United States Patent

[11] 3,530,824

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[22] Filed **Nov. 12, 1968**
Division of Ser. No. 391,928, Aug. 25, 1964, now Pat. No. 3,442,572, May 6, 1969
[45] Patented **Sept. 29, 1970**

[73] Assignee **Optical Coating Laboratory, Inc., a corporation of California**

[54] DEPOSITION APPARATUS INCLUDING ROTATABLE AND ORBITAL MASKING ASSEMBLY

12 Claims, 29 Drawing Figs.

[52] **U.S. Cl.** **118/48**
[51] **Int. Cl.** **C23c 13/08**
[50] **Field of Search** 118/47–49.5, 500, 501, 504, 505; 117/106–107.2; 350/166

[56] **References Cited**

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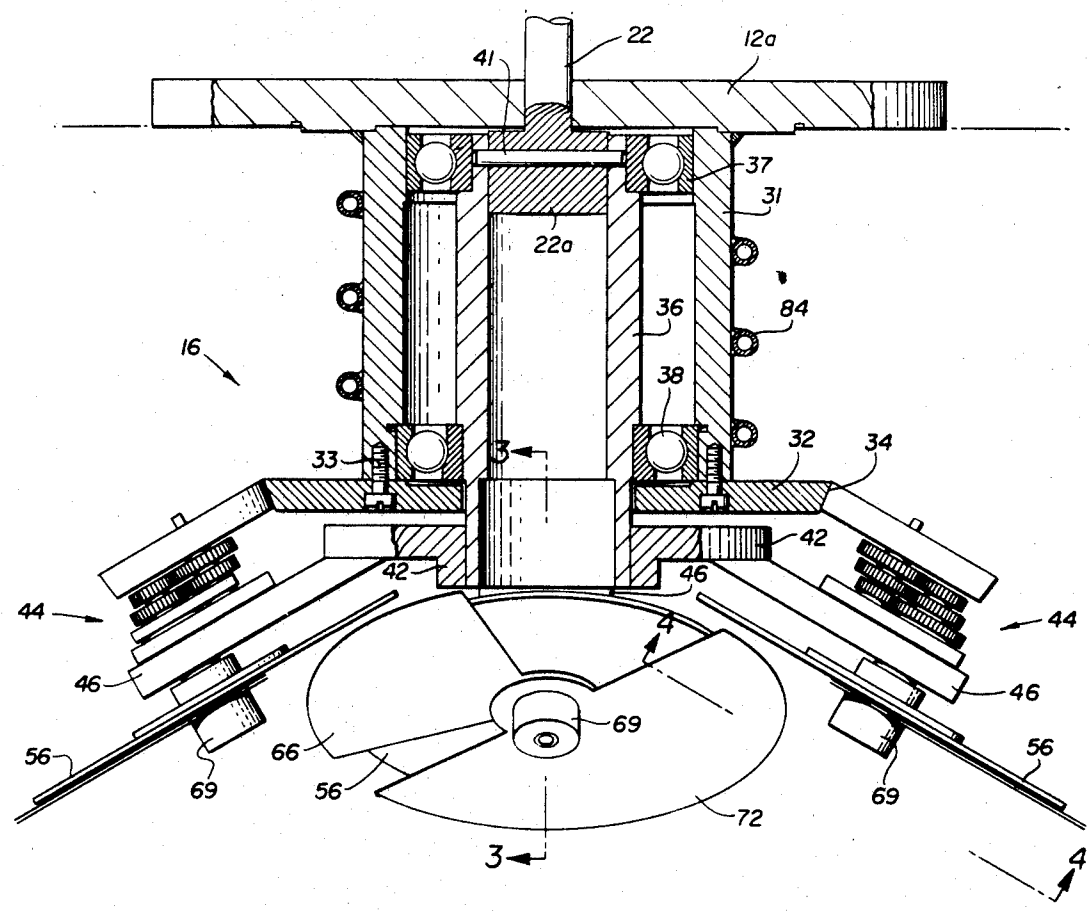
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Primary Examiner—Morris Kaplan
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ABSTRACT: An apparatus for the manufacture of a rotatable variable filter having first, second and third elements in which the first element comprises a substrate, the second element comprises a first mask and the third element comprises a second mask. A source of coating material is provided. The means is also provided for mounting the first, second and third elements so that the second and third elements are positioned between the source of coating material and the first element. The means for mounting includes means for causing different relative rotational movement of at least two of the elements and means for orbiting the assembly of elements about the source of coating material.



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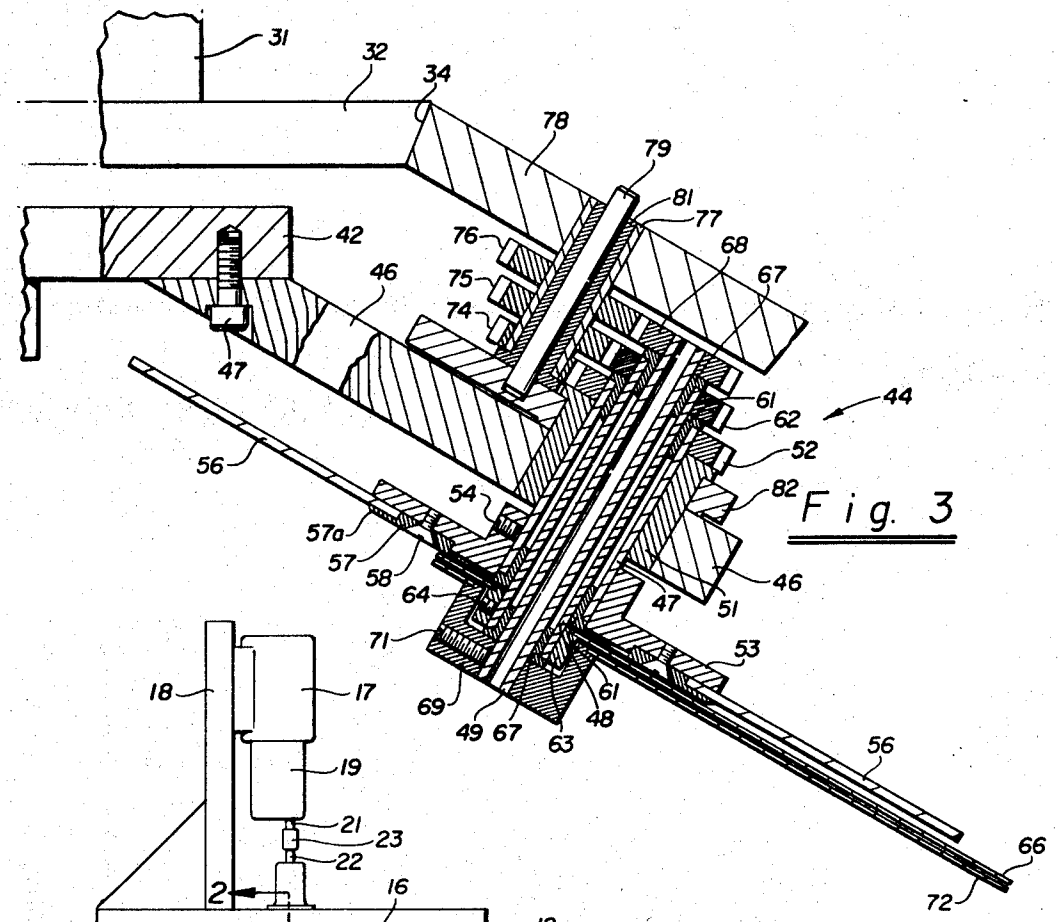


Fig. 3

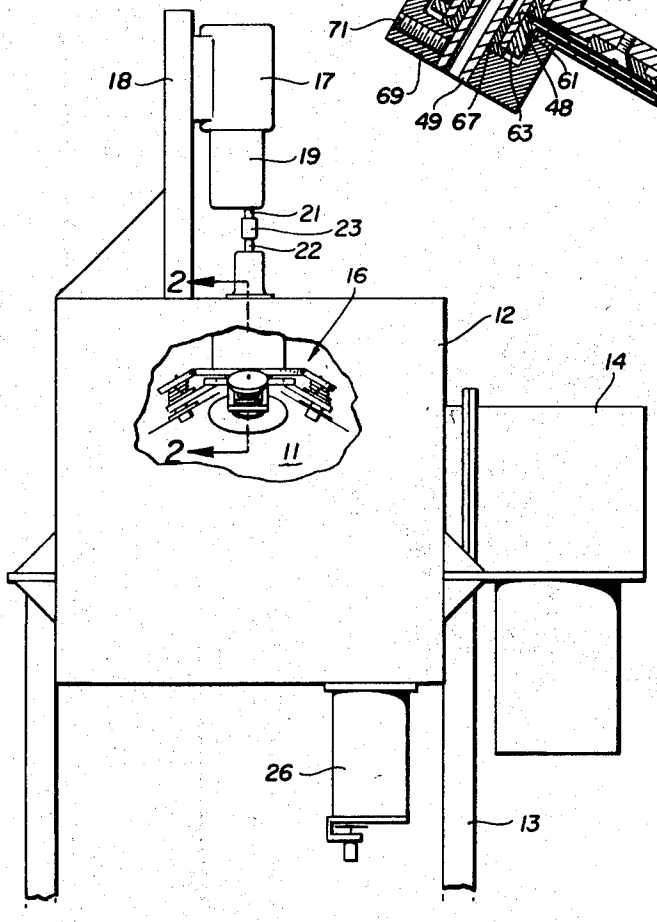


Fig. 1

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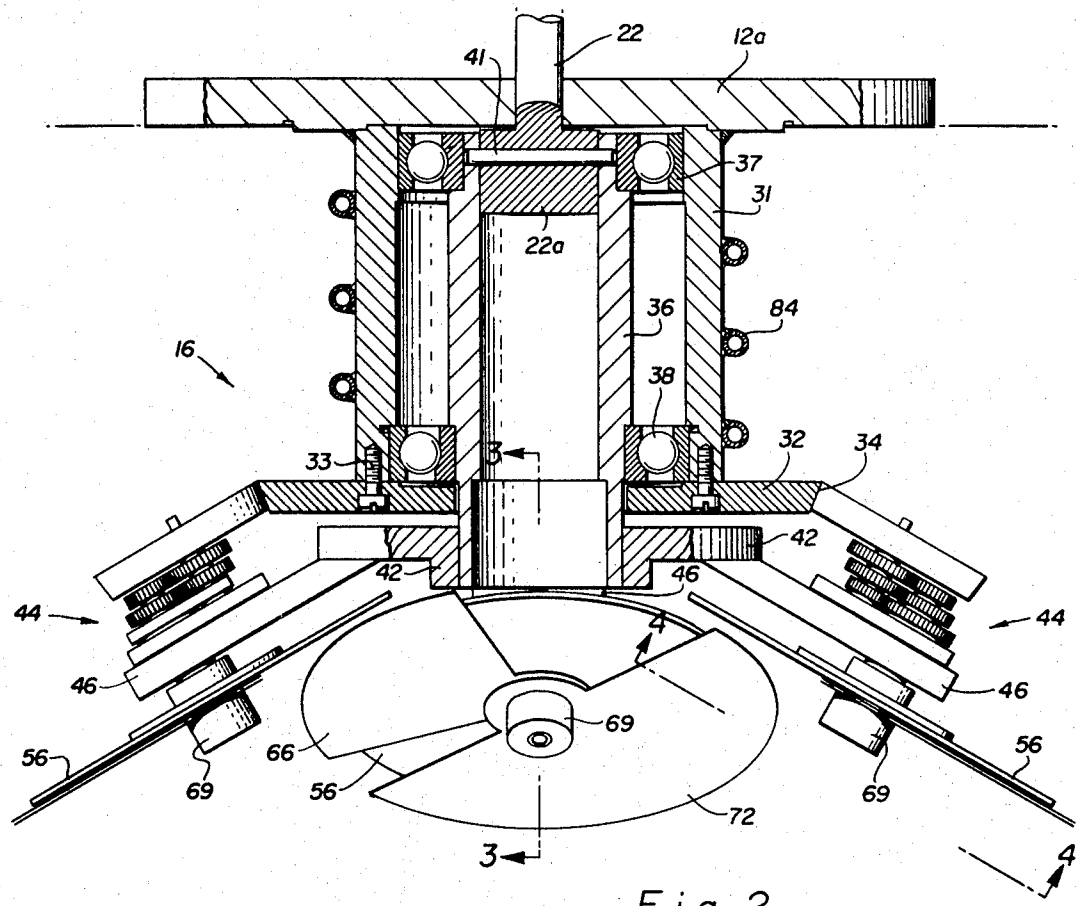


Fig. 2

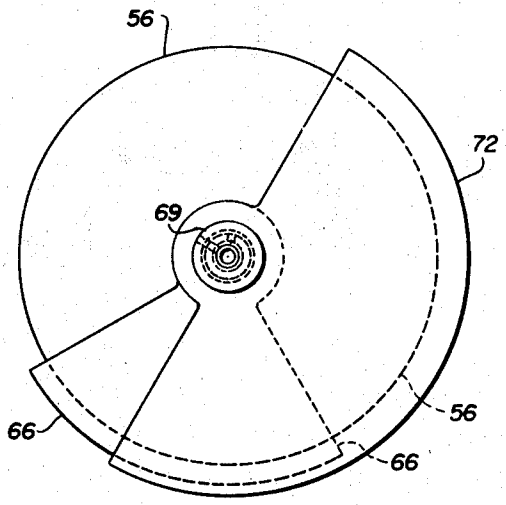


Fig. 4

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Fig. 5

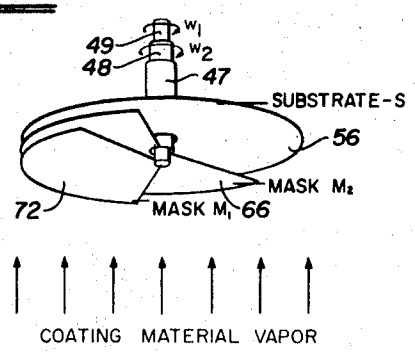


Fig. 6

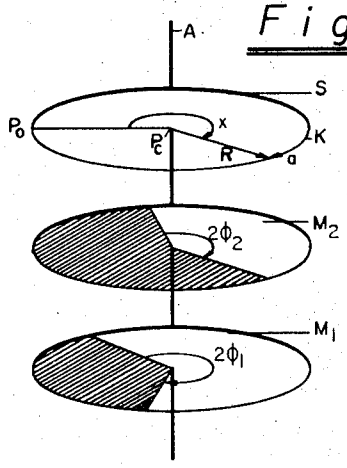
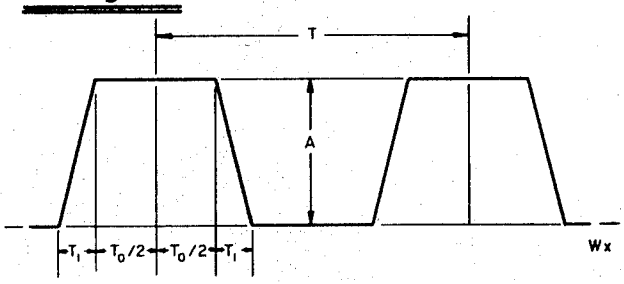


Fig. 7



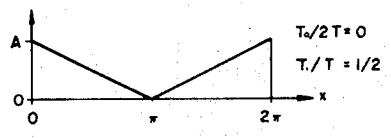


Fig. 9A

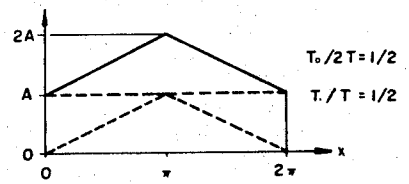


Fig. 9B

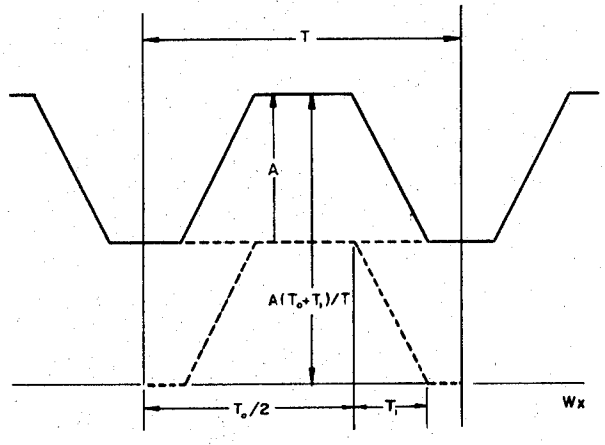


Fig. 8

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Fig. 9C



Fig. 9D



Fig. 9E



Fig. 9F



Fig. 9G

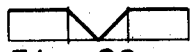


Fig. 9H



Fig. 9I

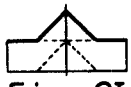


Fig. 9J



Fig. 9K



Fig. 9L

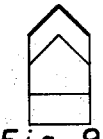


Fig. 9M



Fig. 9N



Fig. 9O

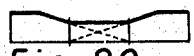
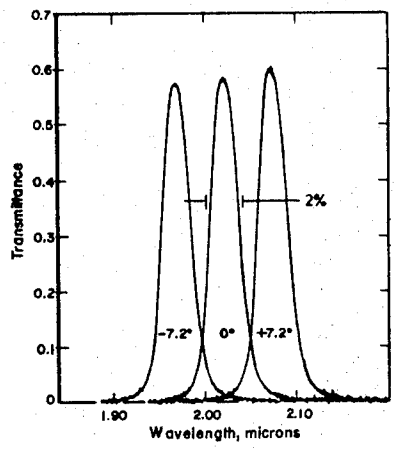


Fig. 9P



Fig. 10



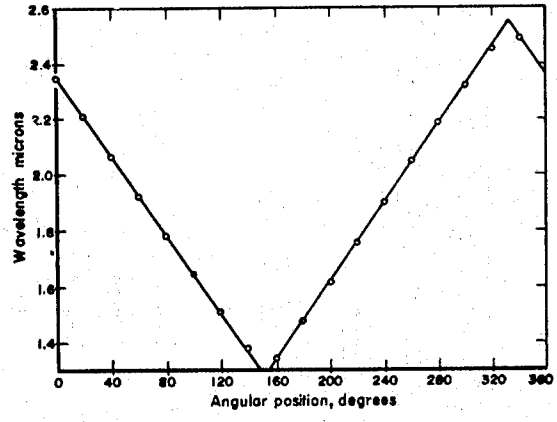


Fig. 11

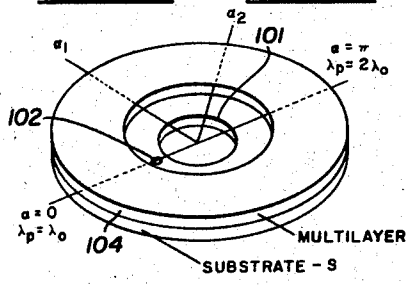


Fig. 12

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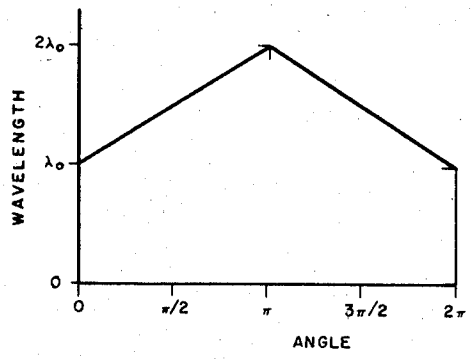


Fig. 13

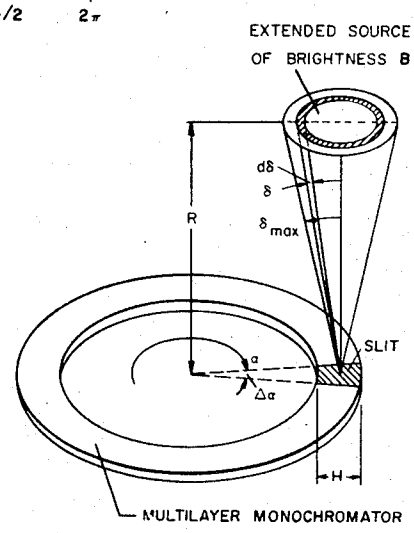


Fig. 14

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DEPOSITION APPARATUS INCLUDING ROTATABLE AND ORBITAL MASKING ASSEMBLY

CROSS-REFERENCE TO RELATED APPLICATION

This application is a division of application Ser. No. 391,928 filed on August 25, 1964 and now Pat. No. 3,442,572.

Straight line variable filters have heretofore been manufactured and sold. However, such straight line variable filters have been limited to coatings deposited upon a rectangular substrate as the parallel lines marking a ruler which transmits light in spectral selectivity through a wavelength range as, for example, from ultra violet (approximately 400 millimicrons) to infrared (approximately 700 millimicrons). In many applications, there is a need for a circular variable filter where the lines are radial in which the transmission changes linearly through a predetermined angle of a circle and covers an unrestricted wavelength range.

In general, it is an object of the invention to provide an apparatus for manufacture of the circular variable filter.

Another object of the invention is to provide an apparatus of the above character which uses sector masks rotating at different speeds.

Another object of the invention is to provide an apparatus of the above character in which uniformity in variation of the optical thickness of coating can be readily achieved.

Another object of the invention is to provide an apparatus of the above character in which the variation in optical thickness is linear.

Another object of the invention is to provide an apparatus of the above character in which only two rotating sector masks are required.

Additional objects and features of the invention will appear from the following description in which the preferred embodiments are set forth in detail in conjunction with the accompanying drawings.

Referring to the drawings:

FIG. 1 is a side elevational view with portions broken away of a vacuum coating apparatus for forming circular wedges incorporating our invention.

FIG.2 is a cross-sectional view taken along the line 2–2 of FIG. 1.

FIG. 3 is a cross-sectional view taken along the line 3–3 of FIG. 2.

FIG. 4 is a view looking along the line 4–4 of FIG. 2.

FIG. 5 is a schematic representation of the substrate and mask arrangement similar to that shown in FIGS. 1—4 utilized for the deposition of circularly wedged coatings.

FIG. 6 is an exploded view of the substrate S and the masks M1 and M2 and defines certain geometrical terms.

FIG. 7 shows the trapezoidal waves generated by the use of the sectors shown in FIG. 5 and gives the characteristic terms for the trapezoidal waves.

FIG. 8 gives an alternate shape for the trapezoidal wave shown in FIG. 7.

FIGS. 9A—9P show a plurality of patterns of thickness distribution where the triangular wave shape is generated by superimposed trapezoidal waves.

FIG. 10 is a graph showing the transmittance of a circular wedge filter which is constructed in accordance with the present invention.

FIG. 11 shows the linear relationship between wavelength and angular position of a circular wedge filter constructed in accordance with the present invention.

FIG. 12 is an isometric view of a circular wedge filter constructed in accordance with the present invention with the depth of the multi-layer coating greatly exaggerated.

FIG. 13 is a calibration chart showing the linearity of the change of thickness of the multi-layer coating with change of angle on the substrate.

FIG. 14 is a schematic illustration of a multi-layer monochromator with a slit and illuminating optics.

The apparatus utilized for manufacturing our circular variable or wedge filter is shown in FIGS. 1—4 and consists of means for forming a vacuum chamber **11**. The vacuum chamber is provided in a rectangular housing **12** which is provided with an access door (not shown). Suitable means is provided for placing the chamber **11** under a vacuum and, as shown, can consist of a diffusion pump **13**. Means (not shown) of a conventional type is provided for mounting a plurality of sources of thermally evaporable material and for evaporating the same. In addition, means (not shown) is provided, also of a conventional type, for evaporating materials by electron bombardment.

Means is provided for carrying the circular substrates which are to be utilized for forming a part of the circular wedge filters in the vacuum chamber **11** and consists of a double rotation assembly **16** somewhat similar to the apparatus for vacuum coating disclosed in the U.S. Letters Pat. No. 3,128,205. Means is provided for driving the double rotation assembly **16** and consist of a drive motor **17** mounted upon a support post **18** carried by the housing **12**. The motor **17** drives speed reducing gearing **19** which drives an output shaft **21** which is connected to a shaft **22** of the double rotation assembly **16** by a coupling **23**.

It should be pointed out that if desired, only single rotation, that is rotation about a single axis, may be used for the substrates where the sources can be centrally located and a single substrate is coated at a time.

Means is provided for monitoring the deposition of coatings upon the substrates carried by the double rotation assembly **16** and consists of an optical monitor **26** of the type described in copending application Ser. No. 321,888, filed November 6, 1963 and now U.S. Pat. No. 3,411,852.

The double rotation assembly **16** consists of a cylindrical support member **31** which is secured to the top wall **12***a* of the housing **12** by suitable means such as welding. A plate **32** is removably secured to the lower extremity of the cylindrical support member **31** by suitable means such as cap screws **33**. The plate **32** is provided with an inclined surface **34** lying in a horizontal plane perpendicular to the support member **31**. A sleeve **36** is rotatably mounted within the support member **31** and in the plate **32** by suitable means such as a pair of upper and lower ball bearing assemblies **37** and **38**, each being comprised of an inner race, an outer race and a plurality of ball bearings as shown. The sleeve **36** is connected to and driven by the shaft **22** by suitable means such as a pin **41** which extends through an enlarged cylindrical portion **22***a* of the shaft **22** and through the upper end of the sleeve **36**. A hub **42** is secured to the lower extremity of the sleeve **36**.

A plurality of masking assemblies **44** are mounted upon the hub **42**. In the embodiment shown in the drawing, three of the masking assemblies **44** have been provided and are positioned symmetrically about the shaft **22**. Each of the masking assemblies consists of a support member **46** which is secured to the hub **42** by suitable means such as cap screws **47** which engage the support member **46** and are threaded into the hub **42**. Three separate hollow shafts **47**, **48**, and **49** are rotatably mounted in a hub bushing **51** carried by the support member **46**. The hollow shaft **47** is rotatably mounted in the bushing **51** and at one end (the upper end) has a spur gear **52** affixed thereto. A flanged hub **53** is secured to the other end (the lower end) of the hollow shaft **47** by suitable means such as a screw **54**. The annular or circular substrate **56** to be coated, and which also can be identified as the substrate S, is mounted upon the flanged hub **53** by suitable means such as a ring **57**. The ring **57** is removably secured to the flanged hub **53** by suitable means such as screws **58** and is provided with an annular portion **57***a* which is adapted to engage the inner margin of the annular substrate **56** and clamp the same to the flanged hub **53** as shown particularly in FIG. 3 of the drawings.

A pair of bushings **61** are mounted on opposite ends of the hollow shaft **47**. The hollow shaft **48** is mounted within the bushings **61** and has a spur gear **62** affixed to one end. A hub **63** is secured to the other end by suitable means such as a

screw **64**. A sector-shaped shielding or masking member **66**, which also can be identified as mask M2, is secured to the member **63**. A pair of bushings **67** are mounted in the opposite ends of the hollow shaft **48**. The hollow shaft **49** is rotatably mounted within the bushings **67** and carries a spur gear **68** at one end and a hub **69** at the other end. The hub **69** is affixed to the shaft **49** by suitable means such as a screw **71**. A sector-shaped member **72**, which also can be identified as mask M1, is secured to the hub **69**.

Means is provided for driving the gears **52**, **62** and **68** and consists of spur gears **74**, **75** and **76**, respectively, which are secured to a sleeve **77** which is affixed to a drive wheel **78**. The drive wheel **78** and the sleeve **77** are rotatably mounted upon a pin **79** by means of a bushing **81** which is disposed within the sleeve **77**. The pin **79** is carried by a plate **82** which is secured to the bushing **51**.

Means is provided for cooling the cylindrical support member **31** and consists of tubing **84** which is coiled about the cylindrical support member **31** and which is supplied with cooling fluid from a source (not shown). The drive wheel **78** is provided with an inclined surface **84** which frictionally engages the inclined surface **34** provided on the stationary plate **32**.

With the arrangement shown, it can be seen that when the motor **17** is operated, the large hub **42** will be caused to rotate which will rotate the circular substrates **56** being coated about an axis which is coincident with the axis of the shaft **22** and the axis of the vacuum chamber. In addition, the substrate **56** will be rotated about its own axis by the gearing hereinbefore described at the same time it is being rotated about the axis coincident with the shaft **22** to thereby, in effect, provide the so-called double rotation system.

In the apparatus shown in FIGS. **1—4**, all three elements, the substrate S and the masks M1 and M2, are rotated. For reasons hereinafter explained, it is only necessary that at least two of the elements be rotated during the coating of the substrate. This means that both masks M1 and M2 can be rotated with the substrate being stationary, or conversely, the substrate can be rotated and one of the masks held stationary. As hereinafter explained, it is only necessary that the proper rotational relationship be maintained between the elements which are rotated and the element which is held stationary. Thus, when it is desired to rotate only two of the elements for reasons of economy and simplicity, gearing for the element to be held stationary can be omitted and the element secured to the member **46**.

Operation of the apparatus shown in FIGS. **1—4** for manufacturing circular wedge filters may best be understood by reference to FIG. **5**. With the arrangement shown in FIGS. **1—4** and from the schematic representation shown in FIG. **5**, two sector masks identified as masks M1 and M2 are placed between the substrate S and the coating source. As hereinafter explained, by proper control of the parameters, a selected variety of circularly wedged coatings can be deposited upon the substrate, the outstanding feature of which is that the coatings have a thickness which changes linearly with the angle on the substrate. Using the apparatus shown to perform the method indicated in the present invention, a collimated beam of coating material strikes the substrate and mask combination at substantially normal incidence. Coating material is deposited on the substrate whenever the path of travel for the coating material is not blocked by one or both of the two sector masks.

In order to understand how a coating can be deposited upon the substrate in which the thickness changes linearly with the angle on the substrate, a mathematical analysis as set forth below proves very helpful. Let A be defined as the common axis of rotation of the two sector masks M1 and M2 (see FIG. **6**). The point P_c where the axis A penetrates the substrate plane S is the center of a circle K with the radius R. Thus $a=xR$ where a is the length of the arc of the circle from the point P_0 and where x is the angle from the point P_0. At the time $t=0$, let it be assumed that the masks M1 and M2 are positioned such that the clear sectors extend from $x=-\phi_1$ to $x=+\phi_1$ for the mask M1 and from $x=-\phi_2$ to $x=+\phi_2$ for the mask M2.

Let is also be assumed further that whenever the path to the substrate is open, the incident coating material deposits upon the substrate at a constant rate:

$$c=\frac{dD}{dt}=\text{const.} \tag{1}$$

where D is the thickness of the coating.

Consequently (again at t=0), dD/dt can be expressed as a function of x by the product of two square wave functions:

$$\frac{dD}{dt}=SQ(\phi_1, x)\cdot SQ(\phi_2, x) \tag{2}$$

where

$$SQ(\phi_n, x)=\frac{2\sqrt{c}}{\pi}\left[\frac{\phi_n}{2}+\sum_{k=1}^{\infty}\frac{\sin k\phi_n}{k}\cos kx\right] \tag{3}$$

since the masks are rotating at the angular speeds:

$$\frac{dx}{dt}=\text{const.}=w_1, w_2$$

at the time t=t the following expression holds:

$$\frac{dD}{dt}=SQ(\phi_1, x+w_1t)\cdot SQ(\phi_2, x+w_2t) \tag{4}$$

or, in detail

$$\frac{dD}{dt}=\frac{4c}{\pi^2}\left[\frac{\phi_1\phi_2}{4}+\frac{\phi_1}{2}\sum_{i=1}^{\infty}\frac{\sin i\phi_2}{i}\cos(ix+iw_2t)+\frac{\phi_2}{2}\sum_{k=1}^{\infty}\frac{\sin k\phi_1}{k}\cos(kx+kw_1t)+\sum_{i=1}^{\infty}\sum_{k=1}^{\infty}\frac{\sin i\phi_2\sin k\phi_1}{ik}\cos i(x+w_2t)\cos k(x+w_1t)\right] \tag{5}$$

By integrating equation (5), the following expression can be derived for the thickness D as a function of x:

$$D=\int_0^t\frac{dD}{dt}dt=\frac{4c}{\pi^2}\left[\frac{\phi_1\phi_2}{4}t+\frac{\phi_1}{2}\sum_{i=1}^{\infty}\frac{\sin i\phi_2}{i^2w_2}\sin i(x+w_2t)+\frac{\phi_2}{2}\sum_{k=1}^{\infty}\frac{\sin k\phi_1}{k^2w_1}\sin k(x+w_1t)+\sum_{i=1}^{\infty}\sum_{k=1}^{\infty}\frac{\sin i\phi_2\sin k\phi_1}{2ik}\left(\int_0^t\cos[(i+k)x+(iw_2+kw_1)t]dt+\int_0^t\cos[(i+k)x+(iw_2-kw_1)t]dt\right)\right] \tag{6}$$

This expression (6) contains terms which steadily increase with time and others which oscillate. If we make the assumption that we integrate over a time period long enough so that all oscillating terms can be neglected against the steadily increasing terms, a uniform thickness distribution can be derived:

$$D=\frac{c\phi_1\phi_2}{2}t\neq D(x) \tag{7}$$

There are cases, though, when the distribution is non-uniform. This is whenever

$$iw_2\pm kw_1=0 \tag{8}$$

Then the following expression for the thickness distribution results out of equation (6):

$$D/cl=\frac{\phi_1\phi_2}{\pi^2}\frac{2w_1}{w_2\pi^2}\sum_{k=1}^{\infty}\frac{\sin k\phi_2 \sin k\phi\frac{w_2}{w_1}}{k^2}\cos k\left(1-\frac{w_2}{w_1}\right)x \quad (9)$$

This equation (9) can be interpreted as a Fourier series of a trapezoidal wave.

The standard form of the Fourier series of a trapezoidal wave is

$$F(Wx)=A\frac{T_0+T_1}{T}+2A\frac{T}{\pi^2T_1}\sum_{k=1}^{\infty}\frac{\sin k\frac{\pi T_1}{T}\sin k\frac{\pi(T_0+T_1)}{T}}{k^2}\cos kWx \quad (10)$$

with the quantities T, T_0, T_1, A, and $W=2\pi/T$ as defined in Figure 7. Comparing equations (9) and (10), we arrive at the following set of interrelating equations:

$$\phi=\frac{w_1}{w_2}\frac{\pi(T_0+T_1)}{T} \quad (11)$$

$$\phi_2=\frac{\pi T_1}{T} \quad (12)$$

$$W=1-\frac{w_2}{w_1} \quad (13)$$

$$A=\frac{w_1}{w_2}\frac{\phi_2}{\pi} \quad (14)$$

$$\frac{T_0}{2T}=\frac{w_2\phi_1-w_1\phi_2}{2\pi w_1} \quad (15)$$

$$\frac{T_1}{T}=\frac{\phi_2}{\pi} \quad (16)$$

Since both ϕ_1 and ϕ_2 can vary from 0 to π the quantities T_0 and T_1 can assume values which do not allow the interpretation of the series (9) by the curve shape given in Figure 7. Whenever

$$1\leq\frac{T_0}{2T}+\frac{T_1}{T}\leq 1/2 \quad (17)$$

The interpretation of FIG. 8 which is basically a trapezoidal wave with half a period out of phase and with an increased average value must be used.

Since the series derived for the thickness distribution in equation (9) has the general form of a Fourier series for trapezoidal waves, the general statement can be made that two rotating sector masks, arranged in the described fashion, generate linear thickness distributions. It is very important to remember, though, that an assumption was made that the "exposure time" is long compared to the period T.

Particular attention must be paid to relation (13). This relation states that the periodicity of the trapezoidal wave is, in general, different from the periodicity of the substrate. For example, when $w_2/w_1=3$ then $W=-2$. This means that two complete cycles of the trapezoidal wave fit around one cycle on the substrate. Yet in the special case

$$w_2/w_1=2 \quad (18)$$

one period of the trapezoidal wave falls just within one cycle on the substrate.

Of special interest are the cases when there are no regions of constant thickness or, in other words, when the trapezoidal wave simplifies into a triangular wave. This is the case when

$$T_1/T=1/2 \text{ and } 2T_0/T=0 \quad (19)$$

or

$$T_1/T=1/2 \text{ and } 2T_0/T=1 \quad (20)$$

FIGS. 9A and 9B give the resulting shapes. The complete specifications are given under *a* and *b* in table I following.

TABLE I

	ϕ_1	ϕ_2	w_1	w_2	W	Degrees $360°-2\phi_1$	Degrees $360°-2\phi_2$	Average thickness	Ratio
Case:									
a	$\pi/4$	$\pi/2$	1	2	1	270	180	1/8	∞
b	$3\pi/4$	$\pi/2$	1	2	1	90	180	3/8	2
c	$\pi/2$	$\pi/4$	2	3	−1/2	180	270	1/8	2
d	$3\pi/4$	$\pi/6$	3	2	1/3	90	300	1/8	2
e	$3\pi/8$	$\pi/6$	3	4	−1/3	225	300	1/16	2
f	$5\pi/8$	$\pi/6$	3	4	−1/3	135	300	5/48	1.5
g	$5\pi/6$	$\pi/4$	2	3	−1/2	60	270	5/24	1.5
h	$15/16\pi$	$\pi/4$	3	4	−1/3	22.5	270	15/64	1.33
i	$3\pi/4$	$\pi/2$	3	2	1/3	90	180	3/8	1.25
j	$3\pi/8$	$\pi/2$	3	4	−1/3	225	180	3/16	1.25
k	$5\pi/8$	$\pi/2$	3	4	−1/3	135	180	5/16	1.143

Cases *a* and *b* assume that relation (18) holds true. These are not the only cases which result in triangular wave shapes, though. By going to

$$|W|<1 \quad (21)$$

parts of the trapezoidal wave can be superimposed. This can be used to advantage to create a selected variety of additional triangular shapes. Cases *c* to *k* of Table I are representative. FIGS. 9C to 9F show the patterns of superimpositions. The main difference between these various cases is the ratio of maximum to minimum thickness. Cases were picked which give a useful variety of thicknesses but keep $|W|$ as large as possible so that the "exposure time" can be kept as small as possible.

Of some special interest is case *e*. Here the triangular wave gives the same ratio as case *c* or *d* but the average thickness is only one-half the corresponding value for *c* or *d*. Consequently, if one exposes the two arrangements to the same coating material stream, one can produce two thickness ranges at the same time.

The ratio set forth in table I is the ratio between the thickest and the thinnest portions of the coating or filter.

From any one point on the substrate S the rate of deposition of the coating material as a function of time can be described as a squarewave function. Thus, when a mask is rotating between a stationary substrate and the vapor coating source, nothing is deposited when the mask is closed with respect to this particular point on the substrate and then when the mask opens, the coating material is deposited at a constant rate until the mask closes again. Thus, an on-off function is generated which is identical to a squarewave. A similar type of squarewave is obtained with the other mask. The result of the two masks rotating is the product of the two squarewave functions which, as established above, will provide a trapezoidal function which describes the thickness of the coating as a function of wavelength on the substrate. FIG. 7 shows such a trapezoidal function.

In FIG. 8, it can be seen that when the trapezoidal function has an undesirable flat portion, there will be a doubling up of thicknesses in certain portions so that thickness does not change with angle. For this reason, it is desirable to find the conditions where the flat portions of the trapezoidal wave are zero, or in other words a triangular function is formed. This makes it possible to make maximum utilization of the surface of the circular substrate.

In FIGS. 9A—9P are shown a number of cases in which triangular wave shapes can be obtained in which thickness changes or varies as a function of angle. Thus, in the FIGS. 9C, 9E, 9G, 9I, etc., shown on the left-hand side, there is shown the pattern after one complete rotation cycle of the elements of the masking assembly; and then in FIGS. 9D, 9F, 9H, etc., shown on the right-hand side, there is shown the pattern obtained after one or more additional cycles of the elements of the masking assembly. From these figures it can be seen that as the additional layers are superimposed one upon the other, a triangular wave always results. From all the different patterns shown in FIGS. 9A—9P, it can be seen that it is possible to obtain different sets of triangular wave forms. This is important because the ratio of peak wavelength can be changed by the different patterns. For example, in one circular wedge filter, the wavelength may change from λ to 2λ, whereas in another, it can change from λ to $1\frac{1}{2}\lambda$.

As hereinbefore explained, the relative angular velocities specified in table I above can be achieved by rotating any two of the three elements of a three-element system, for example, in the case of a system having relative velocities of 0:1:2 for the substrate S, mask M1 and mask M2, respectively, a rotating substrate system with relative velocities of 2:1:0 is completely equivalent and allows one mask to remain stationary. A three-speed system such as shown in FIGS. 1—4 where all the elements of the system are rotating with respect to the source is somewhat more desirable because of improved results which can be obtained. However, rotation of all three elements introduces a considerable degree of complexity and adds additional expense which may not be justified by the improved results. Thus, where economy is desired, one of the elements may be held stationary without unduly affecting the results obtained.

By way of example, an optical circular variable filter incorporating our invention and utilizing the apparatus shown in FIGS. 1—4 was made in the following manner. The sector masks M1 and M2 utilized were 180° and 90° sector masks as shown in FIG. 4. A relative angular velocity of the two was chosen to provide a coating having a linear thickness to angular position relationship. With such a relationship, the maximum thickness of the coating will be twice the minimum value.

The near infrared region (1—3 microns) was selected in order to optimize the parameters of simple multiple layer design, low dispersion of materials, plentiful supply of inexpensive substrate and simple coating techniques. A multi-layer narrow band pass filter design of approximately 2 percent bandwidth was used. The band pass design used is described as

Glass/LHLHLLHLHLHLLHLH/air

Where L and H represent one quarter of the design wavelength optically thick layers of low and high index coating materials. An example of a low index of refraction coating material is silicon monoxide which has an index of refraction of 1.9 ($n=1.9$). A representative material having a high index of refraction is germanium which has an index of refraction of 4.2 ($n=4.2$). With a filter of this design, it would be desirable to use HH spacer layers because of reduced sensitivity to angle of incidence. With germanium as the high index material and without much spacer layers, the absorption and dispersion of the germanium in the spectral region of interest would prevent attainment of the desired wedge linearity. With silicon monoxide as the low index material, there is no such problem because silicon monoxide has a very constant and reproducible index of refraction in the near infrared region.

In the formation of the variable filter which can be called a wedge filter when the variation is linear, sequential evaporation of two materials from the same source location was utilized. A glass substrate disc approximately 6 inches in diameter was positioned above the vapor source concentric with the two masks M1 and M2. In the particular arrangement, the 180° mask, or the mask 72 as shown in FIG. 4, was held stationary, while the 90° mask, mask 66 in FIG. 4, was gear driven from the main rotary motion of the substrate S at one-half of the velocity of the substrate S. The rotary motion velocity was adjusted to ensure that at least 100 sector cycles were completed during the deposition of each layer. Thus, the substrate rotated with a relative speed of two, the 90° mask rotated at a relative speed of one, and the 180° mask rotated at a relative speed of zero or, in other words, was stationary. During the deposition of the coatings, the entire masking assembly 44 is moved rotatably around the source about the axis of shaft 22 to make it possible to achieve still greater uniformity.

In FIG. 10, there is shown a composite transmission scan of a band pass circular wedge filter, made as outlined above, at a point 2.5 inches from the center for three different angular positions, namely, −7.2°, 0° and +7.2° with the 0° angular position being approximately halfway between the extreme high and low ends. FIG. 10 shows the transmission as a function of wavelength with the 2 percent chosen bandwidth.

In FIG. 11, there are plotted positions of the band pass for 20° increments around the finished circular wedge filter. Thus, as shown in FIG. 11, a plot has been obtained with angular position against peak wavelength which shows that good linearity was achieved. The very small departures from linearity are consistent with the degree of non-uniform vapor stream intensity and dispersion in the coating material.

When linearity of a circular wedge filter is being considered, in the case of a band pass filter, it is the change in the location of the center wavelength. In the case of a long wavelength band pass filter, it is the change in the half power point or the 50 percent transmission point.

Other types of filters such as long wavelength pass filters, short wavelength pass filters, narrow band pass filters, wide band pass filters and various combinations thereof can be provided with analogous techniques.

In certain circular wedge filters, it may be desirable to change wavelength linearly up to a predetermined angle and then have it constant through another predetermined angle and then have the wavelength drop off linearly again to the starting point. Such wedge filters can also be readily manufactured with the apparatus and method disclosed herein.

A circular wedge made in accordance with the present invention is shown in FIG. 12 and consists of a circular substrate S which is provided with a central hole 101 and an index hole 102. A multi-layer coating 104 is deposited upon a substrate S. The thickness of the thin film 104 is greatly exaggerated with reference to the substrate S. However, as stated previously, the multi-layer coating is deposited in such a way that the thickness changes linearly with the angle of rotation of the substrate S about its axis or in other words linearly along a line concentric with the axis of rotation. In the design shown, the thickness doubles through a half circle or in 180° and drops back to the original value around the remaining half circle.

Let it be assumed that the multi-layer coating 104 deposited on the substrate S is a narrow band interference filter of the type hereinbefore described. Let it also be assumed that the wavelength of peak transmittance of such a filter changes directly with the thickness of the individual layers. If this circular wedge filter is now rotated behind a slit, a monochromator is formed which passes a wavelength $\lambda_p=\lambda_n$ at $\alpha=0$, $\lambda_p=\lambda_1$ at $\alpha=\alpha_1$, and λ_p 2 λ_n at $\alpha=\pi$, as shown in the drawing in FIG. 12. A calibration chart of such a monochromator is

shown in FIG. 13. The wavelength of the monochromator can be related to the angle on the disc in the following manner:

$$0 \leq \alpha \leq \pi \qquad \lambda_p = \lambda_o\left(1+\frac{\alpha}{\pi}\right) \tag{22}$$

$$\pi \leq \alpha \leq 2\pi \qquad \lambda_p = \lambda_o\left(3-\frac{\alpha}{\pi}\right) \tag{23}$$

If the position of the pass band is measured in wave numbers rather than wavelengths, the relationship can be expressed as follows:

$$0 \leq \alpha \leq \pi \qquad \nu_p = \nu_o \frac{1}{1+\frac{\alpha}{\pi}} \tag{24}$$

$$\pi \leq \alpha \leq 2\pi \qquad \nu_p = \nu_o \frac{1}{3-\frac{\alpha}{\pi}} \tag{25}$$

As is well known to those skilled in the art, a monochromator is always used with illuminating optics. The type of illumination and the width of the slit have an effect on the performance of the monochromator.

In FIG. 14, there is shown schematically the general case of a multi-layer monochromator with illuminating optics. The extended source of brightness B can be a mirror or a lens. The bandwidth and transmittance of the monochromator can be readily computed for a variety of typical cases. A design for a multi-layer monochromator is set forth in table II below.

TABLE II

Layer Number	Type	Refractive index	Relative quarter-wave thickness
	Medium	1.00	
1	H	4.20	1.0
2	L	1.90	1.0
3	H	4.20	1.0
4	LL	1.90	2.0
5	H	4.20	1.0
6	L	1.90	1.0
7	H	4.20	1.0
8	L	1.90	1.0
9	H	4.20	1.0
10	L	1.90	1.0
11	H	4.20	1.0
12	L	1.90	1.0
13	H	4.20	1.0
14	LL	1.90	2.0
15	H	4.20	1.0
16	L	1.90	1.0
17	H	4.20	1.0
18	L	1.90	1.0
19	H	4.20	1.0
20	L	1.90	1.0
	Substrate	1.50	

A design of an infrared wide band pass interference filter is set forth in table III below.

TABLE III

Layer Number	Type	Refractive index	Relative quarter-wave thickness
	Medium	1.00	
1	L	1.90	.8772
2	H	4.20	1.692
3	L	1.90	1.754
4	H	4.20	1.672
5	L	1.90	1.686
6	H	4.20	1.653
7	L	1.90	1.653
8	H	4.20	1.653
9	L	1.90	1.610
10	H	4.20	1.653
11	L	1.90	1.653
12	H	4.20	1.653
13	L	1.90	1.653
14	H	4.20	1.706
15	L	1.90	1.618
16	H	4.20	1.965
17	L	1.90	.9174
18	H	4.20	.3125
19	L	1.90	.6897
20	H	4.20	.6711
21	L	1.90	.6301
22	H	4.20	.6329
23	L	1.90	.6329
24	H	4.20	.6329
25	L	1.90	.6329
26	H	4.20	.6329
27	L	1.90	.6329
28	H	4.20	.6329
29	L	1.90	.5970
30	H	4.20	.6161
31	L	1.90	.6536
32	H	4.20	.3155
33	L	1.90	1.815
	Substrate	1.50	

The bandwidth of a monochromator changes as a function of slit width and cone angle. Also, since interference filters shift with angle, the calibration curve of a multi-layer monochromator will also shift slightly when the monochromator is illuminated with different size light cones.

In general, it can be stated that our monochromator has many distinct advantages. Its performance will not be downgraded appreciably under illumination with low *f*-optics. Its transmittance is a known measurable quantity. It is rotatable and the wavelength calibration curve is linear with angle.

It is apparent from the foregoing that we have provided a new and improved circular wedge or circular variable filter and apparatus for manufacturing the same. The circular wedge filter has many unique characteristics which particularly lends itself to a number of applications as hereinbefore explained.

We claim:

1. In apparatus for the manufacture of a variable filter, first, second and third elements, said first element comprising a substrate, said second element comprising a first mask, and said third element comprising a second mask, a source of coating material, means for mounting said first, second and third elements to form a masking assembly so that the second and third elements are positioned between the source of coating material and the first element, means for rotating the masking assembly about the source, and means for causing different relative rotational movement of at least two of said elements, the rotational movement of each of said two elements being continuous and in one direction for each element.

2. Apparatus as in claim 1 wherein the means for causing relative rotational movement includes means for rotating said two elements at different speeds.

3. Apparatus as in claim 1 wherein said second and third elements are sector-shaped masks.

4. Apparatus as in claim 3 wherein said sector-shaped elements subtend different angles.

5. Apparatus as in claim 1 wherein said means for causing relative rotation of at least two elements includes gearing interconnecting said two elements.

6. Apparatus as in claim 1 together with means for rotating the first, second and third elements as a unit about the source of coating material.

7. In apparatus for the manufacture of a circular wedge filter, first, second and third elements, said first element comprising a circular substrate, said second element comprising a first mask, said third element comprising a second mask, a source of coating material, means for mounting said first, second and third elements to form a masking assembly and for rotational movement with respect to each other about a common axis, means for rotating the masking assembly about the source, and means for causing rotational movement of at least two of said elements at differing speeds with respect to each

other, said rotational movement of each of said two elements being continuous and in one direction for each element.

8. Apparatus as in claim 7 wherein said masks are sector-shaped and extend through angles substantially less than 360°.

9. In apparatus for the manufacture of circular wedge filters, a vacuum chamber, a coating source disposed in the vacuum chamber, a drive shaft mounted in the vacuum chamber, means for rotating the drive shaft, a plurality of masking assemblies generally facing the source and mounted on the drive shaft for rotation with the drive shaft, each of the masking assemblies including first, second and third elements, said first element being in the form of at least a portion of a circular substrate to be coated, said second and third elements being in the form of first and second masks, means for mounting the first, second and third elements so that the first element faces the source of coating material and wherein the second and third elements are disposed between the source of coating material and the first element, and means for causing rotational movement of at least two of said elements as said drive shaft is rotated so that said two elements are rotated at the same time that the masking assemblies are rotated about the source.

10. Apparatus as in claim 9 wherein said means for causing relative rotation of two of the elements includes gearing means connected to two of said elements, a stationary member, and means engaging the stationary member and driving the gearing as the drive shaft is rotated.

11. Apparatus as in claim 9 wherein the masks are sector-shaped and wherein the means for causing rotational movement includes a pair of concentric shafts secured to the masks and drive means secured to the concentric shafts.

12. Apparatus as in claim 11 wherein said first mask extends over 90° and wherein said second mask extends over 180° and wherein the drive means is arranged so that said 180° mask is rotated at twice the speed of the 90° mask.