Range	706	to	805 millimicrons	"	36.00
Range	806	to	900 millimicrons	"	44.00
Range	901	to	1200 millimicrons	Prices upon request.	

Spectrophotometric transmission curves of individual filters furnished upon request with filters Price $15.00 ea.

Cat.-No. 4178 Mask for fitting interference filters into filter holder $1.50