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(54) **SURFACE RELIEF STRUCTURE**

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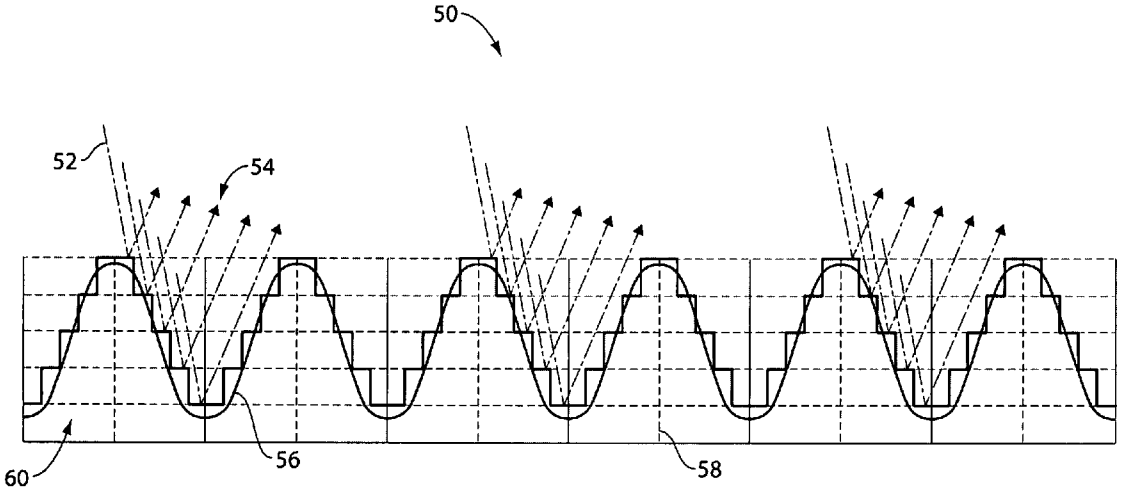
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(57) **ABSTRACT**

A stepped surface relief structure positioned on a substrate is configured to reflect narrow-band light wavelengths and is further configured such that the substrate can be incorporated into at least one of a thread, a fiber or a flake.



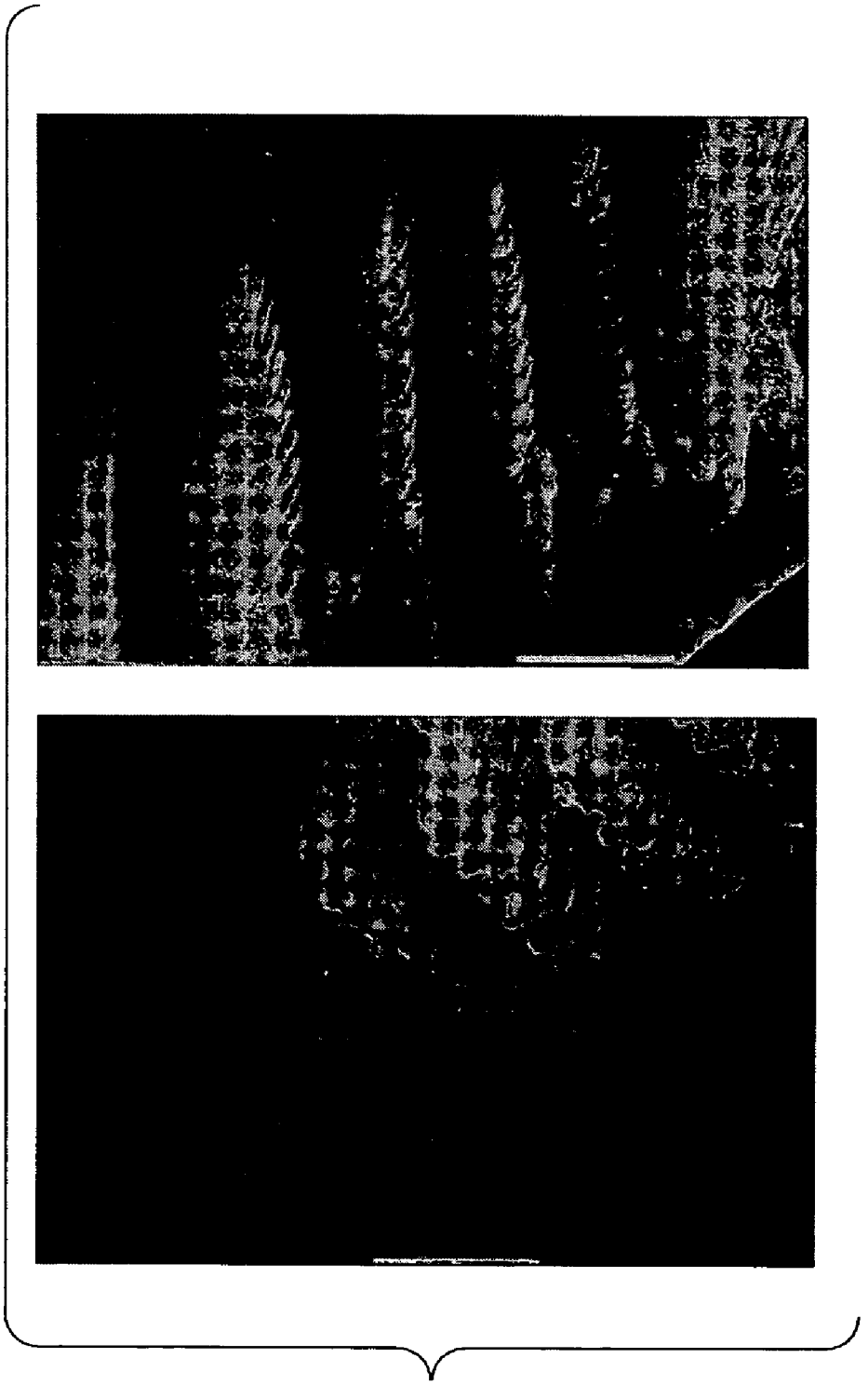


Fig. 1
(prior art)

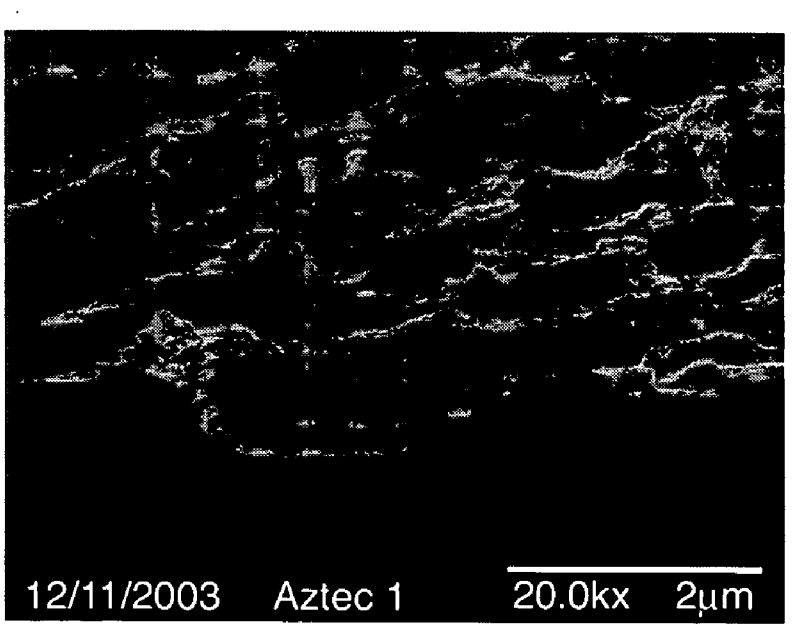


Fig. 2
(prior art)

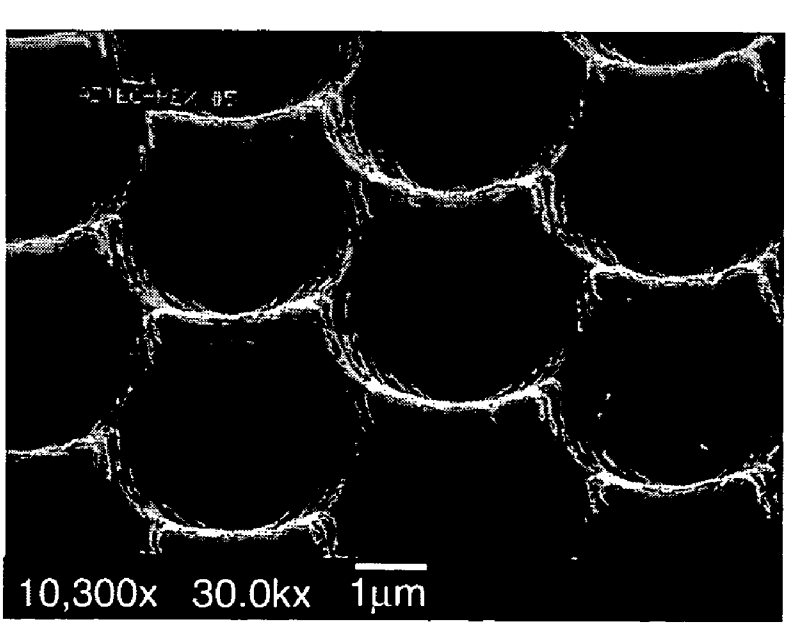


Fig. 3
(prior art)

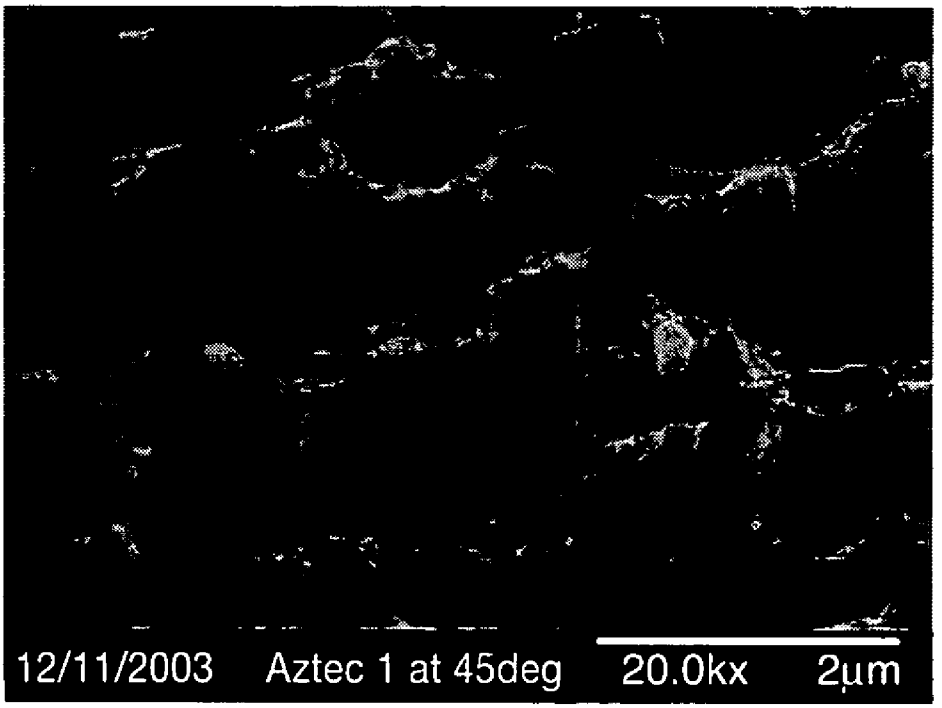


Fig. 4
(prior art)

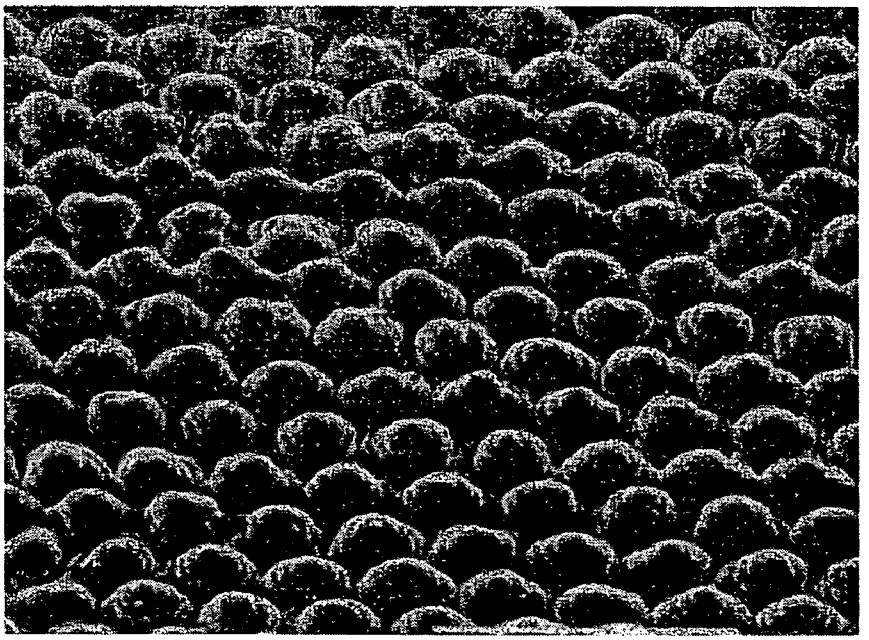


Fig. 5
(prior art)

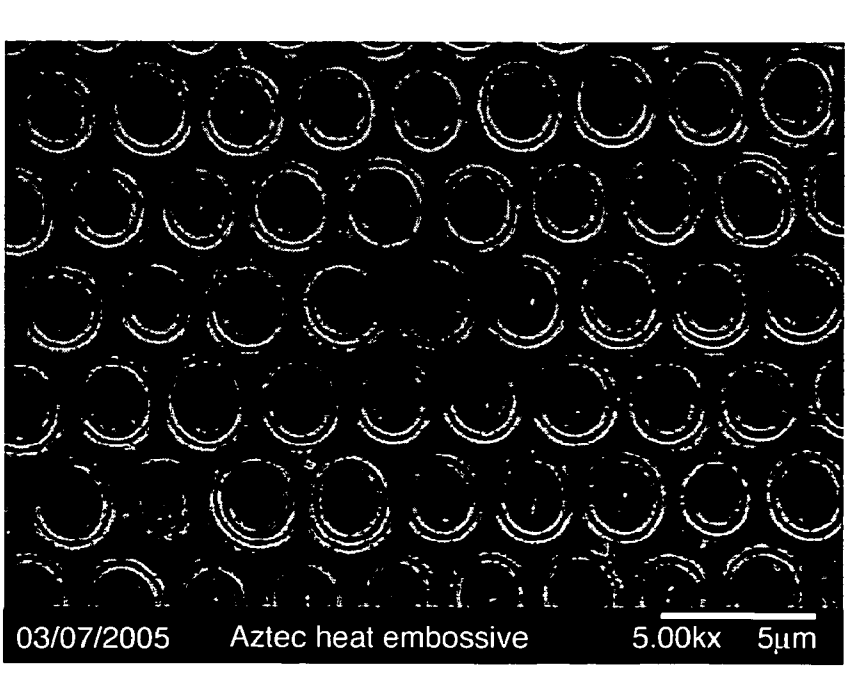


Fig. 6
(prior art)

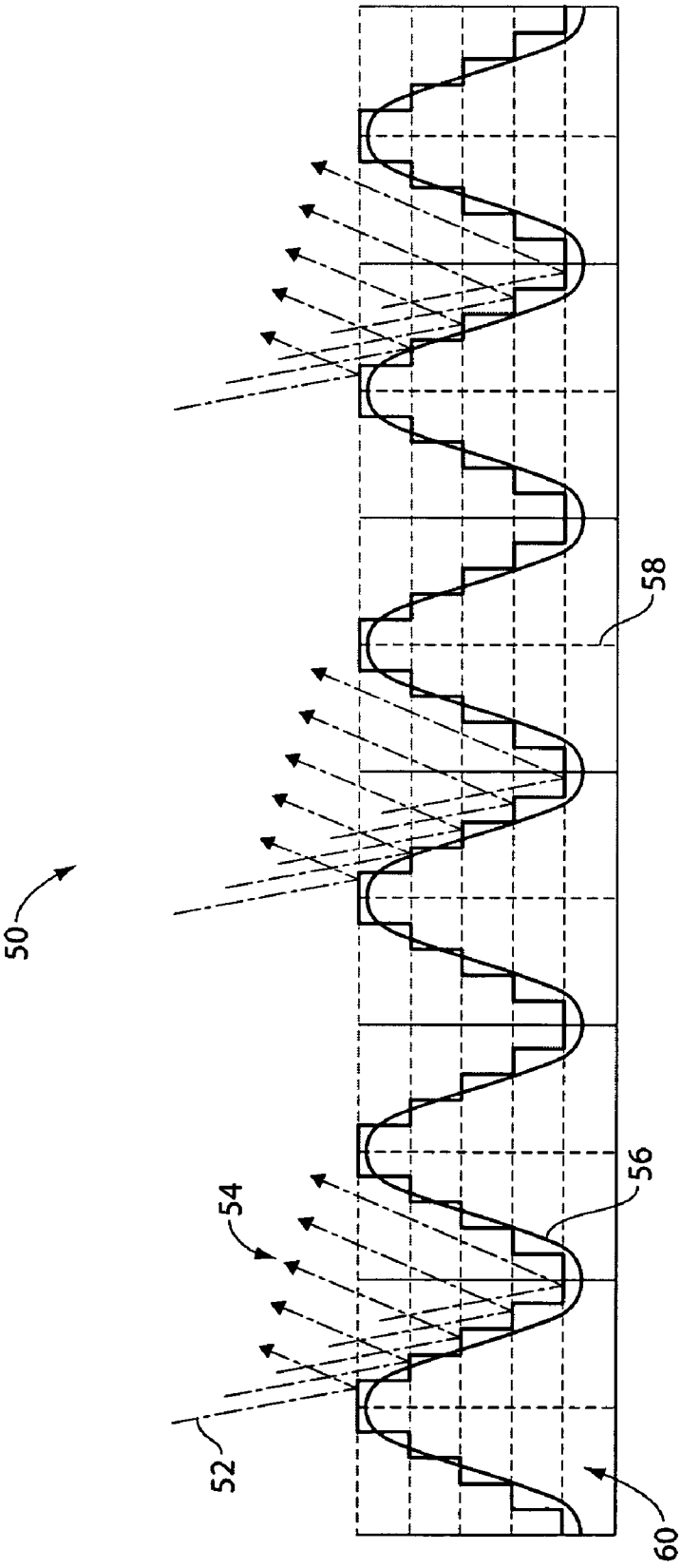


Fig. 7

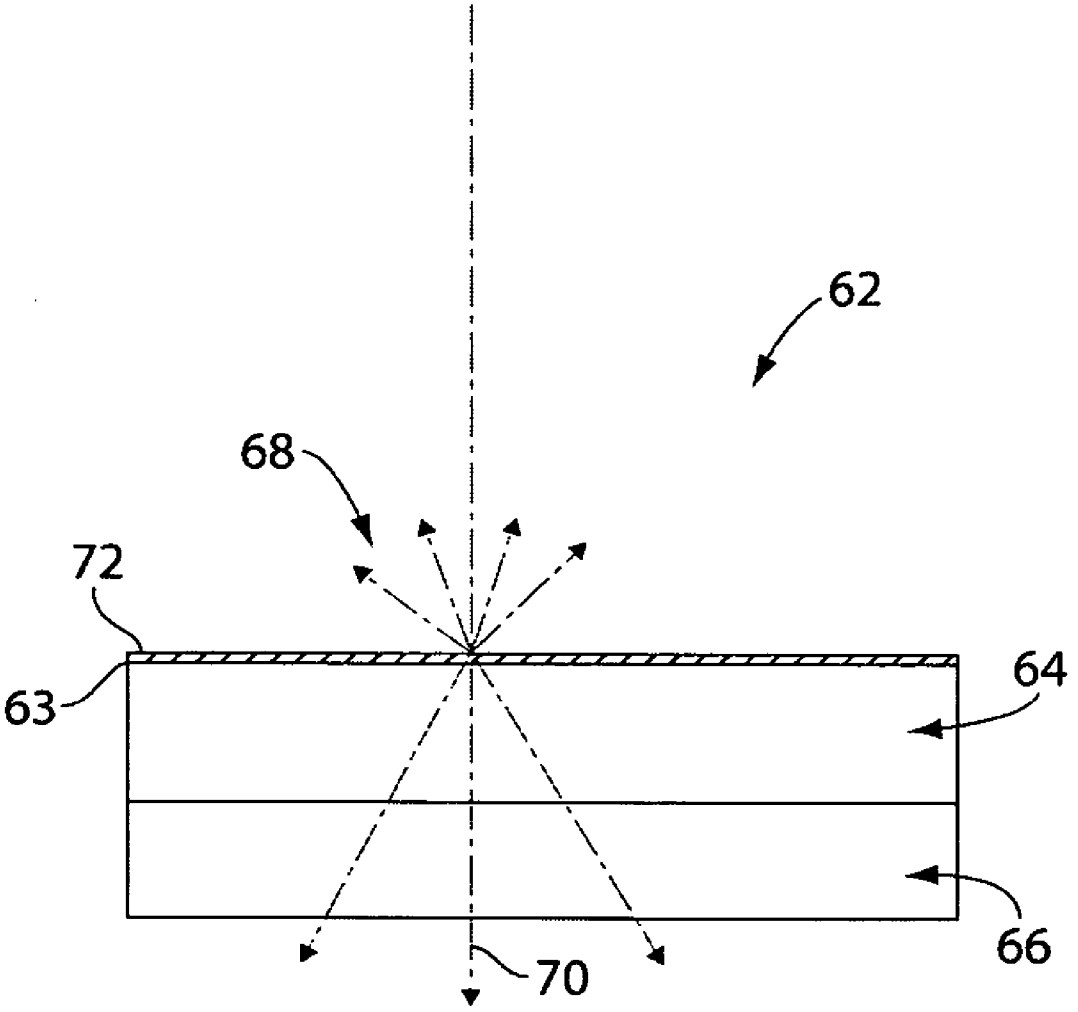


Fig. 8

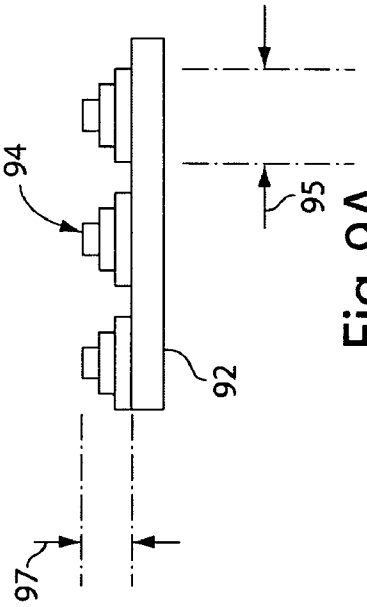


Fig. 9A

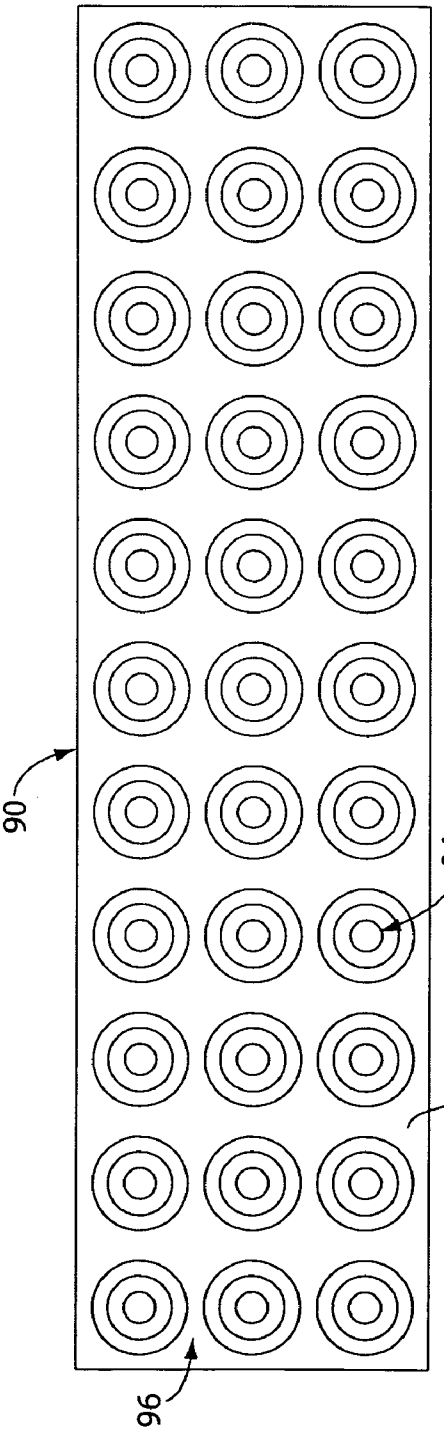


Fig. 9B

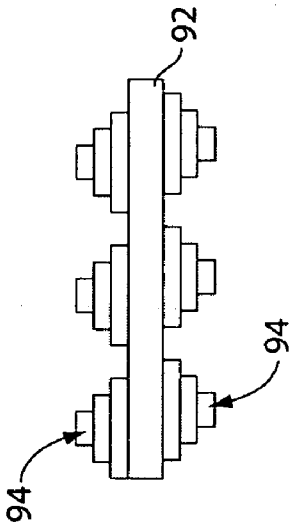


Fig. 10A

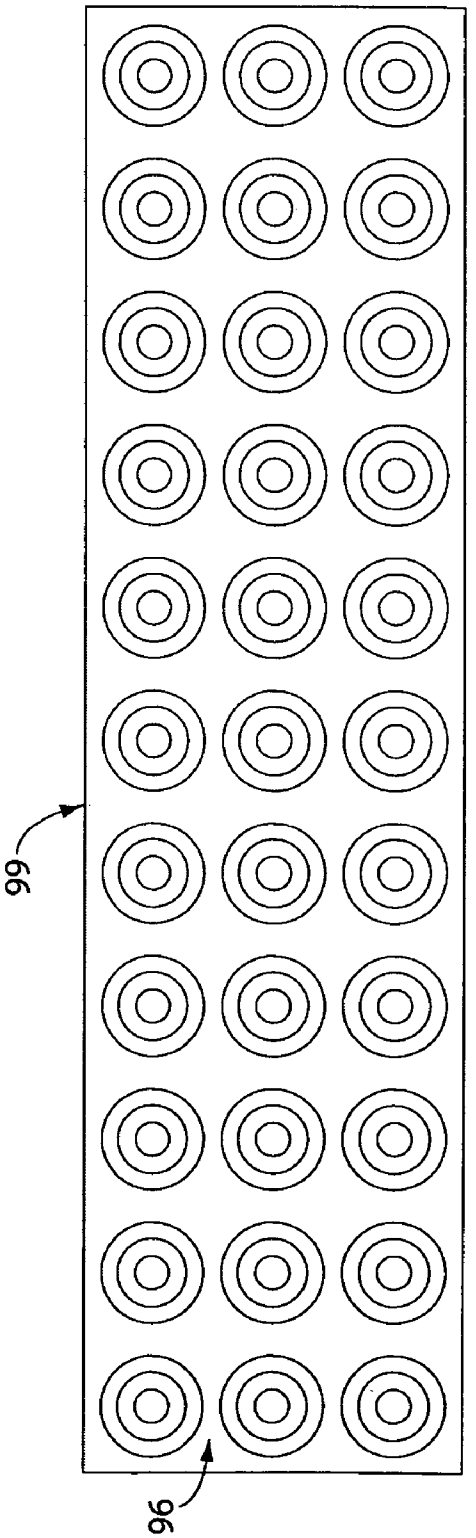


Fig. 10B

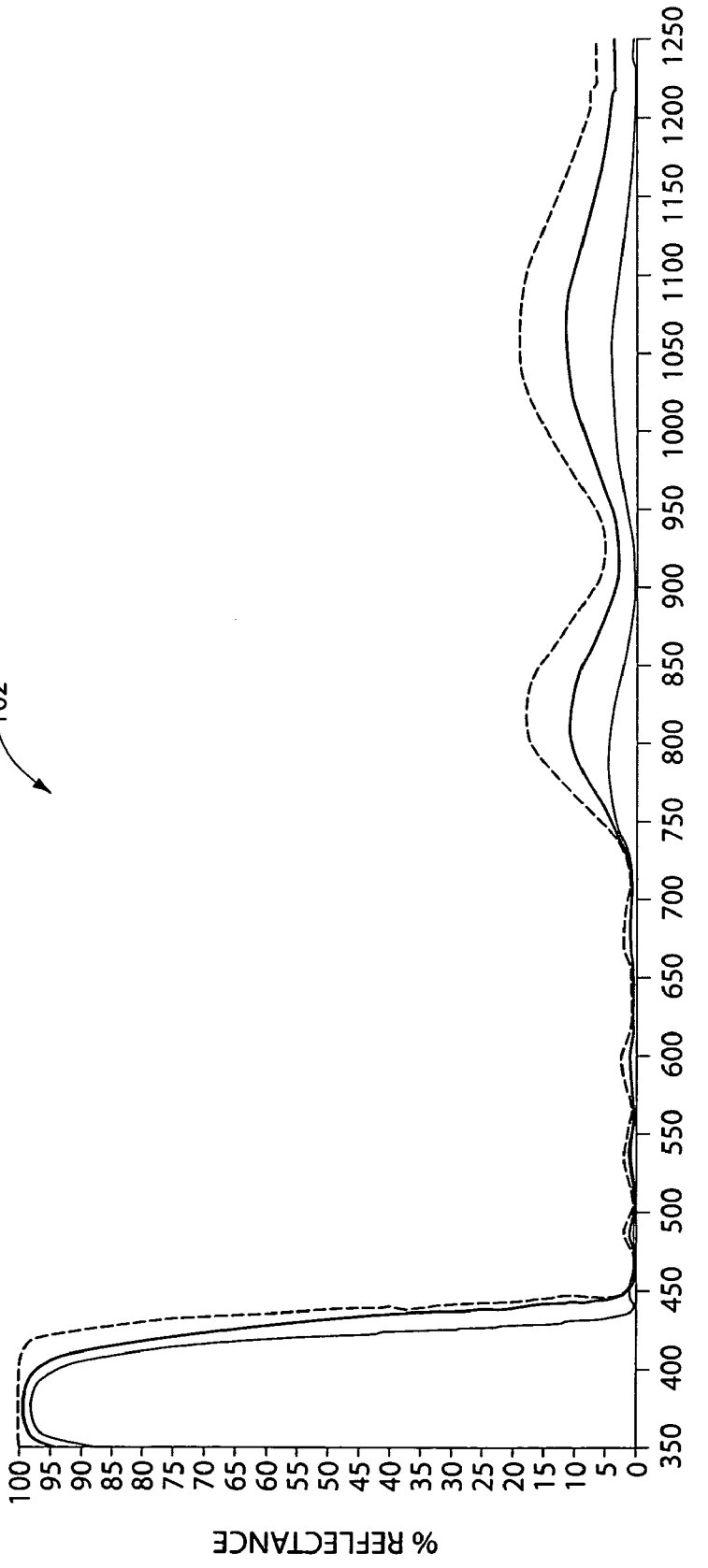

102
% REFLECTANCE
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
WAVELENGTH (nm)

Fig. 11

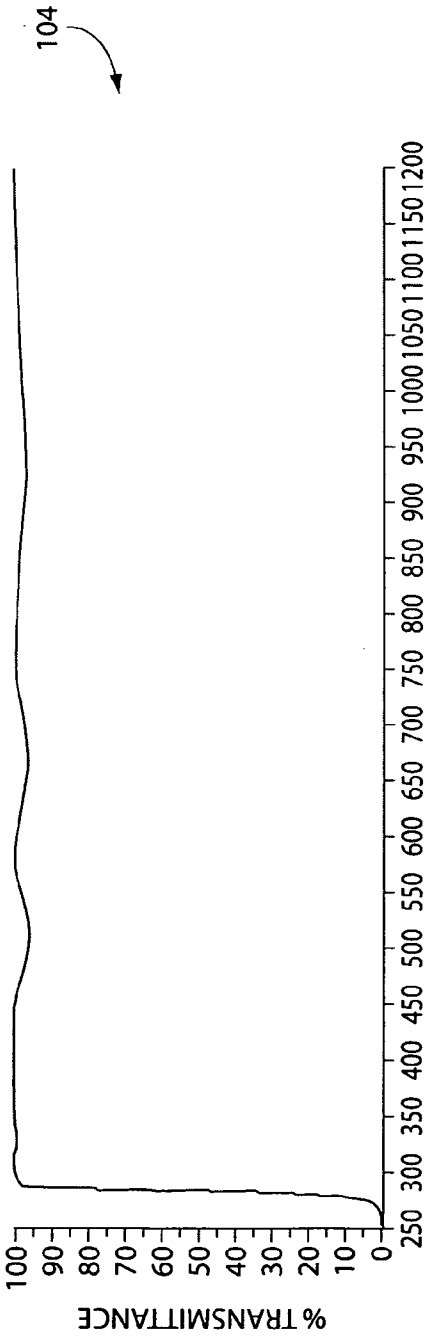


Fig. 12A

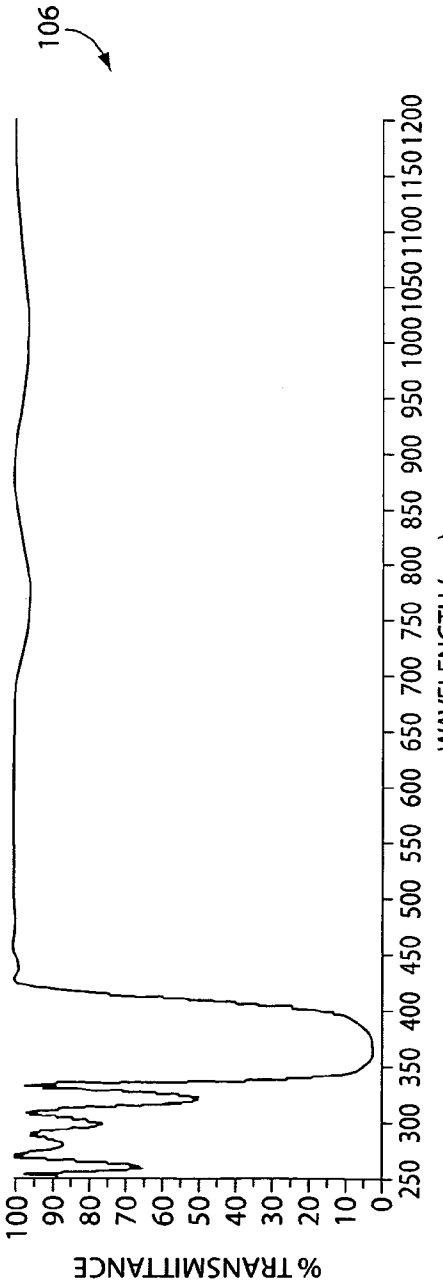


Fig. 12B

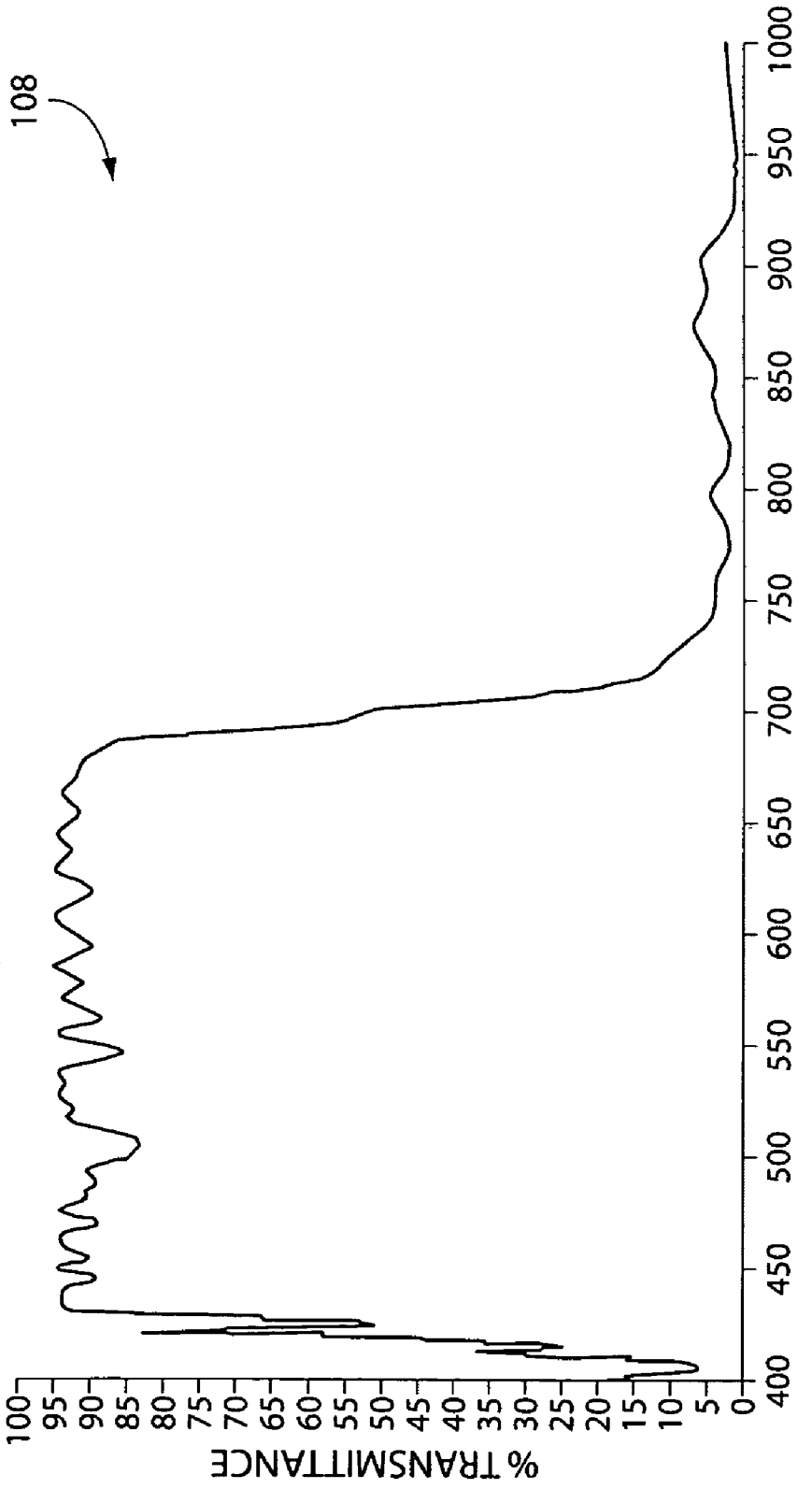

108
% TRANSMITTANCE
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
400
450
500
550
600
650
700
750
800
850
900
950
1000
WAVELENGTH (nm)

Fig. 13

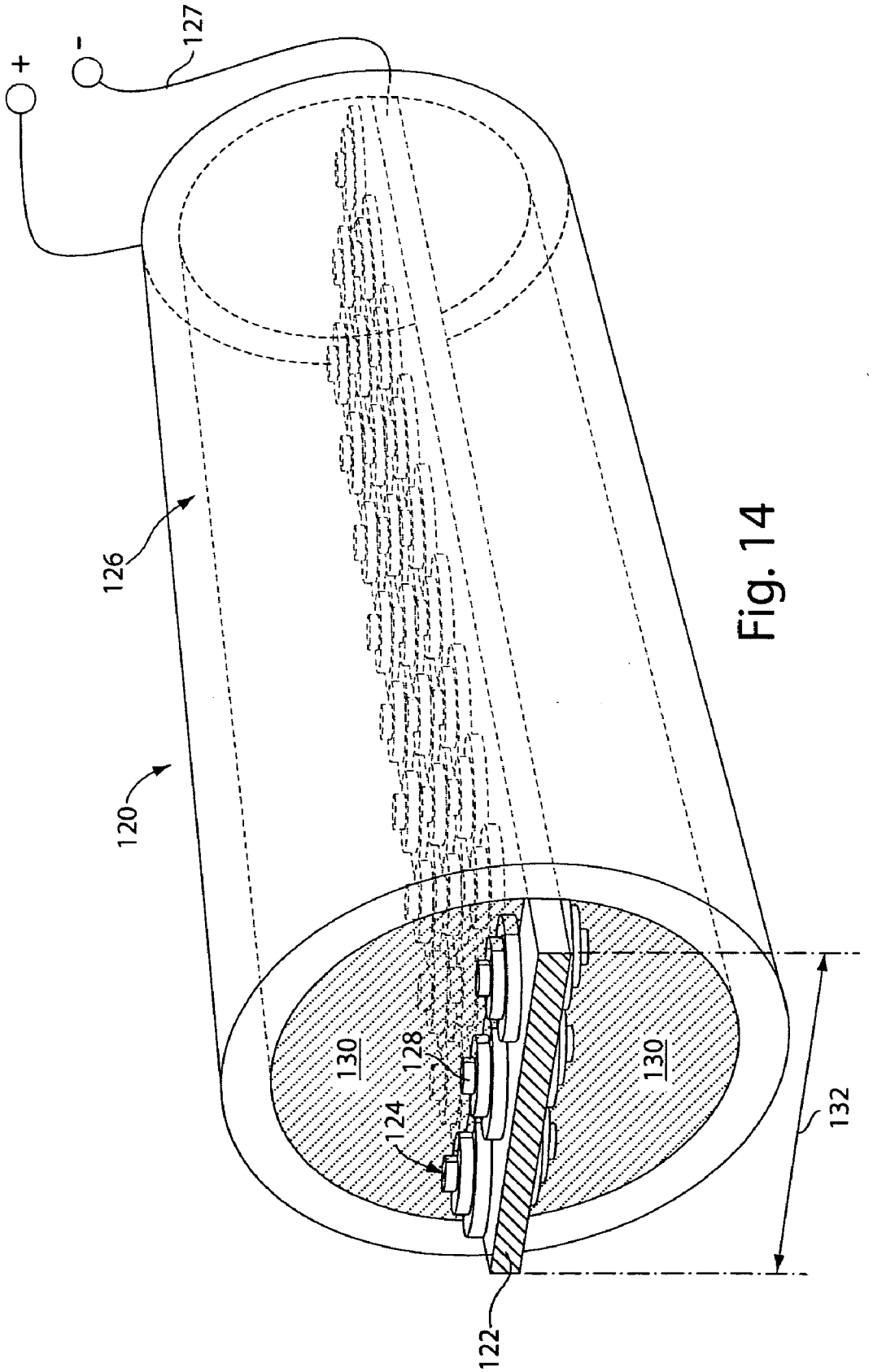


Fig. 14

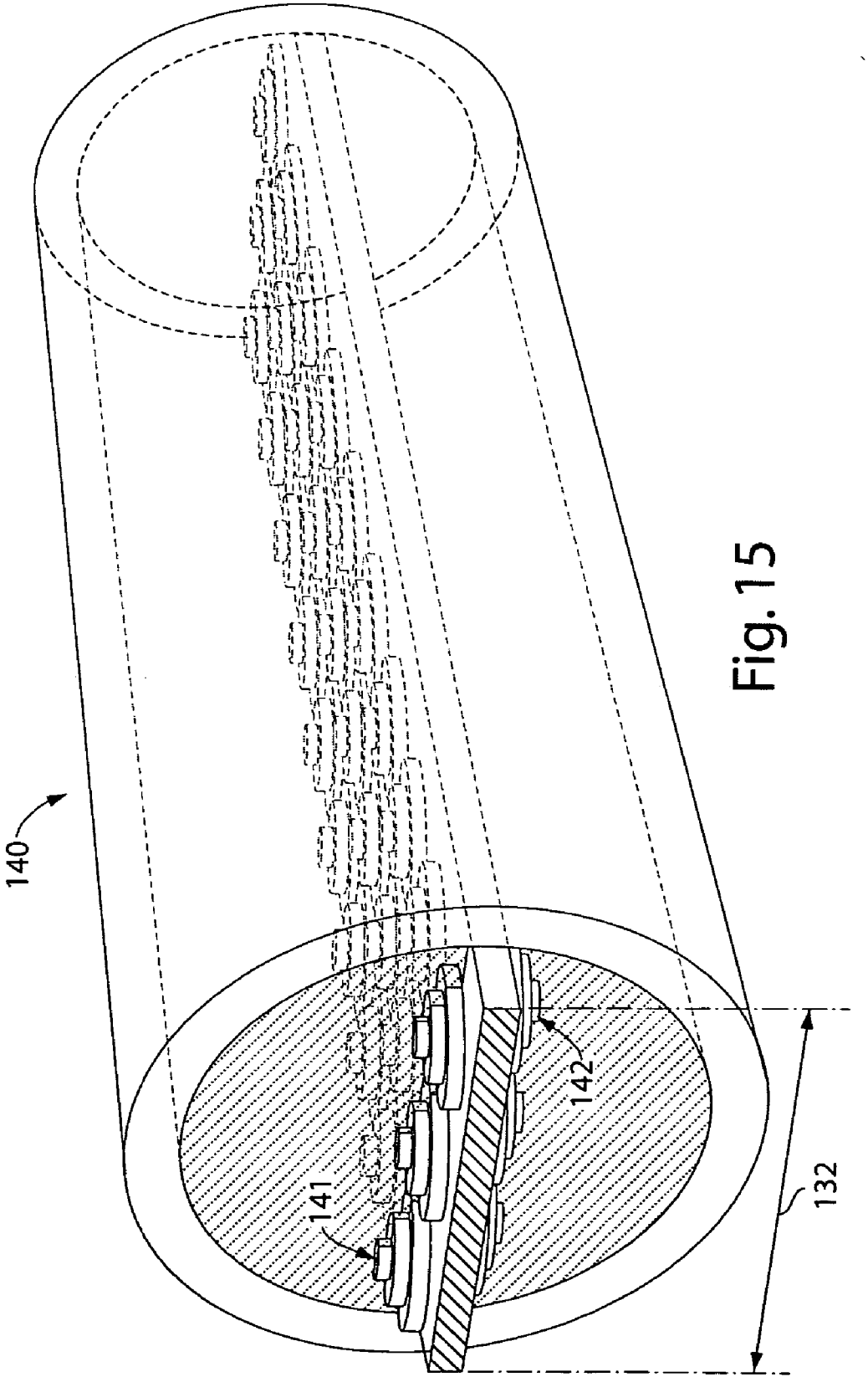


Fig. 15

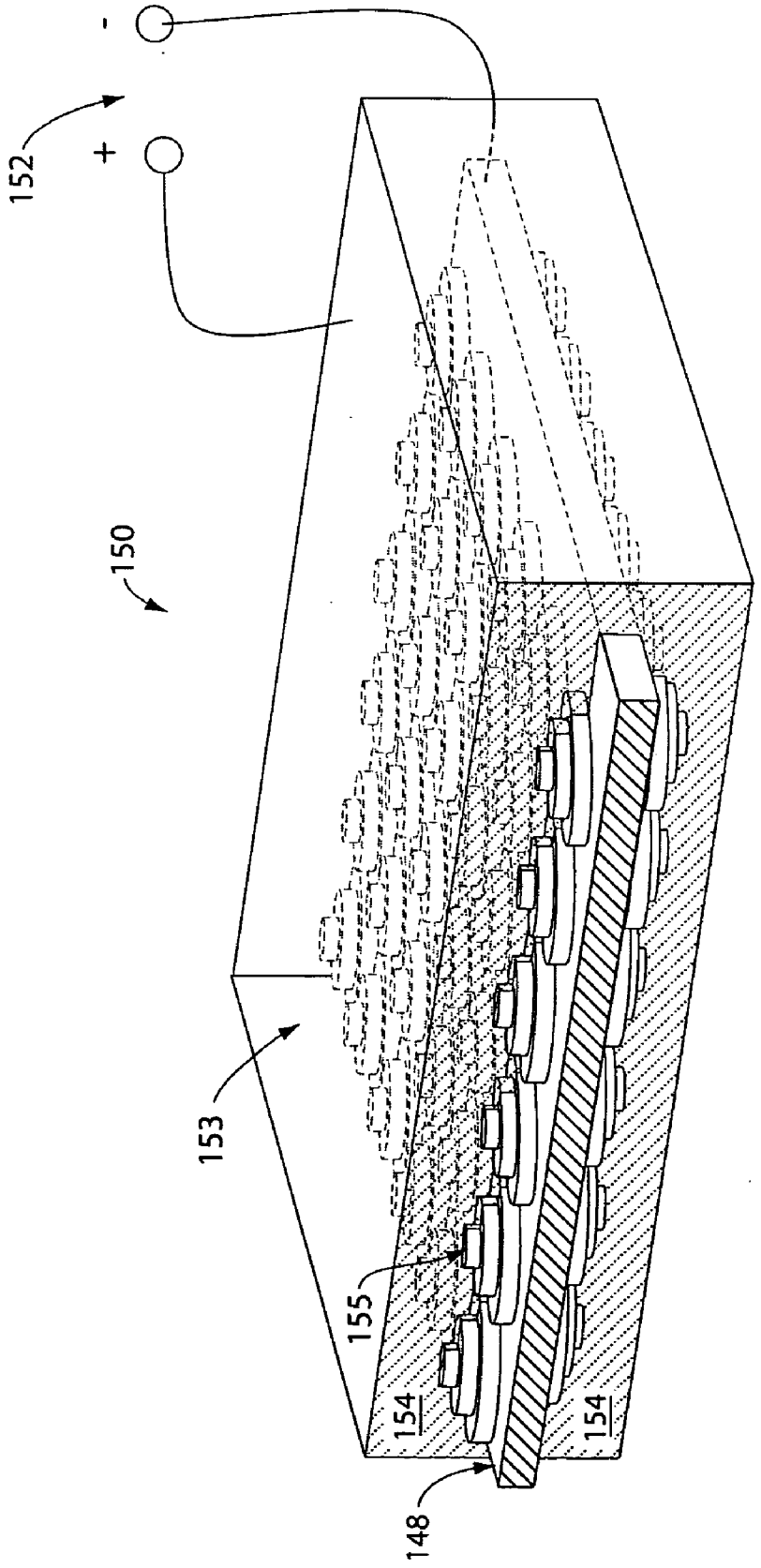


Fig. 16

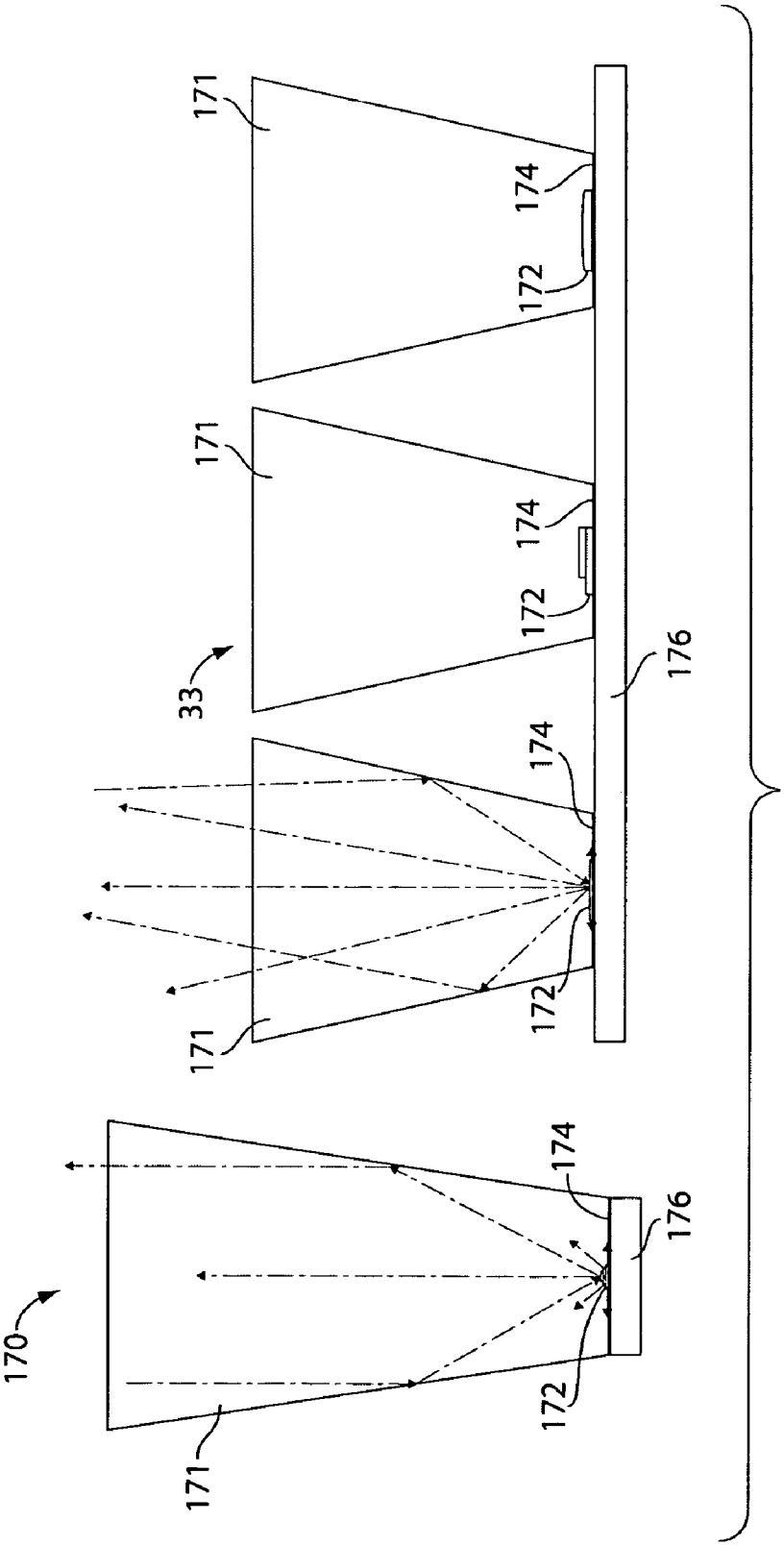


Fig. 17

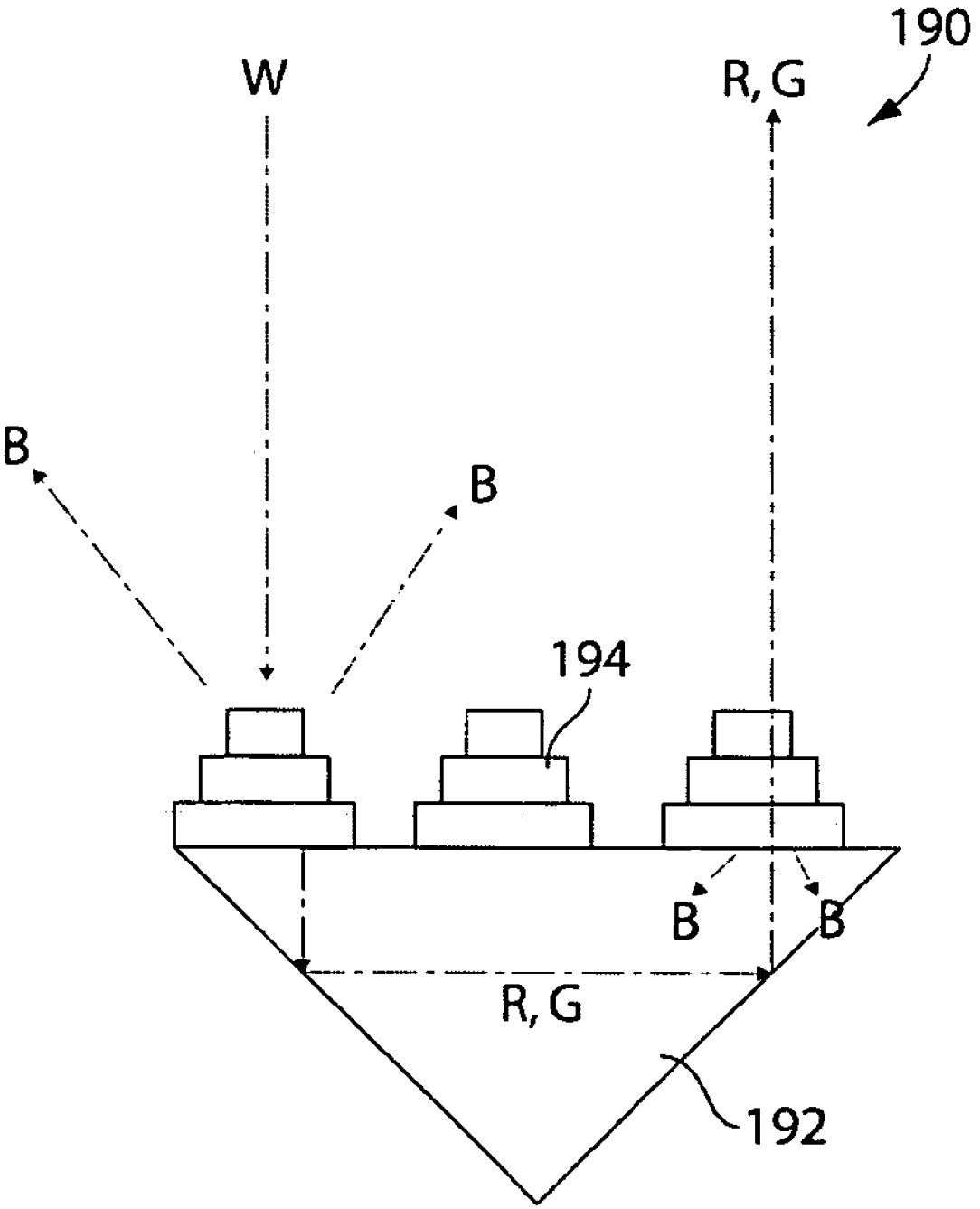


Fig. 18

SURFACE RELIEF STRUCTURE

RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application Ser. No. 60/574,494, filed May 25, 2004 and entitled "Surface Relief Structure," which is herein incorporated by reference.

FIELD OF THE INVENTION

[0002] The present invention relates generally to replicable surface-relief structures that can be applied to threads, fibers, and flakes and which provide special color effects, including both narrow-band and wide-band color.

BACKGROUND OF THE INVENTION

[0003] Stepped surface relief optical structures resonate a narrow band of color and occur in nature, for example, as in the wings of the Morpho Rhetenor butterfly. The stepped resonant structures exhibit unique performance characteristics in the use of the structures for filtering, sensing and display applications.

[0004] Structures and methods of creating the structure which duplicate the narrow band color characteristics found in nature are known. Such stepped surface relief optical structures, which produce a narrow band of color by resonance are known as Aztec structures and can be formed by holographic techniques. The holographic master can be replicated in nickel to form production tooling. The production tooling can be formed into a cylinder that is then mounted onto a continuous film casting or thermoforming machine. The machine is used to cast or thermoform a continuous film having the Aztec structure formed into or onto one side of the film. The film is flexible and has a modulus of elasticity ranging from 1.0×10^8 pascals to 25.0×10^8 pascals. The film is generally supported by a carrier. The master and tooling can be designed to provide an Aztec structure that is a single resonant color or has multiple resonant colors. The finished film can be slit to any desired width and to widths as narrow as 0.008" (200 microns) at companies, such as Metlon Corporation, Cranston, R.I.

SUMMARY OF THE INVENTION

[0005] It is desirable to provide an Aztec structure in the form of one sided and multi sided flakes, chips, threads and fibers which may be used in or with coatings, paints, resins, polymers, fabrics, papers, adhesives, and binders, for example, to create products.

[0006] Embodiments of the invention are directed to a stepped surface relief structure positioned on a substrate, the surface relief structure configured to reflect narrow-band light wavelengths, wherein the substrate is configured to be incorporated into at least one of a thread, a fiber or a flake.

[0007] Implementations of the invention may include one or more of the following features. The stepped surface relief structure can be fabricated in photoresist by means of holographic interferometry. The stepped surface relief structure can be configured to resonate in a visible spectral region. The stepped surface relief structure can be configured to resonate in an infrared spectral region. The stepped surface relief structure can be configured to resonate in an ultraviolet spectral region. The stepped surface relief structure can be configured to be transparent in a first spectral region and reflective in a second spectral region. The stepped surface relief structure can be configured to be replicated in a nickel master plate. The nickel master plate can be configured to be replicated into a particle and electromagnetic radiation curable resin. The nickel master plate can be configured to be replicated into a thermoset plastic. The nickel master plate can be configured to be cylindrical for incorporation into at least one of an embossing, casting or thermoforming production line.

[0008] Implementations of the invention may further include one or more of the following features. A second stepped surface relief structure can be positioned on a second surface of the substrate. Liquid crystal can be incorporated around the stepped surface relief structure, whereby the structure is made conductive, and a cover plate is made conductive, such that the index of refraction of the liquid crystal can be varied electrically, thus varying the resonant color. The structure can include a transparent, conductive tube that incorporates the structure and that is filled with a liquid crystal material, and whose index of refraction can be varied electrically. An outer layer, such as a transparent tube, can be formed from a single material, such as one of thermoplastic, thermset, glass or ceramic. The transparent tube can be hollow or solid and can have a triangular, circular, rectangular, square or elliptical shape. The tube may form a thread that can be woven into a fabric, netting, or a rope. The tube can be sealed in short length to form a fiber or a flake. The fibers or flakes can be dispersed in coatings or polymers. A moth eye surface can be formed into an outer layer of the tubing.

[0009] Still further implementations of the invention may include one or more of the following features. The structure can be contained in an optical horn that concentrates light from a large opening to a small area in which the structure is positioned. The optical horn can include a liquid crystal material and the index of refraction of the liquid crystal material can be varied electrically. A corner cube reflector can contain or be positioned adjacent to a stepped surface relief structure. The corner cube reflector can allow particular colors to be reflected or retro-reflected, and be viewed at given distances. The corner cube can be coated with a reflective coating. The stepped surface relief structure can be made from flexible or elastic materials which are within a modulus of elasticity ranging from 1.0×10^8 pascals to 25.0×10^8 pascals. The invention can be used in currency, documents, fabrics, coatings, polymers, for example.

[0010] The invention may provide one or more of the following advantages. The film, thread or flake may be configured to have Aztec structures on one section of the film, thread or flake and have another micro optical structure such as a corner cube on another section of the other side of the film, thread or flake. Micro optical structures that refracts or reflects light can be used. Aztec resonant structures can be combined with Aztec filters to create remotely activated tunable materials. Selected wavelengths can provide an input to an actuator such as a solar cell that provides the power to cause the LC material to change the index of refraction and create a reflected color shift.

[0011] Aztec structures can be combined with corner cube structures to create a film, thread, fiber, flake and the like that will retro-reflect a predetermined color from a long distance

but will reflect plus retro-reflect a different color form a short distance. The structures may also be tunable to create any desired color shifts using an electrical potential difference. The film, thread or flake can be configured to have Aztec structures on one side of the film, thread or flake and have another micro optical structure such as a corner cube on the other side of the film, thread or flake. Micro optical structures include corner cubes, gratings, moth eye, lens arrays, lenticular prisms or lenses, for example. Micro optical structures that refract or reflect light can be used.

BRIEF DESCRIPTION OF THE FIGURES

[0012] For a better understanding of the present invention, reference is made to the figures which are incorporated herein by reference and in which:

[0013] **FIG. 1** illustrates a micrograph of the wing of the Morpho Rhetenor butterfly.

[0014] **FIG. 2** illustrates an Aztec stepped structure of a reflecting object made holographically.

[0015] **FIG. 3** illustrates an Aztec microzone plate array made holographically.

[0016] **FIG. 4** illustrates an Aztec stepped structure made from a randomly reflecting object.

[0017] **FIG. 5** illustrates a nickel master for an Aztec zone-plate array grating.

[0018] **FIG. 6** illustrates an embossed section of an Aztec zone-plate array grating.

[0019] **FIG. 7** is a side view of an Aztec grating recorded in photoresist.

[0020] **FIG. 8** is an Aztec filter structure applied to a substrate.

[0021] **FIG. 9A** is a side view of an Aztec thread, with an Aztec structure applied to one side of the film.

[0022] **FIG. 9B** is a top view of an Aztec thread, with an Aztec structure applied to one side of the film.

[0023] **FIG. 10A** is a side view of an Aztec thread, with the Aztec structure applied to both sides of the film.

[0024] **FIG. 10B** is a top view of an Aztec thread, with the Aztec structure applied to both sides of the film.

[0025] **FIG. 11** is a graphical representation of a spectral response of a uv/visible beamsplitter.

[0026] **FIGS. 12A and 12B** are a graphical representation of a spectral response for coatings that reflect in the uv and transmit in the visible and infrared.

[0027] **FIG. 13** is a graphical representation of a spectral response of a coating which transmits in the visible and reflects in the infrared.

[0028] **FIG. 14** is an Aztec structure in an enclosed thread.

[0029] **FIG. 15** is an alternative Aztec structure in an enclosed thread.

[0030] **FIG. 16** is a flat surface with an Aztec structure surrounded by liquid crystal.

[0031] **FIG. 17** is an optical horn having an Aztec structure at a bottom portion to reflect a specific color of light.

[0032] **FIG. 18** is a corner cube reflector with an Aztec filter structure on a top portion.

DETAILED DESCRIPTION OF THE INVENTION

[0033] Embodiments of the invention provide a stepped surface relief structure. In embodiments of the invention, the stepped surface relief structures resonate in a narrow band of color and are known as Aztec structures. In embodiments of the invention, replication of the stepped structures by casting or thermoform can be done on one or both sides of a film. In still further embodiments of the invention, slitting can be done to form threads. Embodiments of the invention can be used on or with coatings, paints, resins, polymers, fabrics, papers, adhesives and binders. Embodiments of the invention can be used for other applications that will be apparent according to the following figures and description.

[0034] Aztec structures are made using holographic processes and replicated into nickel masters that are made into production tooling. Such structures can be formed into thread for various uses, for example, the thread can be woven into products or enclosed in a transparent tubing to make a smooth outer surface thread. The transparent tubing can be extruded around the slit Aztec structure thread using a cross head extrusion die. A thread can be adjusted to resonate or reflect different narrow bands of color by having the electric potential shift the index of refraction of a liquid crystal material. The standard and tunable threads can be woven into fabrics to provide unique narrow band iridescent colored fabrics. In one form, the fabrics are tunable to create a change in color. Applications include, but are not limited to, camouflage fabrics and intelligent garments that change color as the environment changes or as the mode of a person or object changes.

[0035] Referring to **FIG. 1** through **FIG. 6**, prior art Aztec recordings are shown. In **FIGS. 1A and 1B**, a natural example of a micrograph of a wing **10** of the Morph Rhetenor butterfly is shown having a ribbed, stepped structure. The wing **10** is shown to scale such that a white bar measures 1 micrometer. Aztec recordings can resemble a naturally occurring stepped structure. **FIGS. 2-6** illustrate Aztec master recordings **20**, **22**, **24**, **26**, **28** made in photoresist, and nickel replicas and embossings made from a master. The structures of **FIGS. 2-6** can be formed according to a number of methods.

[0036] Referring to **FIG. 7**, a side view of an Aztec grating **50** formed in photoresist includes reference beams **52**, reconstructed beams **54**, and a stepped etched structure **56**. The grating **50** is formed by a double exposure to two separate interference patterns. For example, the grating **50** may be formed by exposure to an off-axis exposure where the interference planes are represented by vertical lines **58**, and to a volume exposure, where the interference planes are represented by horizontal lines **60**.

[0037] Referring to **FIG. 8**, an Aztec filter structure **62** includes Aztec structures **63**, a substrate **64**, an adhesive **66**, and an optional top coat **72**. The substrate **64** is transparent to visible light and is positioned on top of an adhesive **66** that is also transparent to visible light. Aztec structures **63** are applied to the top surface of the substrate **64**. The filter **62** is made such that short wavelength light **68** is removed from the incident beam, either by a specific filtration action, or by

scattering out of the main beam. With this configuration, mid- and long wavelength light **70**, such as visible and infrared light, is transmitted. Short wavelength reflecting visible-transmitting reflective coatings **72** can be applied to the Aztec structure **62**. The Aztec structure resonates and reflects a wavelength band while allowing other wavelengths to pass through the body of the structure.

[**0038**] In addition to filters, the Aztec structures can be used in other structures, such as threads. In **FIG. 9**, an Aztec thread **90** includes a polyester base **92** and Aztec structures **94**. The Aztec structures **94** include coated top surfaces. The Aztec structures **94** are positioned in an array **96** on the polyester base **92** to form a thread **90**. An Aztec micro zone plate array **96** is applied by thermosetting or ultraviolet curing to the top surface of the polyester sheet **92**. The Aztec structures **94** are positioned over substantially the whole top side of the polyester base **92**. The thread **90** can be, for example, 1000, 1250, 2500, or 5000 feet long and spooled for use on other products. The polyester base **92** can have a thickness, or height, between about 10 and 50 micrometers. The base width **95** of an Aztec structure **94** can be, for example, about 0.000040 inches to about 0.000080 inches (about 0.04 to 0.08 mils), and the height **97** of a structure **94** can be between about 0.04 to 0.08 mils (about 1 to 2 micrometers). Referring to **FIG. 10**, the Aztec micro zone plate array **96** is applied to both sides of the substrate **92**. The Aztec structures **94** can be applied to both a top and bottom side of the polyester base **92**, for example, by thermosetting or ultraviolet curing. Aztec structures **94** are preferably arranged in an array **96** that extends over the length of the top side and the bottom side of the substrate **92**. A thread **99** is formed having a double-sided base **92**. The thread **90** and the thread **99** reflect light due to the position of the Aztec structures **94**. Visibility of the reflected colors is enhanced, for example, by over-coating the structure **94** with vacuum evaporated aluminum or silver, or with dielectric coatings or with combinations of dielectric and metal coatings, preferably having colors that appear in the visible spectrum.

[**0039**] The Aztec thread **90**, **99** can include high reflectivity in a part of the spectrum that is not in the visible, but rather in some other part of the spectrum. Aztec structures are configured with step heights appropriate for creating resonance or constructive interference of light that is to be reflected. The light reflected can be from any portion of the electromagnetic spectrum. An Aztec step structure can be configured to create constructive interference at any wavelength from about 1.0 nm up to or greater than several thousand nanometers. Referring to **FIG. 11**, a reflectance spectrum **102** of a surface that has high reflectivity in the short wavelength portion of the spectrum (e.g., ultraviolet), but low reflectivity in the mid- and long wavelength portion of the spectrum (e.g., visible and infrared), is shown. For example, at short wavelengths, the reflectance is greater than 95%, and approaches 100% reflectance. Between approximately 450 nm and 750 nm, transmission in the visible is at or near 0% reflectance. **FIGS. 12A and 12B** show transmission spectra **104**, **106** for a coating surface similar to the surface shown in **FIG. 11**, with the transmission low in the short wavelength portion of the spectrum and high in the mid- and long wavelength portion of the spectrum.

[**0040**] Referring again to **FIG. 10** and to **FIG. 13**, the Aztec thread **90** can be altered such that the step heights of the Aztec structures **94** are adjusted to resonate in the short wavelength portion of the spectrum, but to be transparent in the mid- and long wavelength part of the spectrum. This is accomplished by an appropriate combination of the proper step height and dielectric layer coating having high reflectivity in the short wavelength portion and high transmission in the mid- and long wavelength portion. For example, a discussion of the dimensions of an Aztec surface and methods by which the dimensions are calculated can be found in the article entitled, "Aztec Surface Relief Volume Diffractive Structure," by James Cowan (J. Opt. Soc. Am. A Vol. 7, No. **8**, August 1990). A transmission spectrum **108** for a coating that resonates in the ultraviolet and is transparent in the visible and infrared is shown in **FIG. 13**.

[**0041**] When an Aztec structure is exposed to rain, water or some other medium that has an index of refraction different than that in which the Aztec structure is configured to operate, the wavelength that is resonated is shifted to a different wavelength. The different index of refraction causes the effective optical path between the steps to change. The effective optical path is the index of refraction times the distance that the light is traveling in a medium, where the distance is the distance from one step to the next lower or higher step on the Aztec structure. As the index of refraction of the medium that fills the Aztec structure changes, the resonate wavelength changes. Thus, Aztec structures and threads can be enclosed in transparent tubing to prevent changes in performance.

[**0042**] Referring to **FIG. 14**, a thread **120** with an Aztec structure that is enclosed in transparent tubing with a smooth outer surface thread includes a substrate **122**, an Aztec structure **124**, a transparent tube **126** and a voltage input/output **127**. The structure **124** thread can have a conductive coating **128** such as aluminum applied to its surface. The inner wall of the tubing **126** can have a clear conductive coating such as Indium Tin Oxide (ITO) applied to it and the tubing can be filled with liquid crystal (LC) **130**. Adjustment of the voltage via the voltage input/output **127** causes the index of refraction of the LC **130** to change, and the color changes with the change in the index of refraction of the LC **130**. The thread **120** has a width **132** of about between 8 and 12 mils (200 to 300 micrometers). Other widths are possible and envisioned. The thread **120** can be, for example, woven into fabrics to provide unique narrow band iridescent colored fabrics. Multiple Aztec structures **124** can be used to create combinations of colors.

[**0043**] In **FIG. 15**, a thread **140** includes a first Aztec structure **141** and a second Aztec structure **142** on an enclosed thread structure that could, for example, have one Aztec color on one surface, and a different Aztec color on the opposite surface. Threads **140** can be woven into currency or documents to prevent counterfeiting. The thread **140** can be made into polymer fibers which are dispersed into the pulp fibers used during paper manufacturing run to create a counterfeit proof paper. The fibers may be coated such that they are invisible in visible light but are clearly visible in UV or IR lighting, for example.

[**0044**] Referring to **FIG. 16**, an array of Aztec structures **148** can be incorporated into a flat thread **150**. As above, tenability is achieved by varying a voltage between two conductors **152**, one an aluminum or silver coating **155** on the Aztec structure **148**, and the other, a transparent electrode **153**, such as ITO, where the intervening space is filled

with liquid crystal **154**. The flat structure, without electrodes, constitutes a flake. The shape of the flake can be, for example, square, triangular, hexagonal, circular, in sizes ranging from 50 to 6250 microns (0.002" to 0.250"), and with a variety of colors that depended on the step heights of the structures.

[**0045**] Referring to **FIG. 17**, a non-imaging optical horn **170** includes a horn body **171**, an Aztec structure **172** and a LC plane **174**. The optical horn **170** collects and back-reflects light. An Aztec structure **172** is positioned at the base of the horn **170** to reflect specific colors. Adjacent horns **171** may include different structures **172** and thus different reflected colors. The flat area under the horn array may consist of a liquid crystal plane **174** attached to a substrate **176**. The reflected colors can be made tunable by varying an external voltage.

[**0046**] Referring to **FIG. 18**, a filter structure **190** includes a corner cube reflector **192** and an Aztec structure **194** applied to the corner cube reflector **192**. The filter structure **190** at normal incidence, for example, can be fabricated so that a color is transmitted, and that color is retro-reflected. For example, the Aztec structure **194** can transmit red and green light, while back-reflecting blue light. At other angles of incidence there is a color shift such that a different color will be retro-reflected. Conversely, the filter **190** can be made such that a color will be scattered out of the field of view and all other colors are transmitted. The retro-reflected colors are missing the single narrow band color that is removed. The filter structure can be used, for example, in security applications, such as counterfeit-proof securities, stock certificates and documents or papers.

[**0047**] In embodiments of the invention, Aztec threads as discussed with respect to **FIGS. 7-18** may include single Aztec structures or multiple Aztec structures to create different appearances of color. One side of the thread may be configured with a specific Aztec structure or combination of Aztec structures and the opposite side of the thread may be configured with a second Aztec structure or combination of Aztec structures. A single Aztec thread may have multiple variations of Aztec structures to create a color code that may be random, regular, binary and other variations. The code on the thread can be read by a hyper spectral scanner or other decoding device. The security thread created may be woven into currency or documents to prevent counterfeiting. Copiers will not be able to duplicate the color or structure in a copied document of any type. The thread may be made into polymer fibers which are dispersed into the pulp fibers used during a paper manufacturing run to create a counterfeit proof paper. The fibers may also be placed in a pattern on the pre-paper web to create a water mark. The fibers may be coated such that they are invisible in visible light but are clearly visible in ultraviolet (UV) or infrared (IR) lighting.

[**0048**] A one-sided or two-sided Aztec structure film can also be made into flakes, chips or fibers that are of any shape such as square, triangular, hexagonal, rectangular, circular, and the like. The shape can be chosen to maximize the yield from the film. Companies such as Glitterex in Cranford, N.J. have the capability to make these shapes out of film into sizes ranging from 0.002" (50 microns) to 0.250" (6250 microns). These flakes may be used individually to mark objects or may be mixed into paints, coatings, resins, polymers, binders, adhesive, paste and the like to create a medium that can be sprayed, painted, screen printed, gravure coated, off set printed, painted, and the like onto any surface. The surface may be a fabric, a metal, a glass, a ceramic, a stone, a cement, or a polymer, for example.

[**0049**] Combinations of colors can be created by mixing flakes having different Aztec structure features or making the flakes to have more than one design of Aztec structure on a single flake. The coating can be designed to be tunable by providing a conductive coating on the surface of the Aztec structures and an enclosure to enclose an LC material above the flake with the enclosing structure including a transparent conductive coating and a connection to connect an electrical potential difference. One side of the flake may be configured with a specific Aztec structure or combination of Aztec structures and the opposite side of the flake may be configured with a second Aztec structure or combination of Aztec structures.

[**0050**] Aztec structure threads, fibers, flakes and chips can be made with reflective coatings which are transparent in one part of the electromagnetic spectrum and reflect in another part of the electromagnetic spectrum. For example, Aztec structures may be visible in the short wavelength or long wavelength part of the spectrum and transparent in the mid-range part of the spectrum. A suitable light source and detector will allow observing the color reflected, otherwise the material is transparent. The materials may also be tunable such that the material is transparent to defined wavelengths until an electrical potential difference is applied and then the material reflects a chosen color. Examples of coatings include coatings developed by Precision Optical Systems of Norwood, Mass.

[**0051**] In embodiments of the invention, the Aztec structure that is embossed into the film/substrate or cast onto the film/substrate can have a modulus of elasticity that is the same as the substrate film or higher or lower than the substrate film. For example, for an elastic material, the substrate film has a low modulus of elasticity (below 7×10^8 pascals) and the Aztec structure has a high modulus of elasticity (above 15×10^8 pascals), such that the Aztec structure is rigid and retains its shape as the relatively elastic substrate is stretched. An Aztec structure with a low modulus of elasticity positioned on a substrate with a high modulus of elasticity creates a reboundable (elastic) Aztec structure on a rigid substrate film.

[**0052**] Having thus described at least one illustrative embodiment of the invention, various alterations, modifications and improvements will readily occur to those skilled in the art. Such alterations, modifications and improvements are intended to be within the scope and spirit of the invention. Accordingly, the foregoing description is by way of example only and is not intended as limiting.

1. A stepped surface relief structure positioned on a substrate, the surface relief structure configured to reflect narrow-band light wavelengths, wherein the substrate is configured to be incorporated into at least one of a thread, a fiber or a flake.

2. The structure of claim 1 wherein the stepped surface relief structure is fabricated in photoresist by means of holographic interferometry.

3. The structure of claim 1 wherein the stepped surface relief structure is configured to resonate in a visible spectral region.

4. The structure of claim 1 wherein the stepped surface relief structure is configured to resonate in an infrared spectral region.

5. The structure of claim 1 wherein the stepped surface relief structure is configured to resonate in an ultraviolet spectral region.

6. The structure of claim 1 wherein the stepped surface relief structure is configured to be transparent in a first spectral region and reflective in a second spectral region.

7. The structure of claim 1 wherein the stepped surface relief structure is configured to be replicated in a nickel master plate.

8. The structure of claim 7 wherein the nickel master plate is configured to be replicated into a particle and electromagnetic radiation curable resin.

9. The structure of claim 7 wherein the nickel master plate is configured to be replicated into a thermoset plastic.

10. The structure of claim 7 wherein the nickel master plate is configured to be cylindrical for incorporation into at least one of an embossing, casting or thermoforming production line.

11. The structure of claim 1 wherein the stepped surface relief structure is positioned on a first surface and a second surface of the substrate.

12. The structure of claim 1 further comprising an enclosure configured to encapsulate the substrate.

13. The structure of claim 12 further comprising a liquid crystal contained in the enclosure and surrounding the substrate.

14. The structure of claim 13 wherein an index of refraction of the liquid crystal is controllable electrically to vary a resonant color of the stepped surface relief structure.

15. The structure of claim 12 wherein the enclosure comprises a tube made of one of a plastic, a thermoplastic, a thermoset, a glass or a ceramic.

16. The structure of claim 1 further comprising an optical horn configured to contain the stepped surface relief structure.

17. The structure of claim 16 wherein the optical horn is further configured to contain liquid crystal material.

18. The structure of claim 1 further comprising a corner cube reflector positioned substantially adjacent to the stepped surface relief structure and configured to allow at least one color to be reflected at a predetermined distance.

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