A method for manufacturing an optical grating. A substrate (810) is supported on a rotatable support at a first position relative to a pair of coherent light sources (C, D). A photosensitive layer (818) is formed on the surface of the substrate (810), and a mask (820) is formed over a first portion of the photosensitive layer (818), while leaving a second portion of the photosensitive layer (818) unmasked. The unmasked portion of the photosensitive layer (818) is holographically exposed to an interference light pattern from the light sources (C, D) to form a first grating surface pattern (826). The first grating surface pattern (826) is masked, and the mask (820) over the first portion of the photosensitive layer (818) is removed. The substrate (810) is rotated 180 degrees to a second position and the unmasked first portion is holographically exposed. The exposed photosensitive material is developed to form a grating on the substrate (810).
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A METHOD OF FORMING A HOLOGRAPHIC DIFFRACTION GRATING

TECHNICAL FIELD

The present invention pertains to a method of manufacturing a high quality, highly symmetrical holographically formed optical diffraction grating.

CROSS REFERENCE TO RELATED APPLICATIONS

This is a continuation-in-part of U.S. Application Serial Number 08/236,481, filed May 2, 1994, entitled "Holographic Diffraction Grating with Multiple Processing Characteristics".
BACKGROUND

Conventionally, an optical system employing a grating is comprised of a grating structure for diffracting light, and optics for focusing a light image. Proper operation of an optical system employing a grating requires careful alignment of the focusing optics relative to the grating. Alignment of these elements is critical to obtaining good operation of the system. Such systems have been known since the early 1800's, with Fraunhofer's original work using gratings made by winding fine wires on the threads of two parallel screws. Later, screws were used to control the position of a scribe on a ruling engine. Generally, the scribe engraved parallel lines on a metal substrate to produce an optical grating.

Until the late 1940's, virtually all gratings were engraved on a material known as speculum metal, which was an extremely hard alloy of copper and tin. However, most gratings are now ruled in an evaporated layer of aluminum. This has the advantage of giving greater reflection in the ultraviolet light spectrum, while at the same time increasing the life of the diamond ruling point of the scribe.

As can be appreciated from the fact that many gratings have as many as 400 or 600 grooves per millimeter, the cost of a high quality grating, which requires ruling of these grooves with great precision, can be very expensive. Thus, in accordance with modern techniques, a master grating (ruled using a ruling engine or made in accordance with other modern techniques) is used as the basis of a mold for making duplicate gratings, which have almost identical optical characteristics.

Such duplication of gratings is performed by applying polymeric material to the master grating with the polymeric material being separated from the master
grating by a parting compound. After the polymeric material hardens, it forms a duplicate grating, and the parting compound is removed. A layer of aluminum is applied to the molded polymeric material to create a reflective surface and to finish the formation of the duplicate grating. Such techniques for duplicating gratings have been well known in the art for many years, and are routinely applied on a commercial scale.

In the early 1880's, Professor H. A. Rowland, who is also well known for his demonstration of the magnetic effect of a charge in motion and his work in determining the mechanical equivalent of heat, recognized that in addition to the alignment problems created by having separate diffracting and focusing optical elements of the classical grating system, the focusing optics exhibited chromatic aberration. Rowland determined that this problem could be eliminated by ruling a grating on a concave spherical metal blank. Such a concave grating both diffracted and focused the light at the same time, thus doing away with the necessity of using lenses. This also created a grating which, for the first time, could be used to analyze light which is not transmitted by glass lenses, such as ultraviolet light.

Notwithstanding the advantages of the Rowland grating configuration, certain limitations are encountered. Generally, in accordance with this configuration, the spherical surface which defines the unrulled shape of the grating can be regarded as lying on a theoretical sphere which includes the surface of the ruled grating. A spectrum is formed on the surface of the same sphere when a source to be analyzed is located on the sphere. Thus, optical configurations are limited.

In addition to this limited optical configuration, serious aberrations also occur with the Rowland grating
configuration. These aberrations include astigmatism, first and second order coma and spherical aberration.

Notwithstanding the fact that the possibility exists to correct such aberrations by making a grating through the interference of two light sources in a photo-sensitive gelatin layer, and further notwithstanding the fact that this technique was first used by Rayleigh about the turn of the century, it was not until the late 1960's that Flamand fabricated the first interferometrically generated grating on a concave substrate as disclosed in U.S. Patent No. 3,628,849.

As noted above, Flamand's work continued in the tradition of expanding the range and versatility of diffraction gratings which began in earnest with Professor Rowland's work. The object of grating design has thus always been the minimization and economization of grating and other optical elements, achievement of compact grating configurations and maximizing range of the instrument with high quality. However, even now, where extremely large ranges of operation are desired, it is difficult to fabricate satisfactory gratings.

An echelle grating is known in the art, consisting of relatively coarse groove spacing, typically on the order of 280 grooves per centimeter. The echelle grating provides order numbers in the hundreds in a two-dimensional array consisting of a series of short strips corresponding to adjacent diffraction orders. Such a two-dimensional grating array is referred to as an echellegram. Generally, dispersion of the echelle grating is in a direction perpendicular to that of a secondary diffraction grating or prism spectrograph, which must be used in conjunction with the echelle grating in order to separate the various orders in the system.
Thus, even if a concave aberration corrected focusing diffraction grating is used, a minimum of two diffraction gratings must still be used in the system in order to obtain useful results, and these two gratings must be aligned with respect to each other. Yet another complication is the fact that the output of the optical system requires a two-dimensional array of detectors, having both horizontally and vertically arranged photocell detectors. Such an array of photocell detectors is substantially more expensive than a simple line of photocell detectors which is sufficient for most other spectrographic or monochromator applications.

SUMMARY OF THE INVENTION

The present invention is intended to provide a remedy. An object of the present invention is to provide a single grating constructed so that light projected toward the grating is separated and focused by the grating, so that the conventionally required alignment of optics is obviated. The same is achieved in accordance with conventional groove blazing technology. In particular, in accordance with such techniques, the control of groove profile, first made possible when gratings began to be ruled on aluminum, is used to achieve the desired blaze of light at the desired angle, thus making possible control of the confirmation of auxiliary optical elements, for the different functions of an optical system.

In accordance with one aspect of the present invention, a first grating master is ruled having a first set of diffraction characteristics on a support surface, or substrate, having a first predetermined shape. A second grating master having a second grating surface with a second set of diffraction characteristics is ruled on a support surface, or substrate, having a second
predetermined shape. A portion of the first master grating having a portion of the first grating surface disposed thereon is removed. The edge of the removed portion of the first master grating is defined by a first boundary contour in its respective predetermined shape.

The removed portion of the first master grating is located on one side of the first boundary contour. A portion of the second master grating having a portion of the second grating surface disposed thereon is removed. The edge of the removed portion of the second master grating is defined by a second boundary contour matching the first boundary contour, and the removed portion of the second master grating is located on the opposite side of the second boundary contour. The first master grating is attached to the removed portion of the second master grating to form a composite master grating having desired optical characteristics.

In accordance with another aspect of the present invention, an optical grating is manufactured by providing a substrate supported on a rotatable support at a first position relative to a pair of coherent light sources. The substrate includes at least a first section and a second section. A photosensitive layer is formed on the surface of the substrate, and a mask is formed over a first portion of the photosensitive layer covering the first section, while a second portion of the photosensitive layer covering the second section is left unmasked. The unmasked second portion of the photosensitive layer is holographically exposed, in a first holographic exposing step, to an interference light pattern from a first light source and a second light source (the pair of coherent light sources) disposed at a fixed exposing position relative to the unmasked second portion to form a first grating surface pattern. The first grating surface pattern is then masked, and the mask covering the first portion of the photosensitive
layer is removed. The rotatable support is rotated so that the substrate is rotated 180 degrees to a second position. At the second position, the first light source and the second light source are disposed at the same fixed exposing position relative to the unmasked first portion as they were previously disposed relative to the unmasked second portion during the first holographic exposing step. In a second holographic exposing step, the unmasked first portion of the photosensitive layer is then holographically exposed to the same interference light pattern from the first light source, and the second light source disposed at the same fixed exposing position to form a second grating surface pattern on the substrate. The exposed photosensitive material is then developed, and part of the photosensitive layer is removed to form a grating surface on the substrate. An optical grating may then be obtained by forming a metal layer over the grating surface, which grating surface may be comprised of the remaining photosensitive material supported on the substrate. Alternatively, portions of the substrate not covered by the photosensitive layer may be etched, and the remaining photosensitive material may then be removed to form a grating surface etched in the substrate. A metal layer may then be formed over the grating surface etched in the substrate to obtain an optical grating. By this inventive method, an optical grating having symmetrically formed sides is easily and consistently formed from the holographic interference of two coherent light sources.

BRIEF DESCRIPTION OF THE DRAWINGS
One way of carrying out the invention is described in detail below with reference to drawings which illustrate only one specific embodiment of the invention and in which:-
Figure 1 is a top plan view of a grating constructed in accordance with the present invention;

Figure 2 is a cross-sectional view of the grating of Figure 1 along lines 2-2 of Figure 1;

Figure 3 is a diagram illustrating the operation of the grating of Figures 1 and 2;

Figure 4 is a top plan view of a grating manufactured during an intermediate step of the method of the present invention;

Figure 5 is a schematic diagram illustrating the operation of the grating of Figure 4;

Figure 6 is a view of a portion of the grating of Figure 4 incorporating the inventive master grating;

Figure 7 is a schematic view showing the operation of a second grating made using the inventive master grating;

Figure 8 is a top plan view of the grating shown in Figure 7;

Figure 9 is a perspective view of a portion of the grating of Figure 8;

Figure 10 illustrates the assembly of various portions of different gratings to make the inventive master grating;

Figure 11 is a schematic view illustrating the operation of yet another grating used in the manufacture of the inventive master grating;

Figure 12 illustrates the assembled master grating of the invention;

Figure 13 illustrates the operation of the assembled master grating of Figure 12;

Figure 14 illustrates an alternative grating constructed in accordance with the present invention;
Figure 15 is a schematic diagram illustrating another grating constructed in accordance with the present invention;

Figure 16 is a schematic diagram of a system constructed in accordance with the present invention;

Figure 17 illustrates a colorimetry system incorporating a grating constructed in accordance with the present invention;

Figure 18 is a detail of the lines of the grating of Figure 17;

Figure 19 illustrates intermediate gratings for manufacturing a master grating in accordance with the present invention;

Figure 20 illustrates intermediate gratings for manufacturing a master grating in accordance with the present invention;

Figure 21 illustrates two half gratings removed from the gratings of Figures 19 and 20;

Figure 22 illustrates a master grating constructed in accordance with the present invention from the parts illustrated in Figure 21 for the replication of gratings for use in the system of Figure 17;

Figure 23 schematically illustrates a step in the inventive method of manufacture in accordance with the present invention;

Figure 24 schematically illustrates a step in the inventive method of manufacture in accordance with the present invention;

Figure 25 schematically illustrates a step in the inventive method of manufacture in accordance with the present invention;

Figure 26 schematically illustrates a step in the inventive method of manufacture in accordance with the present invention;
Figure 27 schematically illustrates a step in the inventive method of manufacture in accordance with the present invention;

Figure 28 schematically illustrates a step in the inventive method of manufacture in accordance with the present invention;

Figure 29 schematically illustrates a step in the inventive method of manufacture in accordance with the present invention;

Figure 30 is a view of a grating substrate mounted on a rotatable support in accordance with an inventive holographic exposure method of manufacture;

Figure 31 is a view of a grating substrate during an intermediate step of the inventive holographic exposure method of manufacture;

Figure 32 is a view of a grating substrate during another intermediate step of the inventive holographic exposure method of manufacture;

Figure 33 is a view of a grating substrate during another intermediate step of the inventive holographic exposure method of manufacture;

Figure 34 is a view of a grating substrate manufactured in accordance with the inventive holographic exposure method of manufacture; and

Figure 35 is an isolated, enlarged view of the optical grating manufactured in accordance with the present invention.

BEST MODE FOR CARRYING OUT THE INVENTION

Referring to Figure 1, a grating 10 constructed in accordance with the present invention is illustrated.
Grating 10 includes a number of separate diffracting surfaces 12, 14, 16, 18, 20, 22, 24, 26, 28 and 30. Each of these surfaces 12-30 has its own diffracting characteristic.

Surfaces 12-30 together form a continuous surface which generally resembles the surface that would be formed by diffraction grating grooves marked on a single spherical substrate, as illustrated in Figure 2.

More particularly, as illustrated in Figure 3, light of different wavelengths is treated by individual surfaces 12-30. For example, light 32 impinging on surface 12 is caused to be reflected as light 34 toward a detector element 36.

Detector element 36 is part of a linear array 38 of detector elements of a type well known in the prior art.

In similar fashion, light 40 of a wavelength different from the wavelength of light 32, incident on grating 10 is reflected as reflected light 42. Reflected light 42 is, in turn, incident on detector element 44.

In similar fashion, light waves 45, 46, 48, 50, 52, 54 and 56 are incident on respective surfaces 16-30. Light waves 45-56 are all of wavelengths different from the wavelength of light 32 and 40 and are reflected toward respective detector elements 58, 60, 62, 64, 66, 68, 70 and 72.

Thus, in accordance with the present invention, it is possible to present an input light signal to grating 10 through an inlet slit 74. Referring back to Figure 1, it is seen that surfaces 12-30 all have substantially equal areas. In particular, it is noted that surfaces 20 and 22 are the narrowest surfaces lying at the center of grating 10, while surfaces 12 and 30 are the widest
surfaces. Intermediate surfaces between surface 20 and surface 12 are increasingly wider as they get closer to surface 12. Similarly, intermediate surfaces 24-28 are increasingly wider as they get closer to surface 30.

The end result is that all surfaces are (though they do not have to be) of substantially equal area and, accordingly, have light outputs of substantially identical intensity. This particular methodology is used in the case where the various grating surfaces have equal efficiency for the particular wavelengths or wavelength ranges associated with them. However, in the event that such efficiency is not equal or in the event that the source is expected to be concentrated in certain wavelengths, the surfaces may be made wider or narrower in order to achieve the desired operation of the system.

Likewise, each of the surfaces 12-30 may be either all dedicated to single wavelengths of interest or two ranges of wavelengths. The ranges of wavelengths may be continuous or they may be from diverse portions of the spectrum. Likewise, a single grating may combine a number of discrete wavelengths of interest, together with a number of ranges of wavelengths.

Of particular note is the fact that the individual tailoring of grating surfaces 12-30 allows extremely diverse operating characteristics and extremely wide ranges of operation, something which has never been achievable with conventional holographic aberration corrected gratings. In principal, neither the inlet slits nor the detectors need to lie in a plane, as the designer is given complete freedom in this regard.

As alluded to above, the inventive grating illustrated in the Figures 1-3 has a number of different surfaces, each
of which is individually tailored and designed to perform a specific function. Such specific function may be that of a monochromator, or a spectrometer. It may be to analyze a particularly weak signal or a particularly strong signal. If the signal is particularly weak, a particularly large area for the applicable grating surface will be selected. If the signal is relatively strong, a very narrow area may be used and, indeed, the area need not be a strip as illustrated in Figure 1 by surfaces 12-30. Alternatively, the surface may be a portion of a strip.

Likewise, while the example illustrated in Figures 1-3 contemplates the use of a linear detector array 38, any arrangement may be used as a detector as may be practical or convenient for the particular application involved. A linear detector is shown, however, because of the economical nature of such detectors, the ease of assembly of a grating system using such a detector (because it is a single element), and because of the easy availability of a wide range of such linear detectors in the field.

In principal, the inventive grating may be manufactured in accordance with the inventive method by coating a spherical blank with a photo-sensitive material and separately exposing surfaces 12-30 with laser light sources which will create a grating having the desired characteristics. Selective exposure is achieved through the use of a plurality of strip shaped masks whose shape take the form of portions of a spherical shell.

Referring to Figure 4, a grating 112 having a characteristic which is the same desired for surface 12 is illustrated. Grating 112 is manufactured in a unconventional manner to be explained below and, as noted above, has the characteristics of surface 12. Figure 4 shows a blank photo-sensitive apparatus for ruling a
concave grating 112 which sits on a rotatable support 112a. The ruling of the grating 112 takes place in two steps. First, the pair of coherent light sources C and D interfere electrically illuminate and thereby rule a first half grating 112b of the grating 112. Sources C and D are located at 

\[ \lambda_c, \delta_0 \] 

from the apex B of the first half grating 112b. While the first half grating 112b is being ruled, a second half grating 112c is covered by a mask 112d. In the second step of the ruling of the grating 112, the support 112a rotates around its normal to the apex (S) of the grating 112, exposing the second half 112c of the grating 112 to sources C and D while the now-ruled first half grating 112b is masked. Coherent sources C and D now interfere electrically rule the second half grating 112c.

Figure 4 shows the case where the grating 112 comprises only two sections, a first half grating 112b and the second half grating 112c.

Figure 5 shows the case where the grating 112 is composed of ten sections. The ruling of the sections is similar to the ruling described with respect to Figure 4. Ruling by the coherent light sources C and D occurs in a section by section manner; ruling of an unmasked section is followed by rotation of the support or exposing an unmasked section which is then ruled by the coherent sources C and D. This continues until all sections of the grating desired to be ruled have in fact been ruled.

Figures 6 and 7 are top views of the support, grating and mask (S) of Figures 4 and 5. Not shown are the sources C and D.

The result of this operation is the fabrication of a master section 214, as illustrated in Figure 9. As can be seen from Figure 13, the operation of the assembled
master grating is substantially identical to the operation of the grating illustrated in Figures 1-3.

After the master grating illustrated in Figures 12 and 13 has been fabricated, it is then possible to use this master grating to manufacture replicas. Such replication is performed by forming a mold from the master grating and using the mold to form replica gratings in a polymeric material such as epoxy plastic. The replica gratings are then completed by coating the polymeric material with a layer of aluminum or other suitable material, in accordance with conventional replication techniques. The result of replication is a grating such as that illustrated in Figures 1-3.

An alternative embodiment of the inventive method of manufacturing gratings is illustrated in Figures 23-29. Generally, similar parts or parts performing analogous, corresponding or identical functions to those of the Figures 1-13 embodiment are numbered herein with numbers which differ from those of the earlier embodiments by multiples of one hundred.

A great diversity in configuration in operation of gratings is possible in accordance with the method of the present invention. Referring to Figure 14, an alternative grating 310 constructed in accordance with the instant invention is illustrated. In particular, grating 310 includes a plurality of surfaces 310-330, each of which contributes to the overall function of the device. Each of the surfaces 310-330 is designed to function for a desired wavelength or range of wavelengths received from inlet slits 374a-j, respectively. As illustrated in Figure 14, light at the desired wavelength or range of wavelengths coming from inlet slits 374a-j is caused to fall upon detectors 336, 334, 358, 360, 362, 364, 366, 368, 370 and 372, respectively, as illustrated
by the light paths illustrated by arrowed lines in Figure 14.

Referring to Figure 14, still yet another possibility for a grating constructed in accordance with the present invention is illustrated. In this embodiment, two detector elements 444 and 445 are positioned at different points and in different planes with respect to grating 410. Grating 410 includes two regions, namely, grating surface 414 on the left side of the grating and grating surface 416 to the right of the center of the grating. In addition, inlet slits 474 and 475 are positioned at different points with respect to grating 410.

In accordance with the present invention, specific instruments with particularly advantageous characteristics are possible. For example, referring to Figure 16, we may consider a grating 510 comprising three different grating surfaces 512, 514 and 516. Grating 512 is blazed to produce a blaze of light in the direction indicated by arrow 513. Grating surface 514 is blazed to produce a maxima in the direction indicated by arrow 515. Grating surface 516 is blazed to produce a maxima in the direction indicated by arrow 517.

More particularly, grating surface 1 is provided with 4,800 groves per millimeter and thus covers a wavelength range between 150 and 300 nm. The desired wavelengths are imaged by grating surface 512 on a section 536 of a detector array 538. Light in the wavelength range of 300 to 500 nm is reflected by grating surface 514, which is ruled with 3,600 groves per millimeter to cover the wavelength range of 300 to 500 nm and focus that light on section 544 of detector array 538. Finally, grating surface 516 is ruled with 1800 grooves per millimeter and covers from 300 to 850 nm, imaging light in that wavelength range on section 558 of detector array 538.
In contrast with prior systems, all of the grating surfaces (namely, grating surfaces 512, 514 and 516) operate in the first order, and thus result in maximum efficiency. Because each grating surface is accommodating a different part of the spectrum, the entire desired spectrum range is covered with the desired efficiency. In accordance with the present invention, it is contemplated that the grating 510 will have the overall shape of a spherical section with a diameter of about five centimeters. Light is provided to this system by an icp torch 559 which is focused by a lens 561 through a slit 574 which causes light to be analyzed to fall upon grating 510.

The simplicity of this system is remarkable compared to the prior art solution for the same problem. Such a system generally comprises an icp torch which is directed by a pair of mirrors which obtains the desired and required two access rotation. Light only then passes through the entrance slit, and this light must be collimated by a parabolic reflector. The output of the parabolic reflector is then caused to fall on an echelle grating which analyzes the light and reflects it toward a Schmidt cross disperser, which then passes a portion of the light to an ultraviolet camera sphere and then a field flattener which drives an ultraviolet detector. The remaining portion of the light is passed through a prism which analyzes light in the visible spectrum and passes the analyzed light to a compound lens and a detector. Clearly the simplicity of the inventive system is apparent by comparison of it to the above present prior art apparatus for obtaining similar results.

The method and apparatus of the present invention is particularly useful in the context of colorimetry applications. More particularly, in accordance with prior art techniques, a colorimetry instrument is
constructed having a pair of analyzers having identical characteristics and a pair of identical detectors. For each reading, the instrument measures the signal, which may constitute a reflected or transmitted light signal, and reads a reference signal corresponding to the flash from the light source which passes the light through the sample in the case of a transmission system or sends light to the sample for reflection in the case of a reflection system.

The final reading is achieved by dividing the intensity read off the sample by the intensity read directly from the light source. This yields a normalized reading which is corrected for variations in power of the flash.

More particularly, referring to Figure 17, an instrument suitable for colorimetry applications and employing the method and apparatus of the present invention is illustrated. The instrument is built around a grating 610 and includes diffracting surfaces 612 (which have a blaze oriented in the direction indicated by arrow 613) and diffraction surface 614 (which has a blaze oriented in the direction indicated by arrow 615).

Surfaces 612 and 614 are substantially identical mirror images of each other, as is illustrated more clearly in Figure 17. Both surfaces are complementary halves of a single spherical substrate, and are thus made using a pair of spherical blanks which are substantially identical to each other, as will be discussed in detail below. Thus, both gratings share the same groove density, dispersion, efficiency, order and so forth. Moreover, the gratings are both aberration-corrected and take full advantage of conventional flat ccd detector arrays of the linear diode type. This is because both gratings in the disclosed position operate in the First
order, have the same proper geometry, and focus on the
detector at the disclosed positions.

The colorimetry system illustrated in Figure 17 employs a
pair of identical linear diode detector arrays 638 and
639 and has the advantage of reducing alignment needs and
costs, since two sides of the same linear detector are
illuminated. These arrays are driven by light emanating
from inlet slits 674 and 675, respectively, as
illustrated by the ray paths for light 656 in Figure 17.

In accordance with the present invention a grating such
as that illustrated in Figures 17 and 18 is made by first
manufacturing a first master grating 608 as illustrated
in Figure 19. Grating 608 is a blazed grating of the
type having a groove density of approximately 320 grooves
per millimeter and a wavelength range of 380-720 nm.
A second grating 609 substantially identical to grating
608 is also manufactured. Both of these gratings have
numerous grooves 675.

After the gratings are made in accordance with
conventional holographic techniques, the gratings are cut
along the line indicated by their respective lines 680
and 682, as illustrated in Figures 19 and 20. The result
is a pair of substantially identical half gratings 611
and 613 as illustrated in Figure 21. Each half grating
612 and 613 is taken from the left half of its respective
grating. Half 613 is then rotated in the direction
indicated by arrow 699 and joined to grating 611 as
indicated in Figure 22 to make a master grating, as
illustrated in Figure 22. This master grating is then
used to replicate additional gratings having the
characteristics described in connection with Figure 17
and 18. The result is a master grating illustrated in
Figure 22 with, as can be seen from the parts of which it
is made, a groove density of 320 grooves per mm.
Referring to Figures 23 - 27, a particularly advantageous design may be implemented using as a starting point a grating sold under catalog number 550.17.009 of company Jobin-Yvon of Longjumeau, France. This grating has a size of 32 millimeters square with a groove density of 320 grooves per millimeter and covers a wavelength range of 380-720 nanometers. The radius of curvature of this grating is 40.03 millimeters.

If we consider a fabrication process starting with a master grating 710 used for making this grating (known as a generation zero grating), a grating mold can be replicated to form the concave aberration corrected shape of the master as a first generation convex mold. This mold is made to minimize the number of times the master is used. The first generation convex mold may then be used to replicate two second generation concave gratings 710 and 710a which, obviously, will be identical to each other. Such a concave grating 710 is illustrated in Figure 23. Grating 710 has a blaze whose sense is indicated by arrow 715. Each of the gratings 710 and 710a are used to prepare by replication in the form of a pair of "sandwiches", to form a replicated convex mold 727 (Figure 24).

The sandwiches are then cut with a saw along a plane replicated by line 717, which is perpendicular to a tangent to point 719 on grating 710. A second cut along a plane 721 parallel to plane 717 is then made. Plane 721 is separated from plane 717 by 20 millimeters. In accordance with the preferred embodiment, the cutting along the planes 719 and 721 is performed while the convex molds 727 is still attached to the second generation replicas 710 and 710a, as illustrated in Figures 23 and 24. The result is then two half grating molds 727 having a dimension of 20 millimeters.
by approximately 40 millimeters, as illustrated in Figure 24.

These two half grating molds, 727 and 727a, are separated from the sandwiches and glued together to form a single grating mold after rotation of grating mold 727a in the direction of arrow 799. This places face 723 of grating mold 727a in contact with face 725 of grating mold 727. Grating mold 727 and 727a thus form a single unitary grating mold, as illustrated in Figure 25.

after the convex halves are glued, the grating molds 727 and 727a are then ground along a plane 729 and a support 731 attached to maintain the integrity of the grating, as illustrated in Figure 26. The same may then be used to replicate a grating 710r, which may be itself used as a master grating as illustrated in Figure 27.

Referring to Figures 28 and 29, use of grating 710r is illustrated. Light is input to one of the grating halves through an inlet slit 774a, and onto the other grating through inlet 774b. Light is imaged on array detectors 738a and 738b, respectively. The parameters of use for this colorimetry application involve an input path length $L_a$ of 45.33 millimeters at an angle $\alpha$ of 6.25° to a normal 731 to the surface of grating 710r. Detection is done at the end of path $L_h$ which is in a plane displaced from grating 710 by a distance $H$ as illustrated in Figure 29, with emission along a path ranging up to an angle $\beta_h$ of -14.5° with respect to a parallel to the grating axis.

Figures 30 through 35 illustrate another inventive method of manufacturing an optical grating. In accordance with this inventive method, a substrate 810 is supported on a rotatable support 812 at a first position relative to a pair of coherent light sources C,D. The substrate 810 includes at least a first section 814 and a second
section 816. As shown in Figure 31, a photosensitive layer 818 is formed on the surface of the substrate 810, and a mask 820 is formed over a first portion 822 of the photosensitive layer 818 covering the first section 814, while leaving unmasked a second portion 824 of the photosensitive layer 818 covering the second section 816.

As shown in Figure 32, the unmasked second portion 824 of the photosensitive layer 818 is holographically exposed to an interference light pattern from a first light source C and a second light source D (the pair of coherent light sources) disposed at a fixed exposing position relative to the unmasked second portion 824 to from a first grating surface pattern 826. As shown in Figures 30, 32 and 33, the fixed exposing position for light source C is defined by the polar co-ordinates \( g, l_c \) and light source D is defined by the polar co-ordinates \( d, l_c \) relative to the apex B and B' of the first section 814 and second section 816 of the grating substrate 810, respectively.

The first grating surface pattern 826 is then masked, and the mask 820 over the first portion 822 of the photosensitive layer 818 covering the first section 814 is removed. The rotatable support 812 (shown in Figure 30) is rotated so that the substrate 810 is rotated 180 degrees to a second position (shown in Figure 33). At the second position the first light source C and the second light source D are disposed at the same fixed exposing position relative to the unmasked first portion 822 as they were relative to the second portion 824 during the first holographic exposing step.

The unmasked first portion 822 of the photosensitive layer 818 is then holographically exposed to the same interference light pattern from the first light source C
and the second light source D disposed at the same fixed exposing position to form a second grating surface pattern 828 on the substrate 810. The exposed photosensitive layer 818 is developed, and part of the photosensitive layer 818 is removed to form a grating surface on the substrate 810. Stated otherwise, the fixed exposing position for light source C is defined by the polar co-ordinates g, \( I^c \), and light source D is defined by the polar co-ordinates d, \( I^c \) relative to the apex B (first position) and also relative to apex B' (second position), so that a symmetrical and identical interference pattern is recorded on both halves (first section 814 and second section 816) of the grating substrate 810.

As shown in Figure 34 and Figure 35, an optical grating may be then obtained by forming a metal layer 832 over the grating surface 830 comprised of the remaining photosensitive layer 818 supported in a grating pattern on the substrate 810. Alternatively, portions of the substrate 810 not covered by the photosensitive may be etched, and the remaining photosensitive layer 818 then removed to form a grating surface 830 etched in the substrate 810. A metal layer 832 may than be formed over the grating surface 830 etched in the substrate 810 to obtain an optical grating. By this inventive method, an optical grating is easily and consistently manufactured from the holographic interference pattern of two coherent light sources. The optical grating obtained in accordance with the present invention has symmetrically formed sides, in which grooves of the first half grating (first section 814) are parallel to the grooves of the second half grating (second section 816), thereby alleviating many of the drawbacks of the conventional art.

While an illustrative embodiment of the invention has been described above, it is, of course, understood that
various modifications will be apparent to those of ordinary skill in the art. Such modifications are within the spirit and scope of the invention, which is limited and defined only by the appended claims.
Claims:

1. A method of manufacturing a grating wherein a master grating is ruled with a set of diffraction characteristics on a support surface of predetermined shape, characterized in that, for the purpose of manufacturing a composite master grating, the method comprises the steps of:

(a) ruling a first grating master having a first grating surface with a first set of diffraction characteristics on a support surface of first predetermined shape;

(b) ruling a second grating master having a second grating surface with a second set of diffraction characteristics on a support surface having a second predetermined shape;

(c) removing a portion of the first master grating having a portion of the first grating surface disposed thereon, the edge of the removed portion of the first master grating being defined by a first boundary contour in its respective predetermined shape, and the removed portion of the first master grating being located on one side of the first boundary contour;

(d) removing a portion of the second master grating having a portion of the second grating surface disposed thereon, the edge of the removed portion of the second master grating being defined by a second boundary contour in its respective predetermined shape, the second boundary contour matching the first boundary contour [and] when the removed portion of the second master grating is located on the opposite side of the second boundary contour to the one side; and
5 (e) attaching the removed portion of the first master grating to the removed portion of the second master grating to form a composite master grating.

10 2. A method of manufacturing a grating as in claim 1, characterized by further comprising the step of replicating the composite master grating.

3. A method of manufacturing a grating as in claim 1, wherein the ruling is effected holographically by exposing a photosensitive material to a pair of coherent light sources.

4. A method of manufacturing a grating as in claim 2, characterized in that the first and second grating surfaces have substantially the same grating surface configuration.

5. A method of manufacturing a grating as in claim 1, characterized by further comprising the step of blazing the first and second grating masters or the removed portions of the master gratings and wherein the composite master grating has two removed portions which in the position in which they are attached together have opposite blaze angle signs with respect to a vertical to the composite master grating.

6. A method as in claim 1, characterized in that the removal is performed by cutting away the removed portion by cutting at an oblique angle.

7. A method of manufacturing a grating, comprising the steps of:
   a) providing a substrate at a first position, the substrate including at least a first section and a second section;
b) forming a photosensitive layer on the surface of the substrate; and
c) exposing the photosensitive layer to a light pattern from at least one light source to form a grating surface pattern;

characterized by further comprising:
d) forming a mask over a first portion of the photosensitive layer covering the first section while leaving a second portion of the photosensitive layer covering the second section unmasked;
e) exposing the unmasked second portion of the photosensitive layer to a light pattern from at least one light source to form a first grating surface pattern;
f) masking the first grating surface pattern;
g) removing the mask over the first portion of the photosensitive layer covering the first section;
h) rotating the substrate to a second position; and
i) exposing the unmasked first portion of the photosensitive layer to the light pattern from the at least one light source to form a second grating surface pattern on the substrate.

8. A method of manufacturing a grating according to claim 1; characterized by further comprising the steps of:
j) removing part of the photosensitive layer to form a grating surface; and
k) forming a metal layer over the grating surface.

9. A method of manufacturing a grating according to claim 1; characterized in that the step of exposing the
unmasked second portion comprises holographically exposing the unmasked second portion of the photosensitive layer to an interference light pattern from a first coherent light source and a second coherent light source disposed at a fixed exposing position relative to the unmasked second portion; the step of rotating the substrate comprising rotating the substrate to the second position so that the first light source and the second light source are disposed at the fixed exposing position relative to the unmasked first portion; and the step of exposing the unmasked first portion comprises holographically exposing the unmasked first portion of the photosensitive layer to the interference light pattern from the first light source and the second light source disposed at the fixed exposing position relative to the unmasked first portion so that the first portion and the second portion are exposed to the same interference light pattern.

10. A method of manufacturing a grating according to claim 1; characterized by further comprising the steps of:

1) removing some of the photosensitive layer after the step of exposing the first portion;

m) etching portions of the substrate not covered by the photosensitive layer; and

n) removing at least some remaining photosensitive material to form a grating surface etched in the substrate.

11. A method of manufacturing a grating according to claim 10; further comprising the step of forming a metal layer over the grating surface etched in the substrate.

12. A method of manufacturing a grating, characterized by comprising the steps of:
-29-

5 a) providing a substrate at a first position, the substrate including at least a first section and a second section; forming a photosensitive layer on the surface of the substrate;

10 b) forming a mask over a first portion of the photosensitive layer covering the first section while leaving a second portion of the photosensitive layer covering the second section unmasked;

15 c) holographically exposing the unmasked second portion of the photosensitive layer to an interference light pattern from a first light source and a second light source disposed at a fixed exposing position relative to the unmasked second portion to from a first grating surface pattern;

20 d) masking the first grating surface pattern; removing the mask over the first portion of the photosensitive layer covering the first section;

25 e) rotating the substrate 180 degrees to a second position so that the first light source and the second light source are disposed at the fixed exposing position relative to the unmasked first portion; and

30 f) holographically exposing the unmasked first portion of the photosensitive layer to the same interference light pattern from the first light source and the second light source disposed at the fixed exposing position relative to the unmasked first portion to form a second grating surface pattern on the substrate.

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40 13. A method of manufacturing a grating according to claim 12; characterized by further comprising the steps
of:

g) removing part of the photosensitive layer to form a grating surface; and

h) forming a metal layer over the grating surface.

14. A method of manufacturing a grating according to claim 13; further comprising the steps of:

i) removing some of the photosensitive layer after the step of exposing the first portion;

j) etching portions of the substrate not covered by the photosensitive layer; and

k) removing at least some remaining photosensitive material to form a grating surface etched in the substrate.

15. A method of manufacturing a grating according to claim 14 characterized by further comprising the step of forming a metal layer over the grating surface etched in the substrate.

16. A diffraction grating comprising a substrate having a support surface configured and dimensioned to substantially conform to an overall shape of a desired diffraction grating, the shape being substantially without discontinuities characterized by comprising;

a) a first grating section having a set of first grating characteristics, the first grating section being disposed on a portion of the support surface;

b) a second grating section having a set of second grating characteristics, the second grating section being disposed on a portion of the support surface, said first characteristics being different form the second characteristics;
c) a first light input port for receiving light to be analyzed by the grating and passing the light toward said support surface; and
d) a first detector positioned, configured and dimensioned to receive light reflected and focused by the first and second grating sections.

17. A diffraction grating, as in claim 16, characterized in that said first and second grating sections are of identical dimension and configuration.

18. A diffraction grating, as in Claim 16, characterized in that the first and second grating sections are oriented differently and have characteristics for the analysis of reference and sample colorimetric optical signals.

19. A diffraction grating, as in Claim 16, characterized in that the first and second grating sections are blazed with opposite senses.

20. A diffraction grating, as in Claim 16, characterized in that the detector comprises a linear detector array.

21. A diffraction grating, as in Claim 20, characterized in that the linear detector array comprises first and second sections and the grating sections each illuminate a respective one of the sections.

22. A diffraction grating, as in Claim 21, characterized in that the sections correspond to different parts of the spectrum.

23. A diffraction grating, as in Claim 16, further comprising a second input port and a second detector, the
second input port illuminating the second detector.

24. A diffraction grating as in Claim 16, further comprising a second light input port for illuminating the grating.

25. A diffraction grating comprising a substrate having a support surface configured and dimensioned to substantially conform to an overall shape of a desired diffraction grating, the shape being substantially without discontinuities characterized by comprising:
   a) a first grating section having a set of first grating characteristics, the first grating section being disposed on a portion of the support surface;
   b) a second grating section having a set of second grating characteristics, the second grating section being disposed on a portion of the support surface, said first characteristics being different from the second characteristics;
   c) a first light input port for receiving light to be analyzed by the grating and passing the light toward said support surface;
   d) a first detector positioned, configured and dimensioned to receive light reflected and focused by the grating;
   e) a second light input port for receiving light to be analyzed by the grating and passing the light toward said support surface; and
   f) a second detector positioned, configured and dimensioned to receive light reflected and focused by the grating.

26. A diffraction grating as in Claim 25, characterized in that the first and second light input
ports illuminate the first and second grating sections, respectively, and the first and second grating sections focus light on the first and second detectors, respectively.

27. A diffraction grating as in Claim 26, characterized in that the first and second detectors are parts of a single linear array of detector elements.

28. A diffraction grating as in Claim 27, characterized in that the first and second grating sections are blazed in opposite directions.

29. A grating as in Claim 28, characterized in that the first and second grating sections are aberration corrected and manufactured using holographic techniques.

30. A diffusion grating as in Claim 25, characterized by further comprising additional grating sections.

31. A diffusion grating as in Claim 25, characterized by further comprising a linear array of detectors.

32. A grating as in Claim 24, characterized in that the first and second grating sections are aberration corrected and manufactured using holographic techniques.
g) removing part of the photosensitive layer to form a grating surface; and
h) forming a metal layer over the grating surface.

14. A method of manufacturing a grating according to claim 13; further comprising the steps of:
i) removing some of the photosensitive layer after the step of exposing the first portion;
j) etching portions of the substrate not covered by the photosensitive layer; and
k) removing at least some remaining photosensitive material to form a grating surface etched in the substrate.

15. A method of manufacturing a grating according to claim 14 characterized by further comprising the step of forming a metal layer over the grating surface etched in the substrate.

16. An optical system including a diffraction grating comprising a substrate having a support surface configured and dimensioned to substantially conform to an overall shape of a desired diffraction grating, the shape being substantially without discontinuities, a first light input port to admit light to the grating and a detector to receive light reflected and focussed by the grating characterized in that the diffraction grating has at least first and second sections having different optical characteristics, one section from another, and comprises:
a) a first grating section (12, 212, 312, 414, 512 or 612) having a set of first grating characteristics, the first grating section being disposed on a portion of the support surface;
b) a second grating section (14, 214, 314, 416, 514 or 614) having a set of second grating characteristics, the second grating section being disposed on a portion of the support surface, the first grating
characteristics being different from the second grating characteristics, and further characterized in that the detector (38, 444, 538, 638 and 639, or 738) can simultaneously receive light reflected and focussed by the first and second grating sections.

17. An optical system, as in claim 16, characterized in that said first and second grating sections (12, 212, 312, 414, 512, 612 and 14, 214, 314, 416, 514, 614) are of identical dimension and configuration.

18. An optical system, as in Claim 16, characterized in that the first and second grating sections (12, 212, 312, 414, 512, 612 and 14, 214, 314, 416, 514, 614) are oriented differently and have characteristics for the analysis of reference and sample colorimetric optical signals.

19. An optical system, as in Claim 16, characterized in that the first and second grating sections (12, 212, 312, 414, 612 and 14, 214, 314, 416, 614) are blazed with opposite senses.

20. An optical system, as in Claim 16, characterized in that the detector (38, 444, 538, 638 or 738) comprises a linear detector array.

21. An optical system, as in Claim 20, characterized in that the linear detector array (38, 444, 538, 638 or 738) comprises first and second detector sections and each grating section illuminates a respective one of the detector sections.

22. An optical system, as in Claim 21, characterized in that the sections correspond to different parts of the spectrum.

23. An optical system, as in Claim 16, further
comprising a second input port (475) and a second detector (445), the second input port illuminating the second detector.

24. An optical system as in Claim 16, further comprising a second light input port (374b-j, 475, 675) for illuminating the grating.

25. An optical system including a diffraction grating comprising a substrate having a support surface configured and dimensioned to substantially conform to an overall shape of a desired diffraction grating, the shape being substantially without discontinuities, a first light input port to admit light to the grating and a detector to receive light reflected and focussed by the grating characterized in that the diffraction grating has at least first and second sections having different optical characteristics, one section from another, and comprises:

a) a first grating section (12, 212, 312, 414, 512 or 612) having a set of first grating characteristics, the first grating section being disposed on a portion of the support surface;

b) a second grating section (14, 214, 314, 416, 514 or 614) having a set of second grating characteristics, the second grating section being disposed on a portion of the support surface, the first grating characteristics being different from the second grating characteristics;

further characterized in that the optical system comprises:

c) a second light input port (374b-j, 475, 675) to admit light to be analyzed to the grating; and

d) a second detector (445, 639) to receive light reflected and focused by the grating.

26. An optical system as in Claim 25, characterized in that the first and second light input ports (474, 674, and 475, 675) illuminate the first and second grating
sections (12, 212, 312, 414, 512, 612 and 14, 214, 314, 416, 514, 614), respectively, and the first and second grating sections (12, 212, 312, 414, 512, 612 and 14, 214, 314, 416, 514, 614) focus light on the first and second detectors, respectively.

27. An optical system as in Claim 26, characterized in that the first and second detectors (444, 638 and 445, 639) are parts of a single linear array of detector elements.

28. An optical system as in Claim 27, characterized in that the first and second grating sections (12, 212, 312, 414, 512, 612 and 14, 214, 314, 416, 514, 614) are blazed in opposite directions.

29. An optical system as in Claim 28, characterized in that the first and second grating sections (12, 212, 312, 414, 512, 612 and 14, 214, 314, 416, 514, 614) are aberration corrected and manufactured using holographic techniques.

30. An optical system as in Claim 25, characterized by further comprising additional grating sections.

31. An optical system as in Claim 25, characterized by further comprising a linear array of detectors.

32. An optical system as in Claim 24, characterized in that the first and second grating sections are aberration corrected and manufactured using holographic techniques.
STATEMENT UNDER ARTICLE 19

Claims 16 to 32 have been amended more clearly to define the invention as an optical system, to add reference numerals and to better emphasize the novel features.

The invention provides, in essence, a compound diffraction grating wherein adjacent grating sections have, or can have, quite different optical characteristics, for example opposite blaze directions. A wide range of useful optical systems can be provided by the invention. A single grating can have multiple focal points or planes in different directions, depending on the optical characteristics of individual sections of the grating. A broad-spectrum diffraction grating is possible in which adjacent grating sections reflect adjacent wavebands in the spectrum. Some of these possibilities are described in the specification especially, for example page 12 lines 23-38; page 16 line 19 to page 17 line 20; and page 19 lines 8-14.

Referring to the International Search Report dated August 8, 1995 applicant notes that no document is cited as pertinent to claims 1-7. Passeraud lacks grating sections of different optical characteristics and is not deemed prejudicial to the inventive step of method claims 7 to 15. Nor does Passeraud anticipate the listed product claims because Passeraud does not show grating sections that are disposed on portions of a support surface having the overall shape of a diffraction grating as set forth in amended claims 16 and 25. Passeraud discloses distinct gratings 11 and 12 column 6 line 4. Renke merely describes known background art which appears to be similar to that discussed in the specification at page 17 lines 19 to 36.
# INTERNATIONAL SEARCH REPORT

## A. CLASSIFICATION OF SUBJECT MATTER
- **IPC(6):** G03H 1/04; G01J 3/18
- **US CL:** 430/1; 356/228

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
- **U.S.:** 430/1; 356/305, 326, 328, 334; 359/15, 569, 570, 571, 575

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
- **APS**
  - search terms: diffraction grating, composite

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category*</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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</thead>
<tbody>
<tr>
<td>X</td>
<td>US, A, 4,087,183 (PASSEAREAU) 02 May 1978, see Fig. 3, lines 55-66 in column 5, and lines 1-32 in column 6.</td>
<td>16, 17, 20-22</td>
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<td>7-15, 18, 19, 23-32</td>
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<tr>
<td>Y</td>
<td>US, A, 5,251,007 (RINKE) 05 October 1993, see lines 44-55 and 61-66 in column 1.</td>
<td>23-32</td>
</tr>
<tr>
<td>A</td>
<td>US, A, 3,622,411 (KOSHIISHI) 23 November 1971, see lines 64-72 in column 3.</td>
<td>1-6</td>
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<tr>
<td>A</td>
<td>US, A, 3,523,734 (BREHM ET AL) 11 August 1970, see Fig. 2 and lines 44-61 in column 3.</td>
<td>1-32</td>
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</table>

- **X** Further documents are listed in the continuation of Box C.  
- **☐** See patent family annex.

- ***** Special categories of cited documents:
  - "A" document defining the general state of the art which is not considered to be of particular relevance
  - "E" earlier document published on or after the international filing date
  - "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
  - "O" document referring to an oral disclosure, use, exhibition or other means
  - "P" document published prior to the international filing date but later than the priority date claimed
  - "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
  - "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
  - "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
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Date of the actual completion of the international search: 03 AUGUST 1995
Date of mailing of the international search report: 08 AUG 1995

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<tbody>
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<td>A</td>
<td>US, A, 3,791,737 (JOHANSSON) 12 February 1974, see Fig. 1 and lines 32-40 in column 1.</td>
<td>1-32</td>
</tr>
<tr>
<td>A</td>
<td>US, A, 4,729,658 (POULTNEY) 08 March 1988, see Fig. 2, lines 67-68 in column 2 and lines 1-17 in column 3.</td>
<td>1-32</td>
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