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Rich et al.

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(54) **OPTICAL PRODUCTS, MASTERS FOR FABRICATING OPTICAL PRODUCTS, AND METHODS FOR MANUFACTURING MASTERS AND OPTICAL PRODUCTS**

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G03H 1/0011; B42D 25/00; B42D 25/29;
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Primary Examiner — Stephone B Allen

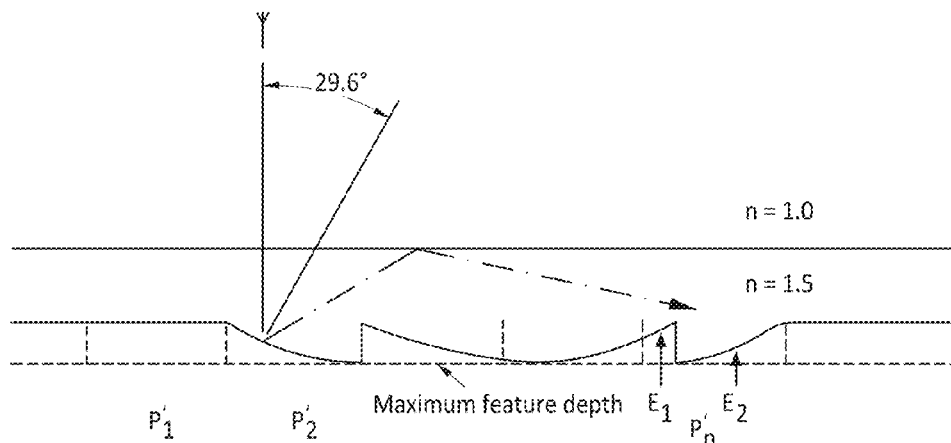
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(57) **ABSTRACT**

An optical product can be configured to be an anti-counter-
feit feature such as a patch, a window, or a thread on a
banknote. The optical product can be configured, when
illuminated, to reproduce by reflected or refracted light, a 3D
image of at least a part of a 3D object. The optical product
can include a first surface and a second surface opposite the
first surface. The second surface can include a plurality of
portions. Each portion can correspond to a point on a surface
of the 3D object. Each portion can include features corre-
sponding to non-holographic elements on the optical prod-
uct. A gradient in the features can correlate to an inclination
of the surface of the 3D object at the corresponding point. An
orientation of the features can correlate to an orientation of
the surface of the 3D object at the corresponding point.

38 Claims, 12 Drawing Sheets



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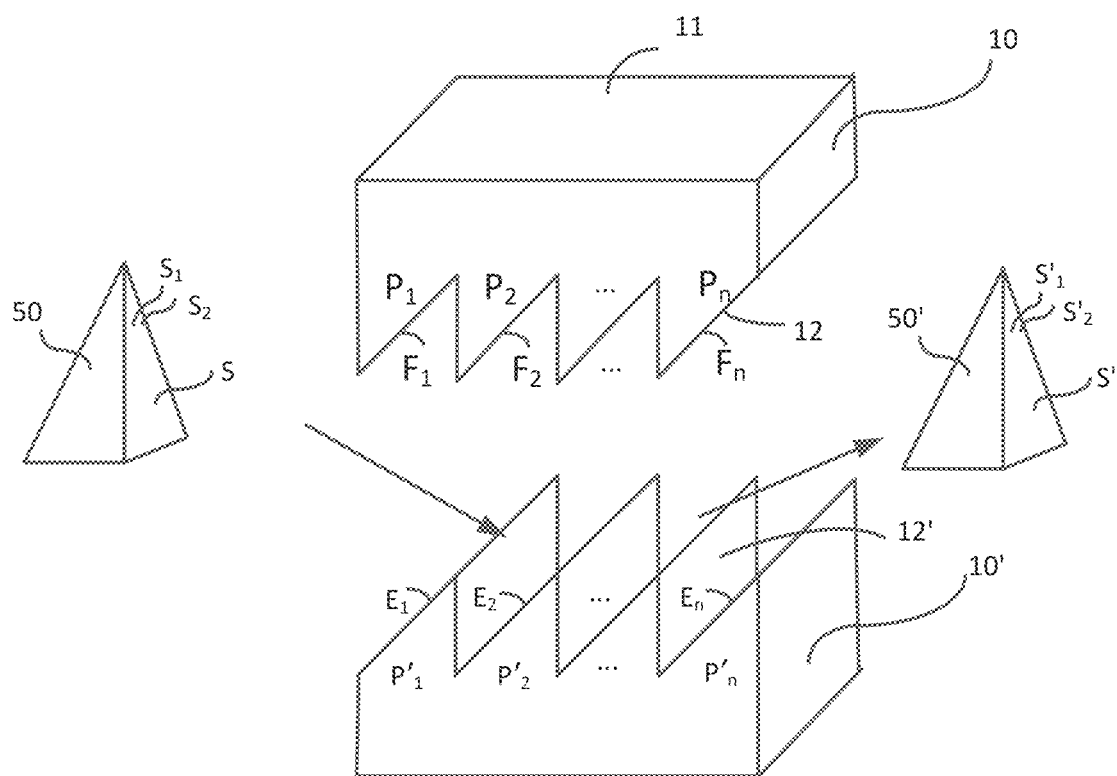


FIG. 1A

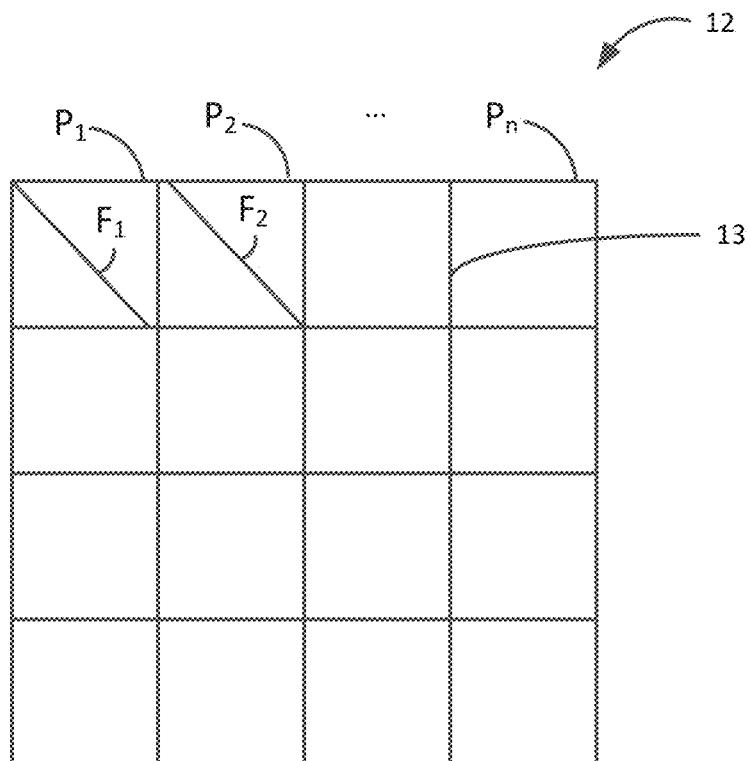


FIG. 1B

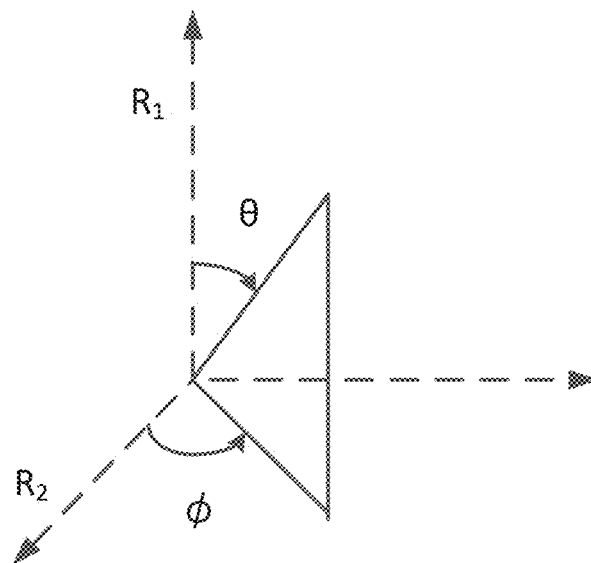


FIG. 1C

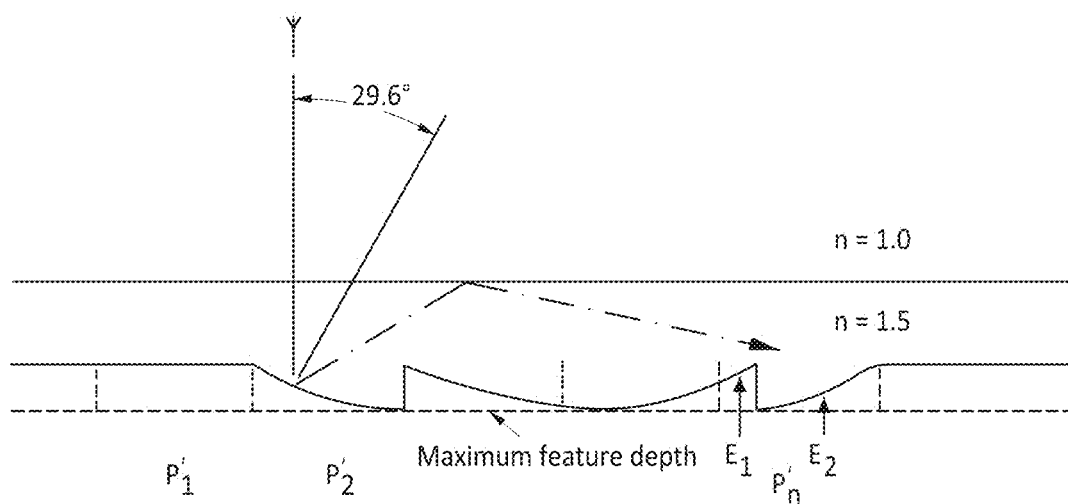


FIG. 1D

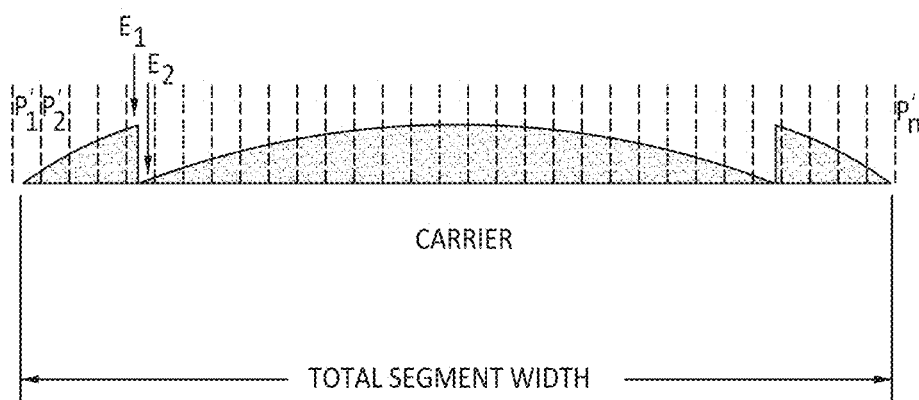


FIG. 1E

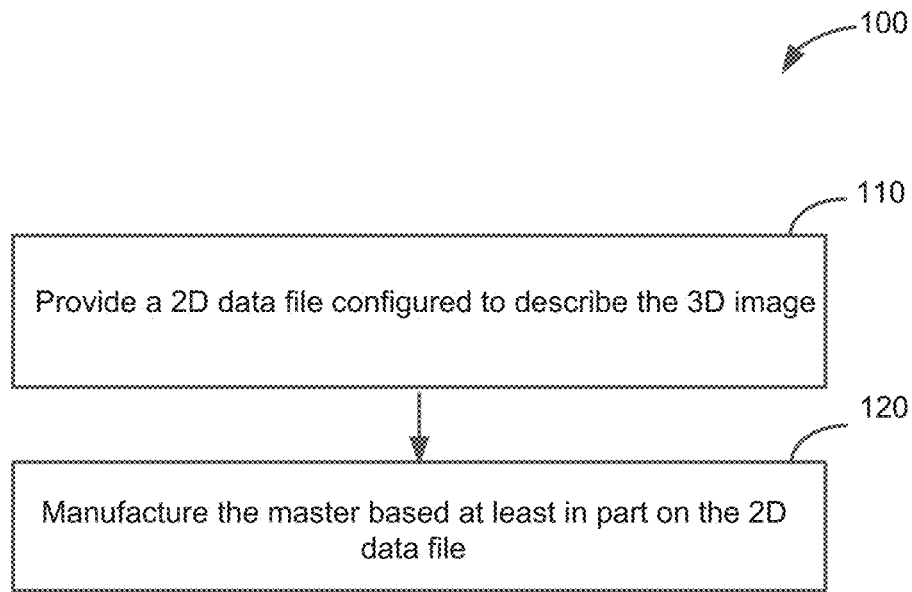


FIG. 2

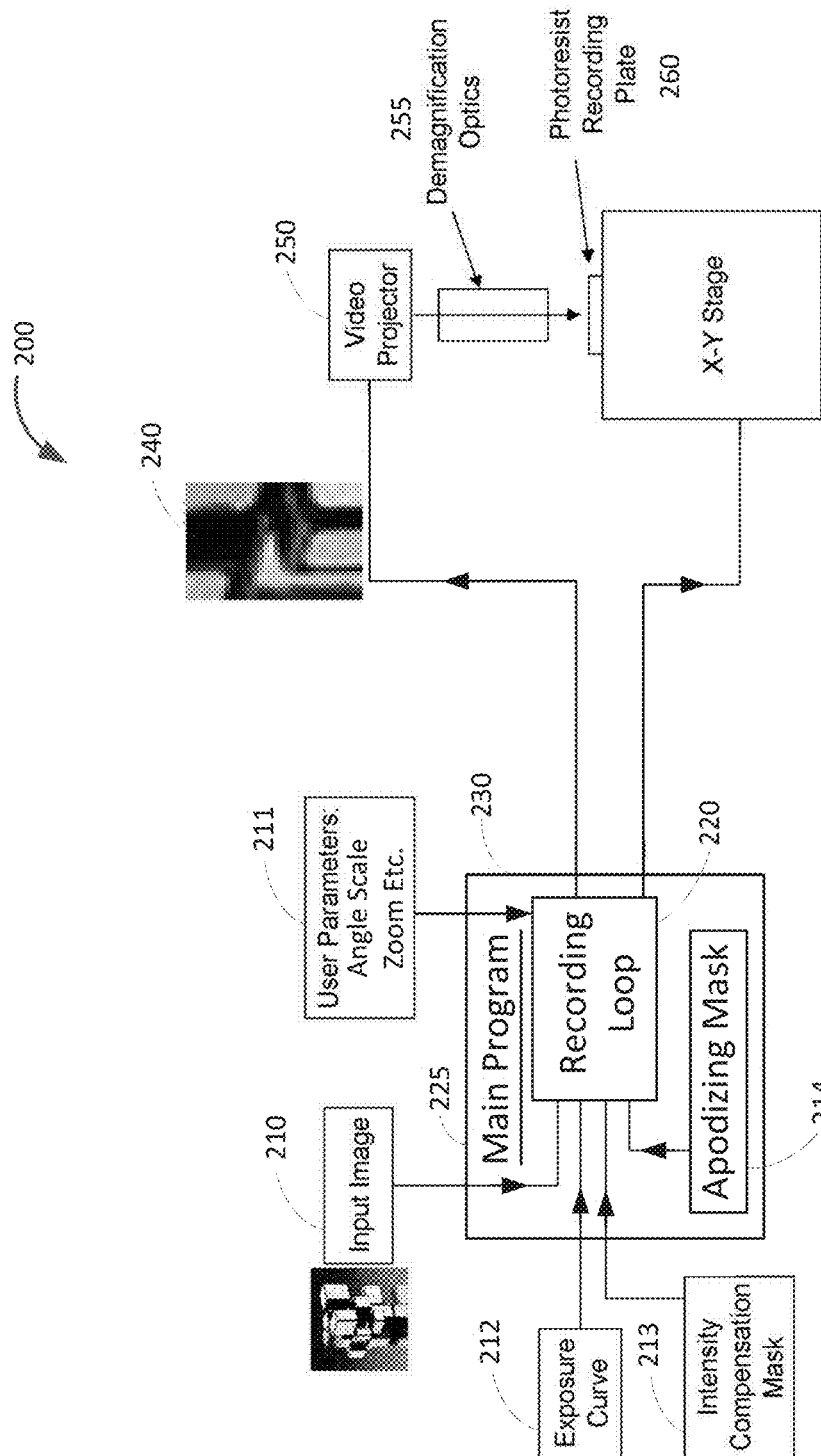


FIG. 2A

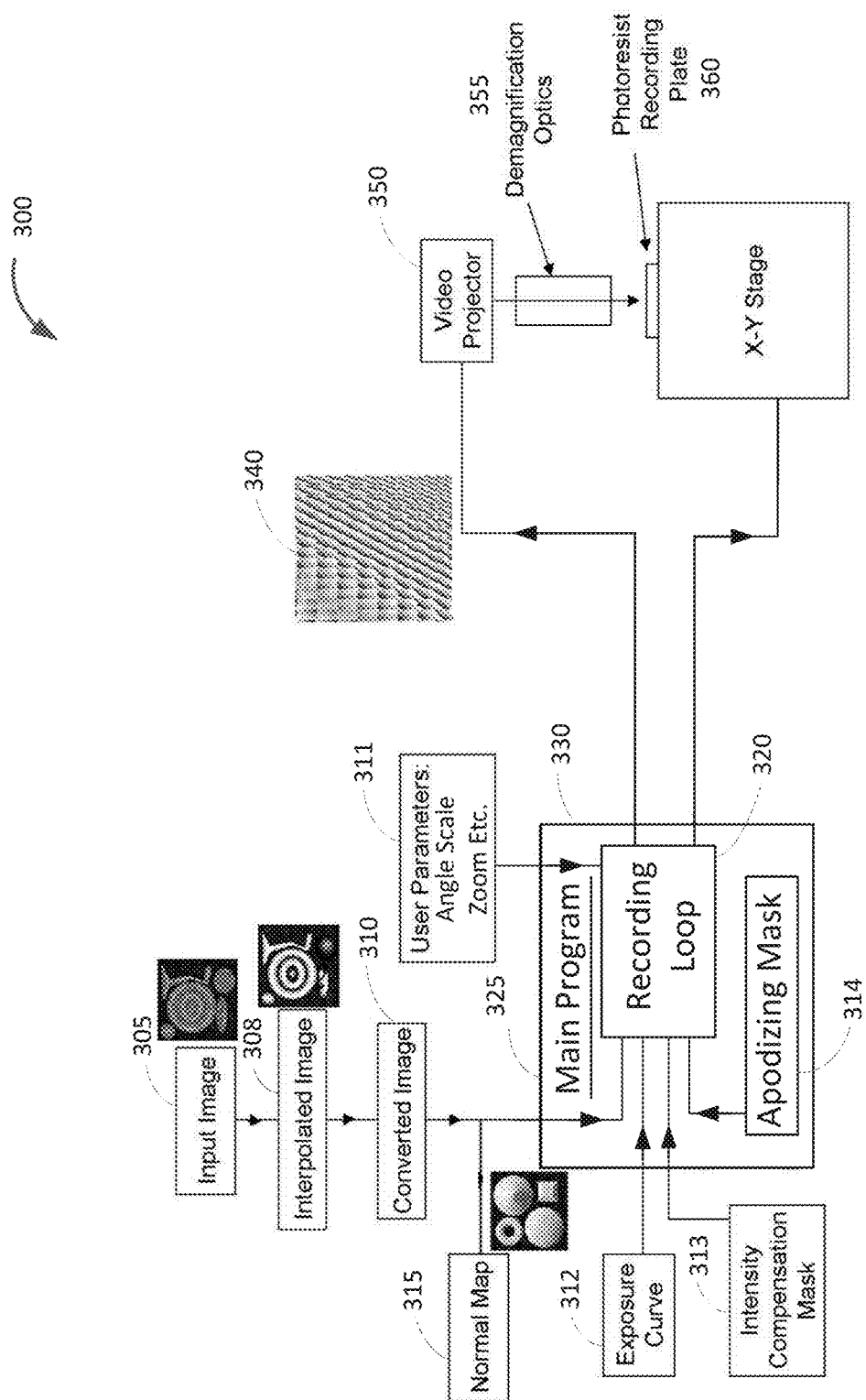


FIG. 2B

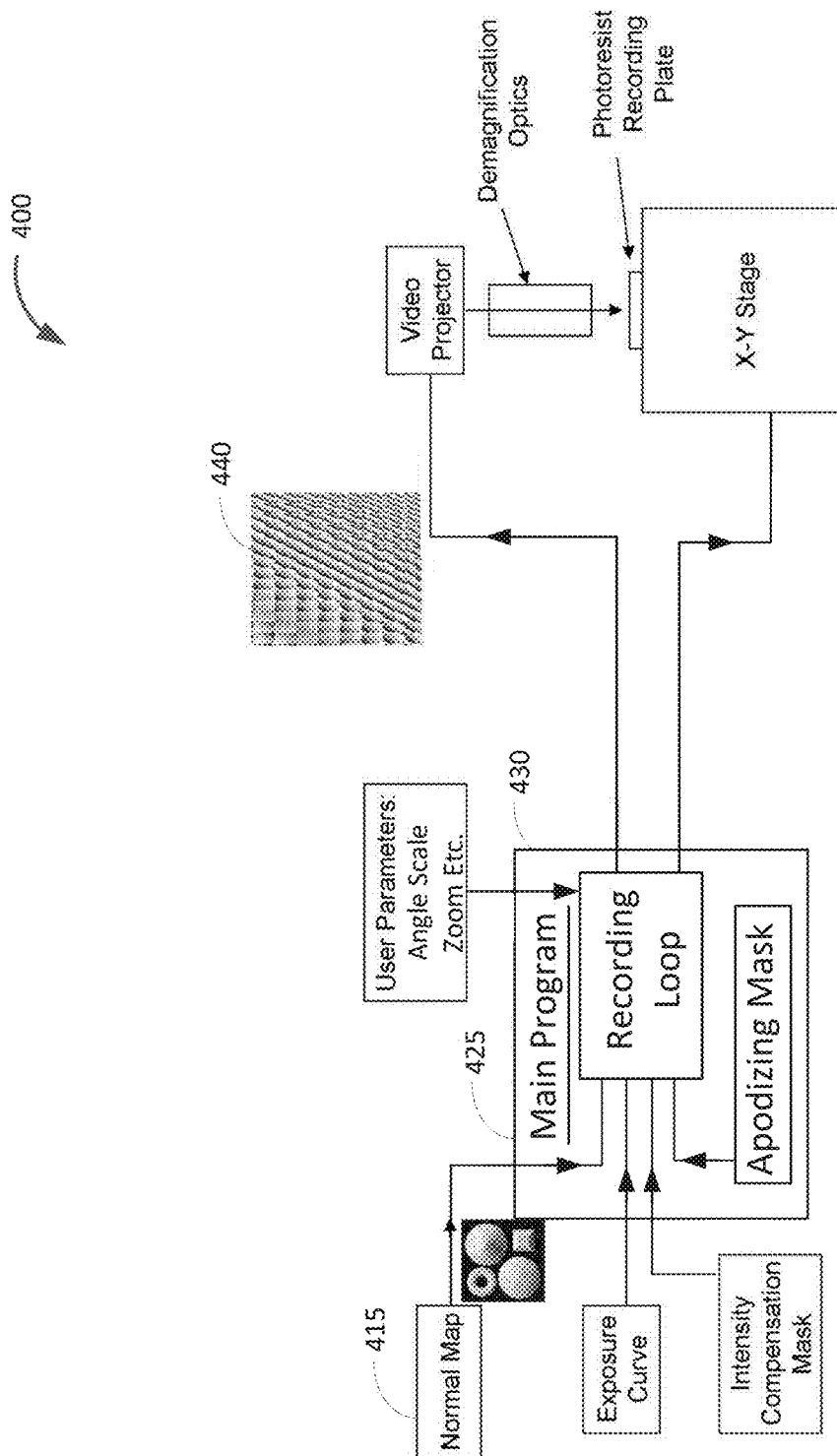


FIG. 2C

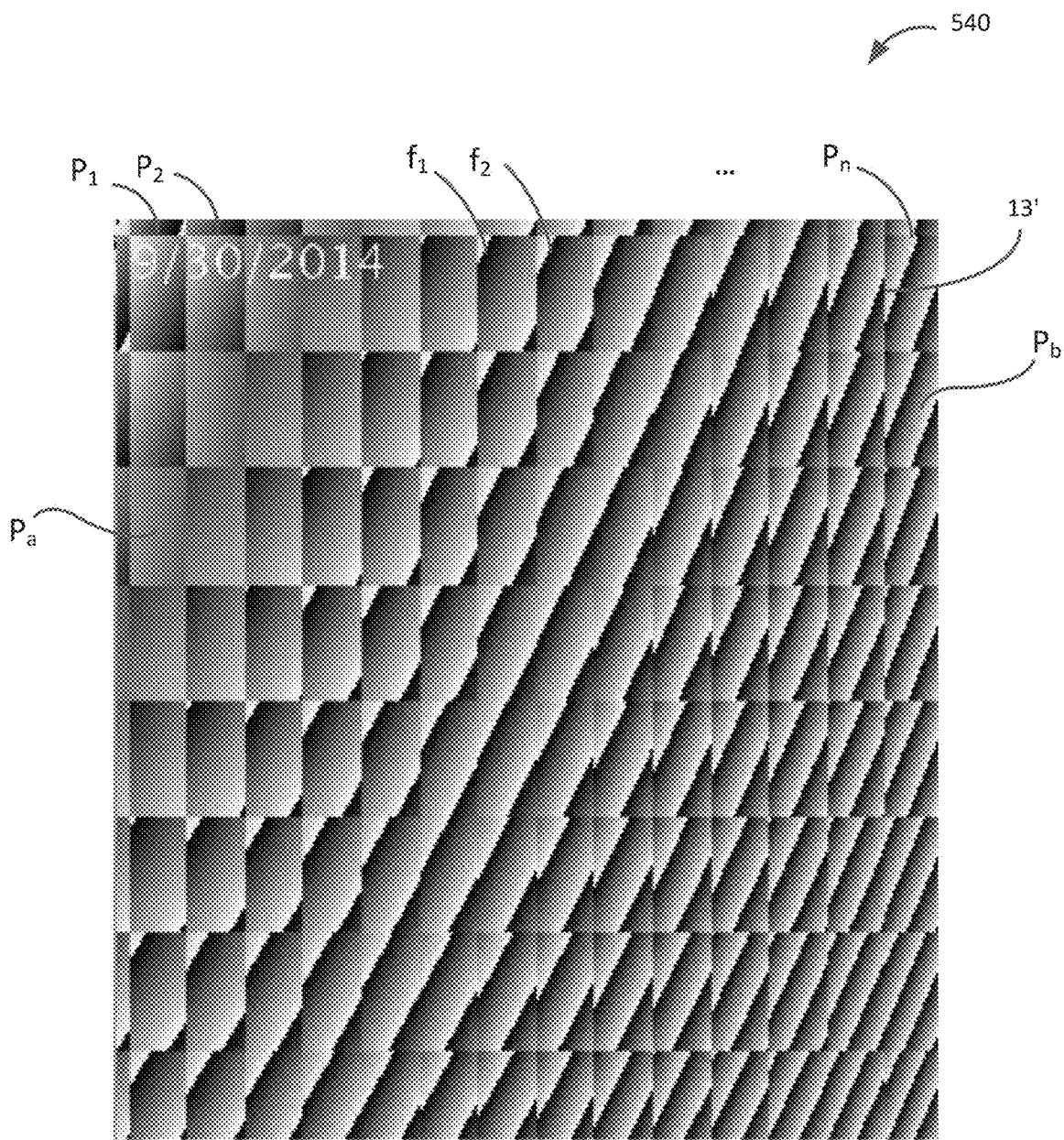


FIG. 3A

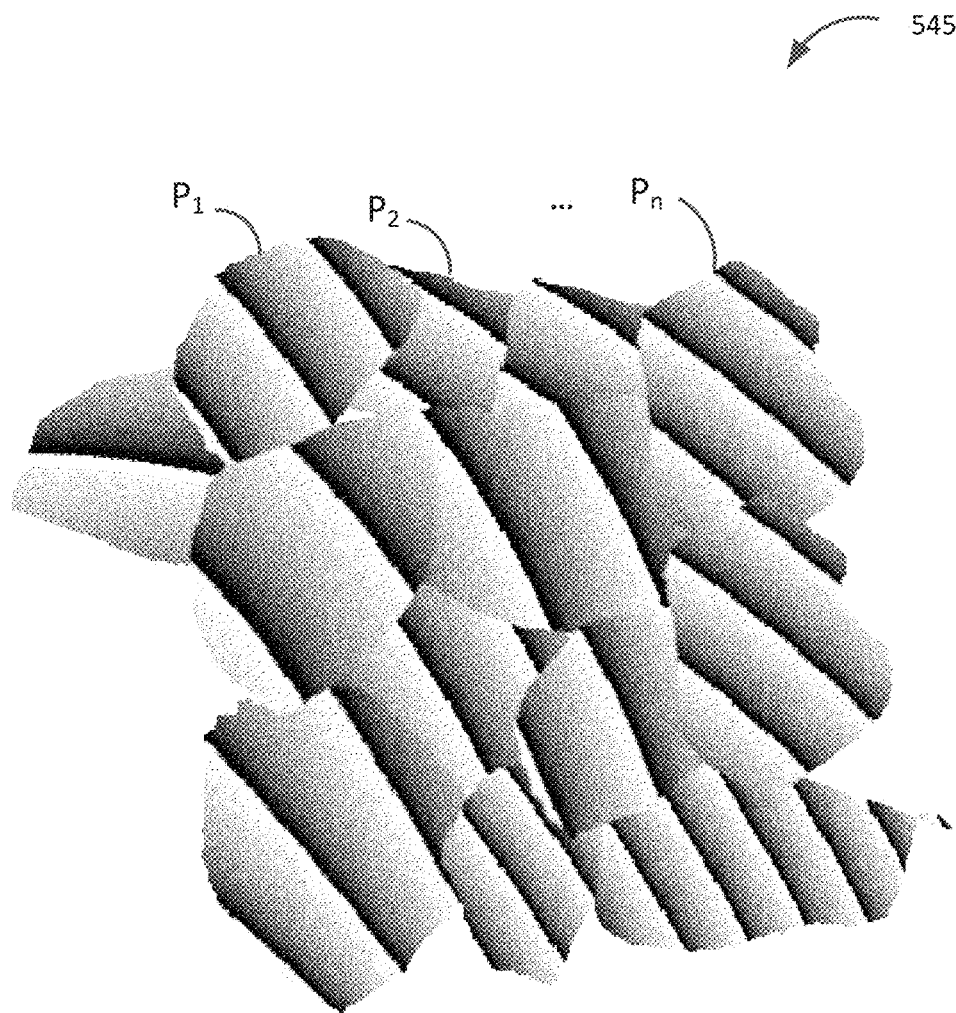


FIG. 3B

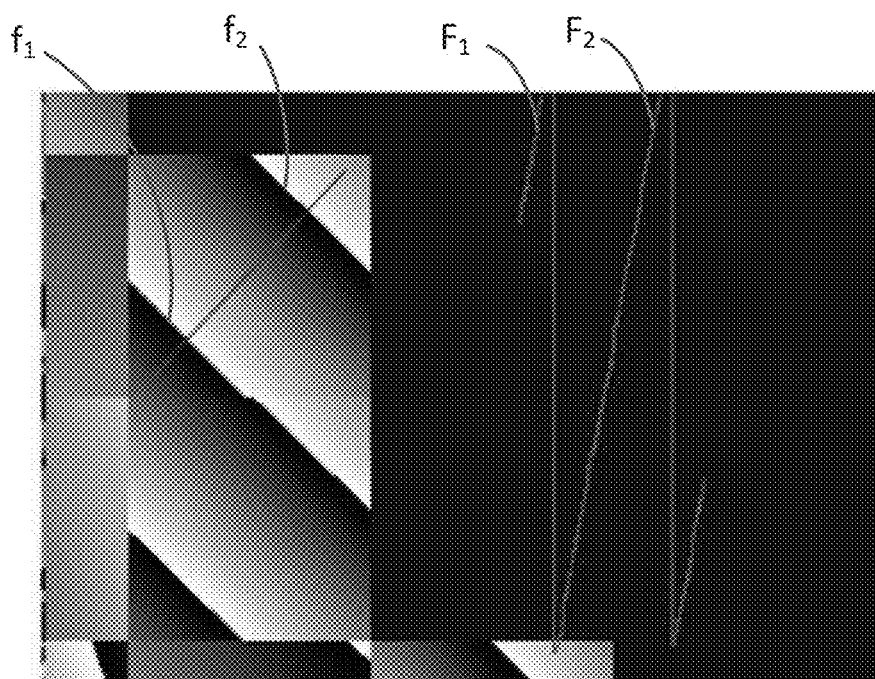


FIG. 3C

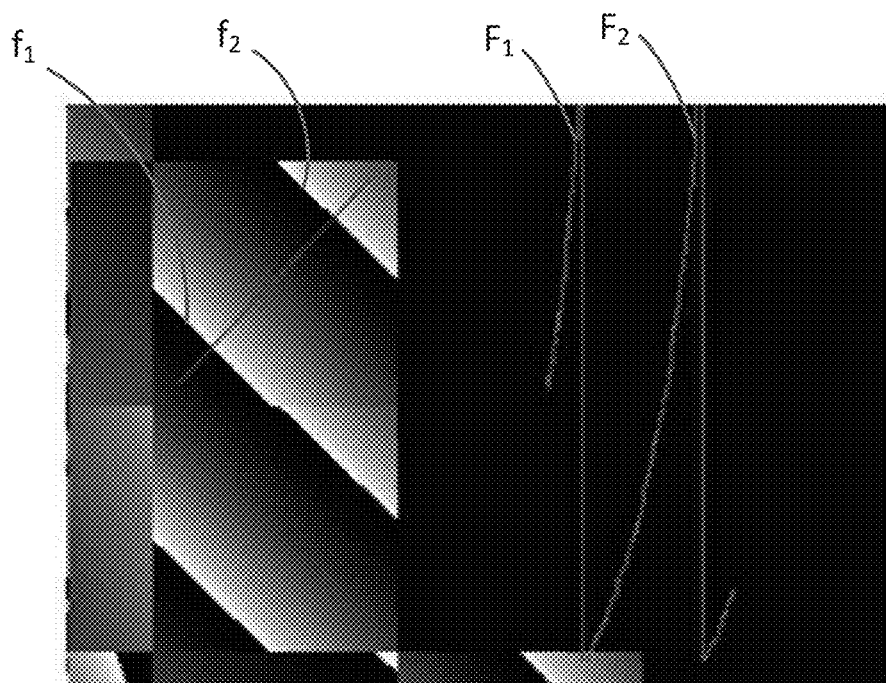


FIG. 3D

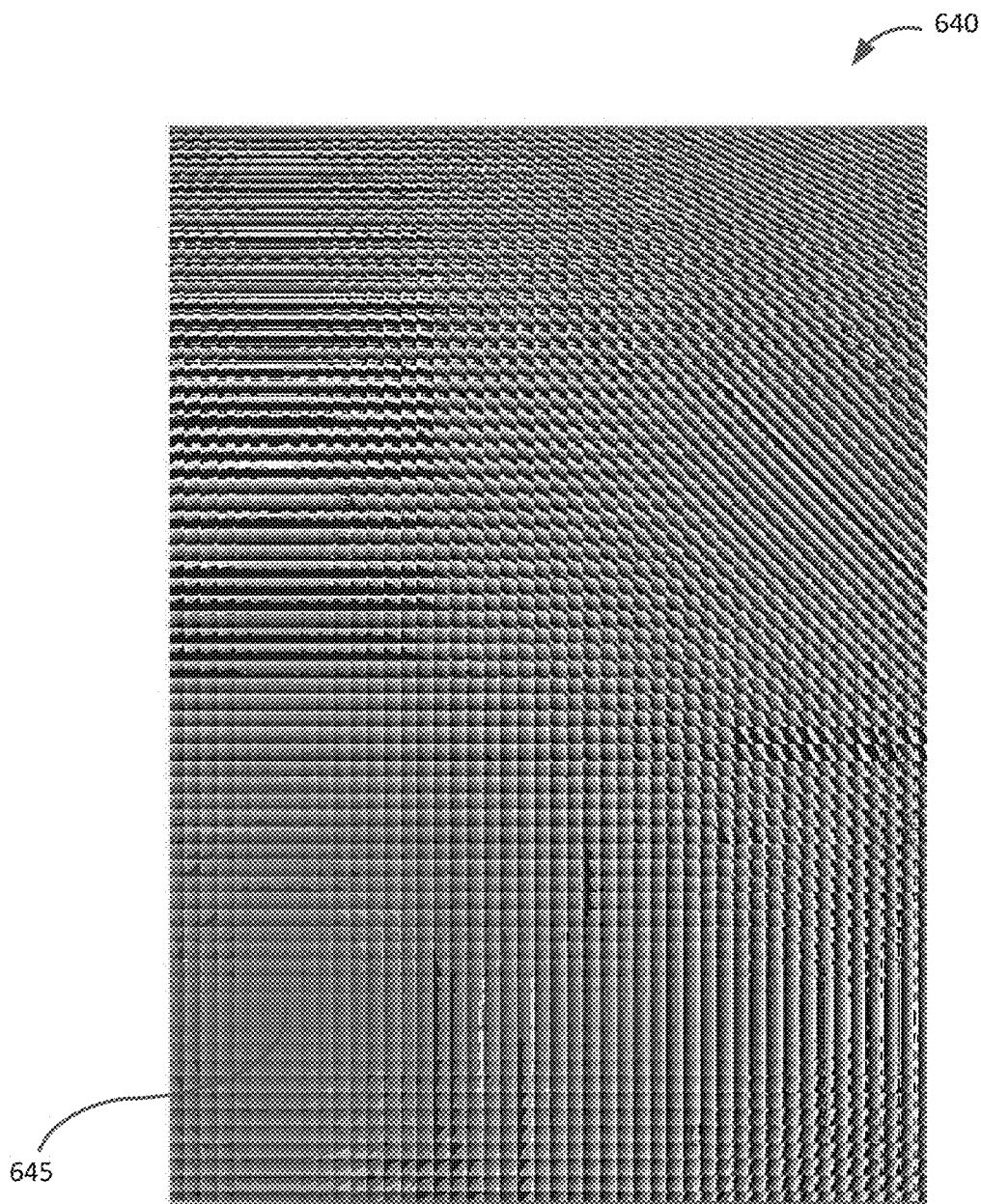


FIG. 4A

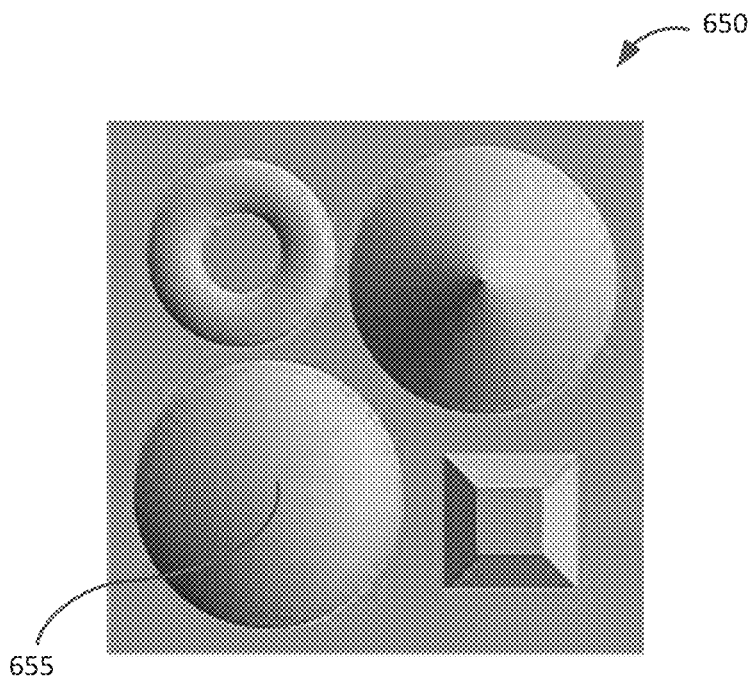


FIG. 4B

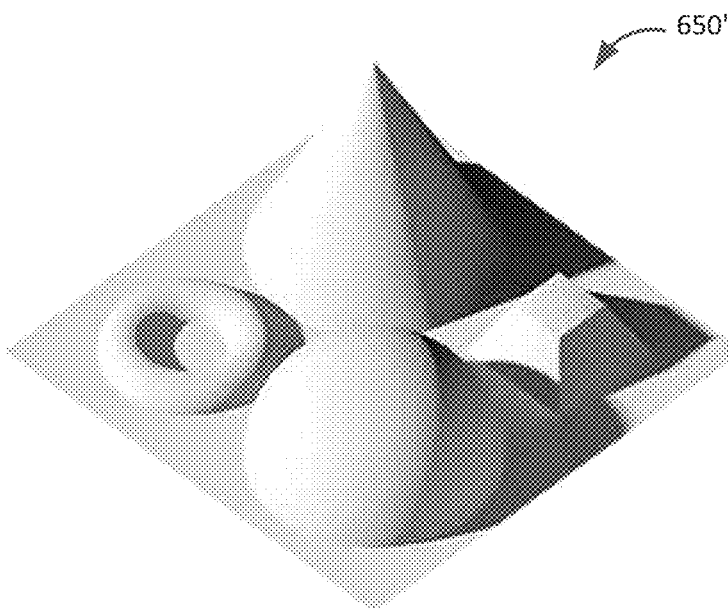


FIG. 4C

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OPTICAL PRODUCTS, MASTERS FOR FABRICATING OPTICAL PRODUCTS, AND METHODS FOR MANUFACTURING MASTERS AND OPTICAL PRODUCTS

INCORPORATION BY REFERENCE TO ANY PRIORITY APPLICATIONS

This application claims the benefit of priority of U.S. Provisional Application No. 62/068,540 filed on Oct. 24, 2014, the entire disclosure of which is expressly incorporated herein by reference.

TECHNICAL FIELD

The present application generally relates to optical products, masters (e.g., master and/or daughter shims) for fabricating an optical product, and methods for manufacturing the masters and optical products. In particular, the optical product can be configured, when illuminated, to reproduce by reflected (or refracted) light, a 3D image (e.g., an image that appears three-dimensional) of at least a part of a 3D object.

DESCRIPTION OF THE RELATED TECHNOLOGY

Optical products can be used for a variety of purposes such as to reproduce a 3D image. Such products can be placed on decorative signs, labels, packaging, and consumer goods. Some optical products can be used as an anti-counterfeit feature, for example, on currency (e.g., a banknote). Holograms have traditionally been used as a counterfeit deterrent. However, this technology has become so widespread with hundreds if not thousands of holographic shops around the world that holograms are now viewed as having poor security. Optically variable inks and optically variable magnetic inks have also enjoyed for the past decade a high security place on banknotes. However, these products have now been simulated or have been even made from similar materials as the originals that these security elements are now being questioned as a high security feature. Motion type security elements have been adopted into banknotes, but even here, security has been compromised as this feature has also been used on commercial products. Thus, what is needed is a new security feature that the average person readily recognizes, has no resemblance to holograms or inks, is readily verified as to its authenticity, is difficult to counterfeit, is easily manufactured in quantity and can be readily incorporated into an item such as a banknote.

Manufacturing optical products, e.g., in relatively large quantities for commercial use, can utilize a master to fabricate the optical product. A master can be either a negative or positive master. For example, a negative master can form a surface of the optical product that is complementary to the surface of the master. As another example, a positive master can provide a surface for the optical product that is substantially similar to the surface of the master.

SUMMARY

Various embodiments described herein comprise a master for fabricating an optical product. The optical product can be configured, when illuminated, to reproduce by reflected light, a 3D image of at least a part of a 3D object. The master can comprise a first surface and a second surface opposite the first surface. The second surface can comprise a plurality

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of portions. Each portion can correspond a point on a surface of the 3D object. Each portion can comprise features corresponding to non-holographic elements on the optical product. A gradient (e.g., slope) in the features can correlate to an inclination of the surface of the 3D object at the corresponding point. In addition, an orientation of the features can correlate to an orientation of the surface of the 3D object at the corresponding point.

Certain embodiments described herein also include an optical product configured, when illuminated, to reproduce by reflected light, a 3D image of at least a part of a 3D object. The optical product can comprise a first surface and a second surface opposite the first surface. The second surface can comprise a plurality of portions. Each portion can correspond to a point on a surface of the 3D object. Each portion can comprise non-holographic features configured to produce at least part of the 3D image of the 3D object without relying on diffraction. A gradient in the non-holographic features can correlate to an inclination of the surface of the 3D object at the corresponding point. In addition, an orientation of the non-holographic features can correlate to an orientation of the surface of the 3D object at the corresponding point.

Furthermore, various embodiments described herein include a method for manufacturing a master for fabricating an optical product. The optical product can be configured, when illuminated, to reproduce by reflected light, a 3D image of at least a part of a 3D object. The method can comprise providing a 2D data file configured to describe the 3D image. The data file can comprise a plurality of portions. Each portion can correspond to one or more points on a surface of the 3D object. Each portion can comprise features of intensity corresponding to non-holographic elements on the optical product. A gradient in intensity can correlate to an inclination of the surface of the 3D object at the one or more corresponding points. In addition, an orientation of the features can correlate to an orientation of the surface of the 3D object at the one or more corresponding points. The method can also comprise manufacturing the master based at least in part on the 2D data file.

Certain embodiments described herein of a master, optical product, and/or data file can also include one or more of the following (1) a majority of the plurality of portions comprising a single non-holographic feature, (2) a majority of the plurality of portions comprising one or more non-holographic features discontinuous with one or more non-holographic features in surrounding adjacent portions, (3) a majority of the plurality of portions comprising one or more non-holographic features having different orientations as one or more non-holographic features in surrounding adjacent portions, and/or (4) one or more non-holographic features comprising non-linear features when viewed in a cross-section. In some embodiments, each portion comprising one or more non-holographic features can be configured to produce at least part of the image without relying on diffraction (1) at a viewing angle at least between 20 degrees to 160 degrees relative to a plane of the optical product as the optical product is tilted and (2) at a viewing angle at least between 20 degrees to 90 degrees relative to the plane of the optical product as the optical product is rotated at least throughout the range of 90 degrees (rotated at least throughout the range of 180 degrees, rotated at least throughout the range of 270 degrees, or rotated at least throughout the range of 360 degrees) in the plane of the optical product.

In some embodiments, the size of the portion may assist in reducing iridescence or a change in color with change in angle of view or change in angle of illumination such as

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results when tilting the product with respect to the viewer and/or source of illumination. Accordingly, in various embodiments, the optical product does not exhibit a rainbow-like array of displayed colors where colors simultaneously appear in the order of a rainbow. Also, in some embodiments, the color of light emanating from the product does not appear to change when tilting the product or the viewer with respect to the product or the illumination with respect to the product, for example, in order of progressively increasing wavelength or in order of progressively decreasing wavelength (e.g., in progressive order of the arrangement of colors in the rainbow).

The size of the portion may be sufficiently large to produce light that can pass through a circular pupil 5 mm in diameter located 24 inches from the product that includes a plurality of colors that mix together to form white light. Accordingly, for a person viewing the product with their eye positioned 24 inches from the product and having a pupil of 5 mm in diameter, light from the product will enter the eye and be mixed together to form white light. The person thus does not see iridescence or change in color with change in angle of view or angle of illumination or tilt of the product. Other factor besides the size of the portion may contribute to this effect, even if the size of the portion is not sufficiently large on its own to cause this lack of iridescence. For example, not having multiple grating like features in a single portion may reduce this effect. Similarly, having a large number or percentage of portions that do not have multiple grating like features but instead have a single surface may contribute to reducing iridescence or change in color with angle. Additionally, having features with a curved surface within the portion may help counter the iridescent effect. The curved features may, for example, enhance mixing of different colors so that white light is sensed by the viewer. Even if multiple features are included in a portion, these features may be curved and this curvature may potentially reduce the iridescence. Also, the amount of portions that have features that are oriented differently from each other may be increased and the amount of portions that have a shift in phase or otherwise introduce a discontinuity may be increased, possibly resulting in increased mixing of color components and reducing this effect of diffractive spectral dispersion

Various embodiments disclosed herein can be used for security documents, in particular, as security threads in bank notes or as a patch or as a window. Other security items such as passports, ID cards, chip cards, credit cards, stock certificates and other investment securities, vouchers, admission tickets and commercial packages that protect items of value such as CD's, medicinal drugs, car and aircraft parts, etc. may also be protected against counterfeiting using the concepts and embodiments described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A schematically illustrates an example master and optical product in accordance with certain embodiments described herein.

FIG. 1B schematically illustrates a top view of the surface of a master for fabricating an optical product in accordance with certain embodiments described herein.

FIG. 1C schematically illustrates the inclination and orientation of a surface of a 3D object at a point on the surface.

FIG. 1D is another example optical product 10' in accordance with certain embodiments described herein.

FIG. 1E is another example optical product 10' in accordance with certain embodiments described herein.

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FIG. 2 illustrates an example method to manufacture a master for fabricating an optical product in accordance with certain embodiments described herein.

FIG. 2A illustrates an example method that can be used to manufacture a surface relief diffuser.

FIGS. 2B-2C illustrate example methods to manufacture a master for fabricating an optical product in accordance with certain embodiments described herein.

FIGS. 3A-3B illustrate example 2D data files in accordance with certain embodiments disclosed herein.

FIGS. 3C-3D illustrate example features on a data file and the corresponding features on the surface of a master for fabricating an optical product in accordance with certain embodiments disclosed herein.

FIG. 4A illustrates another example 2D data file in accordance with certain embodiments disclosed herein.

FIG. 4B illustrates an example normal map used to generate the data file shown in FIG. 4A.

FIG. 4C illustrates the 3D image reproduced by an optical product generated from a master produced using the data file shown in FIG. 4A.

DETAILED DESCRIPTION

In various embodiments, a master (e.g., a master and/or daughter shim) for fabricating an optical product is provided. The optical product, when illuminated, can reproduce an overt 3D image (e.g., an image that appears 3D to the naked eye) of a 3D object. Compared to ink printed images, the reflective surface of various embodiments of the optical product can produce a brighter mirror-like image produced by reflecting (or refracting) light incident on the surface. In certain such embodiments, the surface normals of the 3D object are mimicked as surface relief on the master and/or optical product. The surface relief on the master and/or optical product can be thinner than the 3D object, yet produce the same appearance of the 3D object. This property is similar to Fresnel lenses, where the surface relief allows a lens to be produced that is thinner than a comparable non-Fresnel lens. Unlike Fresnel lenses, however, certain embodiments disclosed herein are not limited in the type of 3D object that can be reproduced (e.g., linear and regularly shaped objects). As such, realistic and bright 3D images can be produced on relatively thin films (e.g., 30 μm and less in thickness, 25 μm and less in thickness, 15 μm and less in thickness, or any ranges in between these values). Thin films may be advantageous for different applications. In addition, special effects can be integrated into the image. In various embodiments described herein, the optical product can advantageously be used in applications for flexible packaging, brand identification, tamper evident containers, currency (e.g., a banknote), decoding messages, authenticity, and security, etc. Some security applications include incorporation of small detailed features, incorporation of non-symmetrical features, incorporation of machine readable features, etc.

In certain embodiments, the optical product can be incorporated into an item as an embedded feature, a hot stamp feature, a windowed thread feature, or a transparent window feature. For example, on an item such as a banknote, the optical product can be a patch, a window, or a thread. The optical product can have a thickness of less than 30 μm , less than 25 μm , or less than 15 μm . In various embodiments, the image can appear 3D by the naked eye.

In some embodiments, the image can be seen at a viewing angle between 20 degrees to 160 degrees, between 15 degrees to 165 degrees, between 10 degrees to 170 degrees,

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between 5 degrees to 175 degrees, or between 0 degrees to 180 degrees relative to the plane of the item (e.g., relative to the banknote plane) as the item is tilted. For example, the image can be viewable within one or more of these viewing angle ranges relative to the plane of the item.

In some embodiments, the image can be seen at a viewing angle between 20 degrees to 90 degrees, between 15 degrees to 90 degrees, between 10 degrees to 90 degrees, between 5 degrees to 90 degrees, or between 0 degrees to 90 degrees relative to the normal of the item as the item is rotated the normal of the item (e.g., in the plane of the item). For example, the image can be viewable and/or visible within one or more of these viewing angle ranges as the item is rotated (e.g., rotated at least throughout the range of 90 degrees, rotated at least throughout the range of 180 degrees, rotated at least throughout the range of 270 degrees, or rotated at least throughout the range of 360 degrees) about the normal of the item (e.g., in the plane of the item).

FIG. 1A schematically illustrates an example master 10 for fabricating an optical product 10' in accordance with certain embodiments described herein. In various embodiments, the master 10 can include a first surface 11 and a second surface 12 opposite the first surface 11. As shown in FIG. 1A, the second surface 12 can include a plurality of portions $P_1, P_2, \dots, P_n$. Each portion P_n can correspond to a plurality of portions $P'_1, P'_2, \dots, P'_n$ on the optical product 10'. The plurality of portions $P'_1, P'_2, \dots, P'_n$ on the optical product 10' can also be referred to as a cell, pixel, or a tile. Each portion P'_n can have a length between 30 μm and 100 μm , between 35 μm and 55 μm , or between 40 μm and 50 μm . Each portion P'_n can have a width between 30 μm and 100 μm , between 35 μm and 55 μm , or between 40 μm and 50 μm . Accordingly, in various embodiments, the aspect ratio of each portion P'_n can be 1:1 or 1:1.1.

Each portion P_n of the master 10 (and each portion P'_n of the optical product 10') can correspond to a point $S_1, S_2, \dots, S_n$ on a surface S of the 3D object 50. Each portion P_n can include features $F_1, F_2, \dots, F_n$ corresponding to elements $E_1, E_2, \dots, E_n$, e.g., non-holographic elements, on the optical product 10'. A gradient (e.g., slope) in the features $F_1, F_2, \dots, F_n$ can correlate to an inclination (e.g., slope) of the surface S of the 3D object 50 at the corresponding point $S_1, S_2, \dots, S_n$. In addition, an orientation of the features $F_1, F_2, \dots, F_n$ can correlate to an orientation of the surface S of the 3D object 50 at the corresponding point $S_1, S_2, \dots, S_n$. Accordingly, with certain embodiments disclosed herein, an optical product 10' fabricated using the example master 10 can be configured, when illuminated, to reproduce by reflected (or refracted) light, a 3D image 50' (e.g., an image that appears 3D) of at least a part of a 3D object 50. The image can be observed by the naked eye and under various lighting conditions (e.g., specular, diffuse, and/or low light conditions).

The optical product 10' can be used on a variety of products to reproduce a 3D image 50' of at least a part of a 3D object 50. For example, the optical product 10' can be placed on decorative signs, advertisements, labels (e.g., self-adhesive labels), packaging (e.g., consumer paper board packaging and/or flexible packaging), consumer goods, collectible cards (e.g., baseball cards), etc. The optical product 10' can also be advantageously used for authenticity and security applications. For example, the optical product 10' can be placed on currency (e.g., a banknote), credit cards, debit cards, passports, driver's licenses, identification cards, documents, tamper evident containers and packaging, bottles of pharmaceuticals, etc.

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In various implementations, the optical product 10' can be a reflective or transmissive device. For example, the optical product 10' can include reflective material (e.g., reflective metal such as aluminum, copper, or silver disposed on the plurality of elements $E_1, E_2, \dots, E_n$, or a transparent, relatively high refractive index material such as ZnS or TiO_2 disposed on the plurality of elements $E_1, E_2, \dots, E_n$ creating a semi-transmitting/partially reflective boundary). Depending on the thickness of the reflective material, the optical product 10' can be reflective or transmissive. Depending on the thickness of the reflective material, the optical product 10' can be partially reflective or partially transmissive. The thickness of the reflective material at which the optical product 10' is reflective or transmissive can depend on the chemical composition of the reflective material.

Accordingly, in some embodiments, the optical product 10' can include a reflective surface 12' from which light can reflect from the elements $E_1, E_2, \dots, E_n$ to reproduce the image 50' of the 3D object 50 or at least part of the 3D object 50. For example, the optical product 10' can be made of a reflective metal (e.g., aluminum, copper, or silver), a semi-transparent metal, or a material (e.g., polymer, ceramic, or glass) coated with a reflective metal. Reflective coatings that employ non-metallic material can also be employed.

In some embodiments where the elements $E_1, E_2, \dots, E_n$ are coated with a reflective metal, the thickness of the coating layer can be greater than or equal to 40 nm such that the layer is opaque. Alternatively, the thickness of the reflective metal can be less than 40 nm such that the layer is semi-transparent (e.g., 30% transparent 40% transparent, 50% transparent, 60% transparent, 70% transparent, or any ranges inbetween these values, etc.). In reflective embodiments, the elements $E_1, E_2, \dots, E_n$ can reflect light towards or away from the observer's eye to reproduce the image 50' of the 3D object 50. For example, the elements $E_1, E_2, \dots, E_n$ can reflect light towards the observer's eye in bright areas, and reflect light away from the observer's eye in dark areas. In some embodiments, the slopes of the elements E_n can be configured to create the 3D depth perception of the image. For example, elements E_n with less steep slopes can cause light to reflect toward the observer's eye creating more brightness, while elements E_n with steeper slopes can cause light to reflect away from the observer's eye creating more darkness.

In some other embodiments (e.g., for a transmissive device), the optical product 10' can include a layer (e.g., a coating) of a transparent, relatively high refractive index material such as, for example, ZnS or TiO_2 . In some such embodiments, light can transmit through the material and can also reflect at each of the elements $E_1, E_2, \dots, E_n$ due to the presence of the relatively high index layer which can create index mismatch and results in Fresnel reflection. The relatively high index material can be up to a full visible wavelength in thickness in some embodiments. If a color tint is used, the relatively high index material can be up to a $\frac{1}{4}$ of a visible wavelength in thickness in some embodiments.

Furthermore, the optical product 10' can include a protective covering, e.g., an organic resin, to protect the elements $E_1, E_2, \dots, E_n$ and/or any coating layer from corrosion from acidic or basic solutions or organic solvents such as gasoline and ethyl acetate or butyl acetate. In various implementations, the protective covering can also provide protection during subsequent processing steps and use of the optical product 10' (e.g., during the manufacturing of currency and/or by general handling by the public).

In various embodiments, the optical product 10' can be placed on or in another surface (e.g., as an embedded

feature, a hot stamped feature such as a patch, a windowed thread feature, or a transparent window feature). In other embodiments, the optical product 10' can be placed under another surface (e.g., laminated under a film and/or cast cured). In some embodiments, the optical product 10' can be placed between two other surfaces (e.g., hot stamped on another surface and laminated under a film). Additional features associated with the optical product 10' will become apparent with the disclosure herein of the master 10 for fabricating the optical product 10'.

The image 50' of at least part of the 3D object 50 can be reproduced when the optical product 10' is illuminated. In various embodiments, the image 50' can be reproduced by a multitude of relatively small mirrors (e.g., each of the elements $E_1, E_2, \dots, E_n$ having both a length and width between 30 μm and 100 μm , between 35 μm and 55 μm , or between 40 μm and 50 μm) which can be curved (e.g., have a freeform curvature) or planar. For example, in some embodiments, a reflective surface of the optical product 10' can provide a surface for specular reflection, such that the image 50' can be produced by the reflected light (e.g., like a mirror). Accordingly, various embodiments can produce a bright, high quality image. Some embodiments can also utilize techniques for producing diffuse reflection, e.g., for special or desired effects. Furthermore, the image 50' can be a substantially similar reproduction (e.g., with similar details), an approximate reproduction (e.g., with less details), and/or a scaled copy (e.g., scaled up or down in size) of the 3D object 50 or part of the 3D object 50.

In general, the 3D object 50 to be reproduced is not particularly limited and can advantageously include rotationally non-symmetrical and/or irregularly shaped objects, as well as symmetrical and/or regularly shaped objects. For example, the 3D object 50 can include one or more alphanumeric characters and/or symbols. For example, the 3D object 50 can include one or more text, one or more alphabetic characters, one or more numeric characters, one or more letters, one or more numbers, one or more symbols, one or more punctuation marks, one or more mathematical operators, etc. The 3D object 50 can also include one or more graphical images or logos, e.g., a company logo, a team logo, product branding designs, etc. Accordingly, the 3D object 50 can include irregularly shaped features in addition to planar and curved features. In some embodiments, the 3D object 50 can comprise animals, humans, plants or trees, landscapes, buildings, cars, boats, airplanes, bicycles, furniture, office equipment, sports equipment, foods, drinks, personal care items, flags, emblems, symbols like country, company or product symbols including trademarks, or parts thereof or groups or combination of these items with or without other items. The objects may be cartoon or artistic renditions. A wide range of other objects are possible.

As set forth herein, in various embodiments, the image 50' can be seen at various viewing angles (e.g., between 20 degrees to 160 degrees, between 15 degrees to 165 degrees, between 10 degrees to 170 degrees, between 5 degrees to 175 degrees, or between 0 degrees to 180 degrees relative to the plane of the item (e.g., relative to the banknote plane). For example, when the example optical product 10' is tilted, upon viewing the example optical product 10' at different viewing angles (or upon different angles of illumination), different sets of elements $E_1, E_2, \dots, E_n$ can be seen by the observer to provide the different images of the 3D object.

In some embodiments, the image can be seen at a viewing angle between 20 degrees to 90 degrees, between 15 degrees to 90 degrees, between 10 degrees to 90 degrees, between 5

degrees to 90 degrees, or between 0 degrees to 90 degrees relative to the normal of the item as the item is rotated about the normal of the item. For example, the image can be viewable within one or more of these viewing angle ranges as the item is rotated (e.g., rotated at least throughout the range of 90 degrees, rotated at least throughout the range of 180 degrees, rotated at least throughout the range of 270 degrees, or rotated at least throughout the range of 360 degrees) about the normal of the item.

Furthermore, in certain embodiments, the image 50' can be substantially without iridescence or change in color with angle. For example, in various embodiments, there are substantially no colors (e.g., rainbow effect), other diffractive colors, or ghosting effects in the image 50'. For example, in certain embodiments, the size of the portions $P'_1, P'_2, \dots, P'_n$ can have a length and width between 30 μm and 100 μm , between 35 μm and 55 μm , or between 40 μm and 50 μm . In some such embodiments (e.g., between 40 μm and 50 μm), the portions P'_n may be small enough such that the portions P'_n are not resolvable by a human observer under normal viewing conditions (e.g., a reading distance of 18 to 24 inches between the eye and the item to be viewed). In addition, without being bound by theory, the portions P'_n may be big enough such that the cone of light passing through the pupil (e.g., 5 mm in diameter) is small enough such that the eye may see a majority of the colors mixed as white light at a distance of 18-24 inches.

As another example, in some embodiments, a majority (e.g., greater than 50%, greater than 55%, greater than 60%, greater than 65%, greater than 70%, greater than 80%, greater than 90%, and any ranges in between these values) of the plurality of portions $P'_1, P'_2, \dots, P'_n$ on the optical product 10' can include a single non-holographic element E_1 (as opposed to a plurality of spaced apart non-holographic elements E_n that may resemble a grating-like feature). Without being bound by theory, grating-like features can cause light to be dispersed with some of the light collected by the pupil of the eye. If the period of the grating-like feature is small enough, the light captured by the pupil may appear as a color. Accordingly, in various embodiments of the optical product 10' that have a majority of the plurality of portions $P'_1, P'_2, \dots, P'_n$ having not more than a single non-holographic reflective or refractive element E_1 , unwanted color caused by grating-like features may possibly be substantially reduced and/or eliminated. Similarly, color change with angle of tilt can be reduced. In some embodiments, at least 20%, at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, or any ranges in between these values) of the plurality of portions $P'_1, P'_2, \dots, P'_n$ on the optical product 10' can include a single non-holographic element E_1 . In various embodiments, the single element may be slowly varying and/or substantially flat. In certain embodiments, the maximum average slope per portion with a single feature is less than $1/2$, less than $1/3$, less than $1/4$, less than $1/5$, less than $1/6$, potentially flat, and any ranges in between these values depending on feature height and width.

In addition, in portions P'_n having a plurality of non-holographic elements $E_1, E_2, \dots, E_n$ (e.g., grating-like features), the elements E_n can be discontinuous and/or having different orientation with non-holographic elements $E_1, E_2, \dots, E_n$ in surrounding adjacent portions P'_n . Without being bound by theory, the discontinuity and/or different orientations between grating-like features can cause a lateral shift of the grating-like feature. The lateral shift may cause the color spectrum to shift as well (e.g., from red to blue to green). The colors may combine on the retina providing an

average white irradiance distribution. Accordingly, in embodiments of the optical product **10'** that have a plurality of portions $P_1, P_2, \dots, P_n$ including a plurality of non-holographic element E_n , unwanted color cause by grating-like features may possibly be substantially reduced and/or eliminated. Similarly, color change with angle of tilt can be reduced.

Accordingly, certain embodiments of the optical product **10'** can utilize a certain portion P_n size, a single non-holographic element E_1 in a portion P_n , discontinuous and/or differently orientated elements E_n to produce images that may be substantially without iridescence or change in color with angle. The application of these features can be dependent on the image to be formed.

Various embodiments described herein can create a 3D image primarily by the reflection of light without relying on diffraction (e.g., without relying on holographic or grating diffraction). In other embodiments, the optical product **10'** can include surfaces which additionally include features from which light can diffract, e.g., at surface defects, at discontinuities at borders, and/or via incorporation of diffractive or holographic elements. Such diffractive or holographic features can be combined with the surface features disclosed herein that produce an image of a 3D object using reflection (or possibly refraction, e.g., in transmission) without relying on diffraction.

In various embodiments, the master **10** can be either a negative or positive master. Whether as a negative or positive master, the method to produce the master **10** is not particularly limited. For example, the features $F_1, F_2, \dots, F_n$ on surface **12** of the master **10** can be produced using any technique known in the art or yet to be developed, including but not limited to photolithography (e.g., UV or visible light), electron beam lithography, and ion beam lithography to name a few. Additionally, the materials that can be used to manufacture the master **10** are not particularly limited and can include glasses, ceramics, polymers, metals, etc.

As a negative master, the master **10** can form a surface **12'** of the optical product **10'** that is complementary to the surface **12** of the master **10**. For example, as shown in FIG. 1A, the features $F_1, F_2, \dots, F_n$ on the surface **12** of the master **10** can be the inverse of the elements $E_1, E_2, \dots, E_n$ on the surface **12'** of the optical product **10'**. In such embodiments, the master **10** can be used to form the optical product **10'**. For example, the master **10** can be used to emboss the elements $E_1, E_2, \dots, E_n$ onto a metal sheet, a polymeric substrate such as a thermoformable polymer, or a UV curable photoresist layer such as a UV curable resin, or to injection mold the elements $E_1, E_2, \dots, E_n$ onto a polymer.

As another example, as a positive master, the master **10** can provide a surface **12'** for the optical product **10'** that is substantially similar to the surface **12** of the master **10**. The features $F_1, F_2, \dots, F_n$ on the surface **12** of the master **10** can be substantially similar to the elements $E_1, E_2, \dots, E_n$ on the surface **12'** of the optical product **10'**. In some such embodiments, the positive master **10** can provide a model for the optical product **10'**. In other such embodiments, the positive master **10** can be used to create an inverse image of the 3D object **50**. In addition, the positive master **10** can be used to fabricate one or more negative masters.

Although the master **10** is shown producing a product directly, in certain embodiments the master **10** is employed to produce one or more other masters (e.g., daughter shims) or intermediate surfaces that can in turn be used to produce a product. For example a first negative master can be used to produce a second master that is a positive master. The second positive master can be used to make a third negative

master. The third negative master can be used to produce a fourth positive master. The fourth positive master can be used to produce a product. Accordingly, a tooling tree of masters (e.g., four, five, six, etc. generations deep) can be produced.

Certain embodiments of the optical product **10'** disclosed herein can be advantageously manufactured on a large industrial scale. Some embodiments can be manufactured by embossing the elements $E_1, E_2, \dots, E_n$ into an UltraViolet (UV) curable resin coated onto various polymeric substrates, such as, for example, polyethylene terephthalate (PET), oriented polypropylene (OPP), low density polyethylene (LDPE), linear low density polyethylene (LLDPE), polypropylene (PP), polyvinyl chloride (PVC) polycarbonate (PC) or any other type of plastic film or carrier. For thermoformable plastics such as PVC and PC, the elements $E_1, E_2, \dots, E_n$ can be embossed directly into the substrate without the UV curable layer. In various embodiments, the polymeric substrate can be clear. The polymeric substrates can have a thickness less than or equal to 30 microns, less than or equal to 25 microns, or less than or equal to 15 microns. Some such polymeric substrates having elements $E_1, E_2, \dots, E_n$ can be formed into security threads that can be incorporated into a banknote having a paper thickness of 100 microns.

With continued reference to FIG. 1A, the master **10** can include a first surface **11** and a second surface **12**. The first surface **11** is shown for simplicity as a planar surface. However, the shape of the first surface **11** is not particularly limited. The second surface **12** can be opposite the first surface **11**. The second surface **12** can include a plurality of portions $P_1, P_2, \dots, P_n$. In some embodiments, the plurality of portions $P_1, P_2, \dots, P_n$ can form a single cell (e.g., a mono-cell). In other embodiments, the plurality of portions $P_1, P_2, \dots, P_n$ can form a plurality of cells. For example, each of the plurality of portions $P_1, P_2, \dots, P_n$ can form a cell of the plurality of cells. The number of cells is not particularly limited and can depend on factors such as size and resolution of the image to be reproduced. In various embodiments, the portions $P_1, P_2, \dots, P_n$ can form a pixelated surface. For simplicity, only one row of portions $P_1, P_2, \dots, P_n$ is shown in FIG. 1A. However, certain embodiments can include additional rows and columns of portions $P_1, P_2, \dots, P_n$. For example, as shown in FIG. 1B, the portions $P_1, P_2, \dots, P_n$ can include a plurality of rows and columns spanning across the surface **12** of the master **10**. For simplicity, only the first row is labeled as $P_1, P_2, \dots, P_n$. Furthermore, although FIG. 1B shows a 4x4 array of portions $P_1, P_2, \dots, P_n$, the numbers of rows, columns, and portions $P_1, P_2, \dots, P_n$ are not particularly limited.

As also shown in FIG. 1B, in some embodiments, borders **13** can surround at least part of the portions $P_1, P_2, \dots, P_n$. The borders **13** can substantially surround a portion P_n , or can surround just part of a portion P_n . In some embodiments, discontinuities can extend around all or substantially all of the portion P_n . In other embodiments, discontinuities may extend on just a part of the portion P_n . The borders **13** can help define the size and shape of the portions $P_1, P_2, \dots, P_n$ in some embodiments. However, the size and shape of the portions $P_1, P_2, \dots, P_n$ are not particularly limited. For example, some of the portions $P_1, P_2, \dots, P_n$ can comprise a symmetrical shape. For example, the symmetrical shape can include a rectangle, a square, a rhombus, an equilateral triangle, an isosceles triangle, a regular polygon (e.g., a regular pentagon, a regular hexagon, a regular octagon, etc.), to name a few. The symmetrical shape can also include curvature, e.g., a circle, an ellipse, etc. In other embodi-

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ments, some of the portions $P_1, P_2, \dots, P_n$ can comprise a non-symmetrical shape, e.g., a non-rotationally symmetrical shape, and/or an irregular shape. In some embodiments, some of the portions $P_1, P_2, \dots, P_n$ can have a shape that is substantially the same as other portions $P_1, P_2, \dots, P_n$. In some embodiments, at least 20%, at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90% (or any range in between these percentages) of the portions $P_1, P_2, \dots, P_n$ can have the same shape, size, or both. In other embodiments, some of the portions $P_1, P_2, \dots, P_n$ can have a shape that is different from other portions $P_1, P_2, \dots, P_n$.

Arrangement of the portions $P_1, P_2, \dots, P_n$ is not particularly limited. For example, whether with or without borders, whether symmetrically shaped or non-symmetrically shaped, or whether regularly or irregularly shaped, the portions $P_1, P_2, \dots, P_n$ can form a periodic array. In other embodiments, whether with or without borders, whether symmetrically shaped or non-symmetrically shaped, or whether regularly or irregularly shaped, the portions $P_1, P_2, \dots, P_n$ can form an aperiodic array. In yet other embodiments, the portions $P_1, P_2, \dots, P_n$ can form a combination of periodic and aperiodic arrays.

With continued reference to FIG. 1A, each portion P_n can correspond to a point $S_1, S_2, \dots, S_n$ on the surface S of the 3D object **50**, and each portion P_n can include one or more features $F_1, F_2, \dots, F_n$. For simplicity, the features $F_1, F_2, \dots, F_n$ shown in FIG. 1A appear linear and substantially similar to each other. However, the features $F_1, F_2, \dots, F_n$ can vary in number, size, shape, and orientation.

In certain embodiments, the features $F_1, F_2, \dots, F_n$ can include linear and/or curved features, for example as seen from a top or front view. In some embodiments, the features $F_1, F_2, \dots, F_n$ can include facets, such as linear or curved saw tooth shaped features. The size of the features $F_1, F_2, \dots, F_n$ are not particularly limited. However, from a manufacturing and economic perspective, in some embodiments, a smaller height (e.g., 0 μm to 10 μm) can be advantageous to reduce the amount of material used. Accordingly, in some embodiments, the heights of the features $F_1, F_2, \dots, F_n$ can be from close to 0 μm to 0.1 μm (e.g., 0 nm to 100 nm, 1 nm to 75 nm, or 1 nm to 50 nm), from close to 0 μm to 1 μm (e.g., 0 nm to 1000 nm, or 1 nm to 500 nm), from close to 0 μm to 5 μm (e.g., 1 nm to 5 μm , 10 nm to 5 μm , 50 nm to 5 μm , 75 nm to 5 μm , 0.1 μm to 5 μm , 0.5 μm to 5 μm , or 1 μm to 5 μm), or from close to 0 μm to 8 μm (e.g., 1 nm to 8 μm , 10 nm to 8 μm , 50 nm to 8 μm , 75 nm to 8 μm , 0.1 μm to 8 μm , 0.5 μm to 8 μm , or 1 μm to 8 μm), or from close to 0 μm to 10 μm (e.g., 1 nm to 10 μm , 10 nm to 10 μm , 50 nm to 10 μm , 75 nm to 10 μm , 0.1 μm to 10 μm , 0.5 μm to 10 μm , or 1 μm to 10 μm). In other embodiments, the heights of the features $F_1, F_2, \dots, F_n$ can go up to 15 μm , up to 20 μm , up to 25 μm , or any ranges from 1 μm , 2 μm , or 3 μm up to 25 μm . In yet other embodiments, the heights of the features $F_1, F_2, \dots, F_n$ can go up to 50 μm if needed, e.g., depending on the desired size of the 3D image to be reproduced.

Furthermore, in some embodiments, the lateral dimensions of the features $F_1, F_2, \dots, F_n$ are not particularly limited, but can depend on the details of the 3D object. For example, for text, the lateral dimensions of the features $F_1, F_2, \dots, F_n$ can be less than 1 μm . Accordingly, the lateral dimensions of the features $F_1, F_2, \dots, F_n$ can be from close to 0 μm to 0.1 μm (e.g., 0 nm to 100 nm, 1 nm to 75 nm, or 1 nm to 50 nm), from close to 0 μm to 1 μm (e.g., 0 nm to 1000 nm, or 1 nm to 500 nm), from close to 0 μm to 5 μm

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(e.g., 1 nm to 5 μm , 10 nm to 5 μm , 50 nm to 5 μm , 75 nm to 5 μm , 0.1 μm to 5 μm , 0.5 μm to 5 μm , or 1 μm to 5 μm), or from close to 0 μm to 8 μm (e.g., 1 nm to 8 μm , 10 nm to 8 μm , 50 nm to 8 μm , 75 nm to 8 μm , 0.1 μm to 8 μm , 0.5 μm to 8 μm , or 1 μm to 8 μm), or from close to 0 μm to 10 μm (e.g., 1 nm to 10 μm , 10 nm to 10 μm , 50 nm to 10 μm , 75 nm to 10 μm , 0.1 μm to 10 μm , 0.5 μm to 10 μm , or 1 μm to 10 μm).

In various embodiments, a lateral distance between two features can be defined in some embodiments as a pitch. In some embodiments, the pitch between features within a portion P_n can be substantially the same within the portion P_n . For example, in various embodiments, in portion P_1 of the portions $P_1, P_2, \dots, P_n$, the feature F_1 can comprise a plurality of features that form a periodic array such that the pitch is substantially the same within portion P_1 . In addition, in some embodiments, the features $F_1, F_2, \dots, F_n$ among the multiple portions $P_1, P_2, \dots, P_n$ can form a periodic array such that the pitch is substantially the same among the portions $P_1, P_2, \dots, P_n$. In other embodiments, the features could be chirped and form an aperiodic array such that the pitch may be different among multiple portions $P_1, P_2, \dots, P_n$. However, although the pitch may be different for different portions $P_1, P_2, \dots, P_n$, the pitch can be slowly varying (e.g., less than 15% change per lateral distance, less than 12% change per lateral distance, less than 10% change per lateral distance, less than 8% change per lateral distance, less than 5% change per lateral distance, less than 3% change per lateral distance, or less than 1% change per lateral distance) among the portions $P_1, P_2, \dots, P_n$. In some embodiments, the pitch may uniformly change across multiple portions $P_1, P_2, \dots, P_n$. In other embodiments, the features could be chirped within a portion P_n such that the pitch may be different within the portion P_n . In some such embodiments, the pitch within the portion P_n may slowly vary (e.g., less than 15% change per lateral distance, less than 12% change per lateral distance, less than 10% change per lateral distance, less than 8% change per lateral distance, less than 5% change per lateral distance, less than 3% change per lateral distance, or less than 1% change per lateral distance). In some embodiments, the pitch may uniformly change with the portion P_n . The pitch in certain embodiments can be between 1 μm and 100 μm , between 1 μm and 75 μm , between 1 μm and 50 μm , or between 1 μm and 25 μm .

With continued reference to FIG. 1A, the features $F_1, F_2, \dots, F_n$ can correspond to elements $E_1, E_2, \dots, E_n$ on the optical product **10'**, and since the optical product **10'** is configured to reproduce the 3D object **50**, aspects of the features $F_1, F_2, \dots, F_n$ can correlate to aspects of the surface S of the 3D object **50** at the corresponding point $S_1, S_2, \dots, S_n$. For example, a gradient (e.g., slope) in the features $F_1, F_2, \dots, F_n$ can correlate to an inclination of the surface S of the 3D object **50** at the corresponding point $S_1, S_2, \dots, S_n$. For example, in various embodiments, each feature can include a slope. A slope of the feature F_1 can correlate to the inclination of the surface S of the 3D object **50** at the corresponding point S_1 . As shown in FIG. 1C, the slope of the feature F_1 can correlate to the polar angle θ_1 from reference line R_1 of the 3D object **50**. Accordingly, the slopes of the features $F_1, F_2, \dots, F_n$ can mimic the surface normals of the 3D object **50**.

Various embodiments can advantageously have a uniform gradient (e.g., uniform slope) within each portion P_n such that the gradient is a single value (e.g., a single polar angle θ_n) at the corresponding point S_n on the surface S of the 3D object **50**. In other embodiments, the feature F_n within a portion P_n includes a plurality of features, and the features

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within the portion P_n may have more than one gradient (e.g., different slopes). In such embodiments, the average gradient (e.g., average slope) of the features within the portion P_n can correlate to the inclination of the surface S of the 3D object **50** at the corresponding point S_n .

In some embodiments, varying the slopes within and/or among portions $P_1, P_2, \dots, P_n$ can create contrast on the surface and therefore, on the image **50'**. Furthermore, varying at least one of the height of features, pitch between features (e.g., lateral distance between two features), and slope of the features in one or more portions $P_1, P_2, \dots, P_n$ can be used in authenticity and security applications. For example, one can intentionally vary the pitch within one or more portions P_n , but maintain the given slopes. The image **50'** of the 3D object **50** would be reproduced, yet upon closer inspection of the presence of the intentional variation within one or more portions $P_1, P_2, \dots, P_n$, authenticity can be verified. Other variations are possible.

In various embodiments, the orientation of features $F_1, F_2, \dots, F_n$ can correlate to an orientation of the surface S of the 3D object **50** at the corresponding point $S_1, S_2, \dots, S_n$. For example, an orientation of the feature F_1 can correlate to the orientation of the surface S of the 3D object **50** at the corresponding point S_1 . As shown in FIG. 1C, the orientation of the feature F_1 can correlate to the azimuth angle φ_1 from reference line R_2 of the 3D object **50**. Various embodiments can advantageously have a uniform orientation within each portion P_n , such that the orientation is a single value (e.g., a single azimuth angle (P_n)) at the corresponding point S_n on the surface S of the 3D object **50**. In other embodiments, the feature F_n within a portion P_n includes a plurality of features, and the features within the portion P_n may have more than one orientation (e.g., different orientations). In such embodiments, the average orientation of the features within the portion P_n can correlate to the orientation of the surface S of the 3D object **50** at the corresponding point S_n . Furthermore, the orientation of the features within and among the portions $P_1, P_2, \dots, P_n$ can slowly vary (e.g., less than 15% change per lateral distance, less than 12% change per lateral distance, less than 10% change per lateral distance, less than 8% change per lateral distance, less than 5% change per lateral distance, less than 3% change per lateral distance, or less than 1% change per lateral distance) within and among the portions $P_1, P_2, \dots, P_n$.

In some embodiments, where a feature F_1 includes multiple features within a portion, the features can appear discontinuous with other features within the portion. In some embodiments where the surface **12** of the master **10** is pixelated (e.g., having a plurality of cells), the features $F_1, F_2, \dots, F_n$ can appear discontinuous with features in surrounding adjacent portions. In other embodiments, the portions $P_1, P_2, \dots, P_n$ can form a single cell or a mono-cell. In some such embodiments, the features $F_1, F_2, \dots, F_n$ can appear continuous and smoothly varying depending on the shape. In other such embodiments, the features $F_1, F_2, \dots, F_n$ can appear discontinuous due to discontinuities in the 3D object **50**.

In some embodiments, the features $F_1, F_2, \dots, F_n$ can comprise linear features corresponding to a substantially smooth region of the surface S of the 3D object **50**. The features $F_1, F_2, \dots, F_n$ can also comprise non-linear features, e.g., curved features as seen from a top or front view, corresponding to a curved region of the surface S of the 3D object **50**, e.g., instead of flat facets. In some embodiments, features $F_1, F_2, \dots, F_n$ that are linear can be used to correspond to a curved region of the surface S of the 3D object **50**. In some such embodiments, linear features on a

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master **10** can be used to represent a curved region by using a piecewise approximation function (e.g., a piecewise linear function such as a function comprising straight line sections). In some other embodiments, features $F_1, F_2, \dots, F_n$ that are non-linear can be used to correspond to a substantially smooth region of the surface S of the 3D object **50**. In some such embodiments, non-linear features on a master **10** can be used to represent smooth regions on the surface S of the 3D object because the features $F_1, F_2, \dots, F_n$ can correspond to relatively small sized features on the optical product **10'**. For example, the pitch and/or texture on the optical product **10'** can be between 1 μm and 100 μm , between about 1 μm and about 75 μm , between about 1 μm and about 50 μm , or between about 1 μm and about 25 μm .

With continued reference to FIG. 1A, as described herein, the features $F_1, F_2, \dots, F_n$ can correspond to aspects of the surface S of the 3D object **50** and can also correspond to elements $E_1, E_2, \dots, E_n$ on the optical product **10'** such that the optical product **10'** can reproduce an image **50'** of the 3D object **50**. In various embodiments, the elements $E_1, E_2, \dots, E_n$ on the optical product **10'** can be non-holographic. For example, the elements $E_1, E_2, \dots, E_n$ do not need to rely on holography (e.g., effects based on diffraction and/or based on optical interference) to render a 3D image **50'** of the 3D object **50**. In some such embodiments, the features $F_1, F_2, \dots, F_n$ on the surface **12** of the master **10** can include non-sinusoidal features or non-quasi-sinusoidal features. In general, sinusoidal or quasi-sinusoidal features can be diffractive with $\pm$ orders of equal intensity that generate a twin image. One positive order and one negative order can share the incident light and result in a simultaneous twin image with counter-intuitive movement of one image with respect to the other. Such effects may be non-ideal. In some embodiments that include non-sinusoidal or non-quasi-sinusoidal features, the features $F_1, F_2, \dots, F_n$ on the surface **12** of the master **10** can include other shapes, such as saw toothed shapes as described herein.

Although various embodiments described herein do not necessarily rely on holography to reproduce an image, some embodiments can include diffractive or holographic features (e.g., less than about 50% of the surface area, less than about 40% of the surface area, less than about 30% of the surface area, less than about 20% of the surface area, less than about 10% of the surface area, less than about 5% of the surface area, less than about 3% of the surface area, less than about 2% of the surface area, or less than about 1% of the surface area) to be used in conjunction with the non-holographic elements $E_1, E_2, \dots, E_n$ described herein. For example, in some embodiments, the second surface **12** of the master **10** can further comprise features corresponding to holographic elements on the optical product **10'** in one or more portions $P_1, P_2, \dots, P_n$. In other embodiments, a holographic layer can be added over or under the surface **12'** of the optical product **10'**.

FIG. 1D is another example optical product **10'** in accordance with certain embodiments described herein. As shown in FIG. 1D, the optical product **10'** can include a plurality of portions $P'_1, P'_2, \dots, P'_n$. Each portion P'_n can include elements $E_1, E_2, \dots, E_n$, e.g., non-holographic elements, on the optical product **10'**. In some such embodiments, the elements $E_1, E_2, \dots, E_n$ can be embossed on the bottom surface of the substrate, e.g. UV curable resin having a refractive index of 1.5. The elements $E_1, E_2, \dots, E_n$ can be coated with a reflective coating. The elements $E_1, E_2, \dots, E_n$ may then be embedded between the substrate and the item to which the optical product **10'** is attached. As described herein, the slopes of the elements $E_1, E_2, \dots, E_n$ can be

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configured to create the 3D depth perception of the image. For example, elements $E_1, E_2, \dots E_n$ with less steep slopes can cause light to reflect toward the observer's eye creating more brightness, while elements $E_1, E_2, \dots E_n$ with steeper slopes can cause light to reflect away from the observer's eye creating more darkness. In this example of an embedded optical product **10'**, elements $E_1, E_2, \dots E_n$ with steep enough slopes can cause light to be totally internally reflected within the substrate (which has a higher index than the surrounding medium), and creating even more darkness.

FIG. 1E is another example optical product **10'** in accordance with certain embodiments described herein. As shown in FIG. 1E, the optical product **10'** can include a plurality of portions $P'_1, P'_2, \dots P'_n$. Each portion P'_n can include elements $E_1, E_2, \dots E_n$, e.g., non-holographic elements, on the optical product **10'**. As described herein, utilizing embodiments of the optical product **10'** having elements $E_1, E_2, \dots E_n$ (or masters having features $F_1, F_2, \dots F_n$) with smaller height can be advantageous to reduce the amount of material used. However in cases where height is less important, certain embodiments can utilize elements $E_1, E_2, \dots E_n$ with slowly varying surfaces (e.g., slopes) creating a substantially contiguous surface from one portion P'_n to another. In various embodiments, the number of substantially contiguous portions can include at least two, three, four, five, eight, ten, fifteen, twenty, or more, or be in any range in between these values.

Various methods can be used to manufacture the master **10** for fabricating an optical product **10'**. An example method **100** is shown in FIG. 2. As shown in operational block **110**, the method **100** can include providing a data file, e.g., a 2D data file, configured to describe, characterize, and/or record features the 3D object and/or 3D image **50'**. The data file can provide the pattern of the features $F_1, F_2, \dots F_n$ on the surface **12** of the master **10**.

For example, the data file can comprise a plurality of portions (as will be described further herein). Each portion can correspond to one or more points on a surface **S** of the 3D object **50**. Each portion can comprise features of intensity corresponding to non-holographic elements on the optical product **10'**. A gradient in intensity can correlate to an inclination of the surface **S** of the 3D object **50** at the one or more corresponding points. In addition, an orientation of the features can correlate to an orientation of the surface **S** of the 3D object **50** at the one or more corresponding points. As shown in operational block **120**, the method **100** can further include manufacturing the master **10** based at least in part on the 2D data file.

As described herein, certain embodiments of the optical product **10'** can produce a bright, mirror-like image. In some implementations, a matte finish may be desired. FIG. 2A illustrates an example method that can be used to manufacture a surface relief diffuser and also to determine a height displacement file used to manufacture the diffuser. In the method **200** shown in FIG. 2A, an input image **210** of the 3D object **50** (e.g., a 2D photograph of the 3D object) is entered into the recording loop **220** of the main program **225** of the processor **230**. Other information, such as user parameters **211** (e.g., angle, scale, zoom, etc.), exposure compensation curve **212**, intensity compensation mask **213**, and apodizing mask **214** can also be entered into the recording loop **220**. The processor **230** can produce a height displacement file **240** that is configured to describe the intensities of the 3D object **50**. This height displacement file **240** can be used as a map to generate the pattern of the diffuser. In some examples of the height displacement file **240**, the intensities of the 3D object can be correlated to a depth for the diffuser.

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For example, the black sections of the 3D object **50** can correlate to the surface of the diffuser, white sections of the 3D object **50** can correlate to a lower depth (e.g., down 10 μm), and grey sections of the 3D object **50** can correlate to some depth in between. Other variations are possible.

In the example method **200** shown in FIG. 2A, a digital micromirror device (DMD) video projector **250** can be used along with the photoresist recording plate **260**, each receiving the inputted information from the recording loop **220**. The DMD video projector **250** includes a DMD chip that includes a plurality of micromirrors that in certain embodiments can correspond to the pixels of the height displacement file **240**. The pixels of the height displacement file **240** can also correspond to the regions on the X-Y stage of the photoresist recording plate **260** in some embodiments. Each micromirror of the DMD chip can be used as a spatial light modulator that, for example, reflects light from a light source in the video projector **250** in the on-state, and that does not reflect light in the off-state. Varying the amount of light intensity can be produced by varying the time the micromirror is in the on- and off-states (e.g., pulse width modulation, etc.). As shown in FIG. 2A, demagnification optics **255** can be used to produce the pattern of the diffuser in a light sensitive material, e.g., a photoresist, on the resist recording plate **260**. In some embodiments, the resist can be used as the diffuser. As disclosed herein, other techniques, such as electron beam lithography on electron sensitive material and ion beam lithography on ion sensitive material can also be used. Certain embodiments of the diffuser can be used with certain embodiments of the optical product **10'** to produce a diffuse or hazy layer over the reflected image **50'** to produce an image with a matte finish.

FIG. 2B illustrates an example method that can be used to manufacture the master **10** and also to determine the data file to be used to manufacture the master **10**, e.g., to determine the pattern of the features $F_1, F_2, \dots F_n$ on the surface **12** of the master **10**. Certain such embodiments can be advantageous as a 3D physical object and/or a 3D model utilizing physical dimensions of the 3D object (e.g., topographical calculations) are not required. For example, in the method **300** shown in FIG. 2B, the input image **305** can be a 2D input image (e.g., a 2D photograph of the 3D object) or 2D image converted from a 3D image. In some embodiments, the input image **305** can be converted into a 2D interpolated image **308** and produced as a 2D converted image **310**. The 2D image of the 3D object can be translated into a gray scale image (e.g., a normal map **315** wherein black, white, and gray regions correlate to different heights of the 3D object). In the method **300** shown in FIG. 2B, the converted image **310** (or a normal map **315**) is entered into the recording loop **320** of the main program **325** of the processor **330** in accordance with certain embodiments described herein. Similar to the method **200** in FIG. 2A, other information, such as user parameters **311** (e.g., angle, scale, zoom, etc.), exposure compensation curve **312**, intensity compensation mask **313**, and apodizing mask **314** can also be entered into the recording loop **320**. The processor **330** can produce a data file **340**, e.g., a 2D data file, that is configured to describe the 3D image **50'** of at least a part of the 3D object **50**. In some embodiments, the intensities in the data file **340** can be assigned based on gray scale. For example, the data file **340** can comprise a plurality of portions. Each portion can correspond to one or more points on a surface **S** of the 3D object **50**. Each portion can comprise features of intensity corresponding to non-holographic elements on the optical product **10'**. A gradient in intensity can correlate to a gradient or an inclination of the surface **S** of the 3D object

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50 at the one or more corresponding points. In addition, an orientation of the features can correlate to an orientation of the surface **S** of the 3D object **50** at the one or more corresponding points. This data file **340** can be used as a map to generate the pattern of features $F_1, F_2, \dots, F_n$ on the surface **12** of the master **10**. An example data file is discussed with respect to FIG. **3A**.

Similar to method **200** in FIG. **2A**, a digital micromirror device (DMD) video projector **350** can be used along with the photoresist recording plate **360**, each receiving the inputted information from the recording loop **320**. The plurality of micromirrors in the DMD video projector **350** in certain embodiments can correspond to the pixels of the data file **240**. The pixels of the data file **340** can also correspond to one or more portions $P_1, P_2, \dots, P_n$ of the surface **12** of the master **10** in some embodiments. As shown in FIG. **2B**, the demagnification optics **355** can be used to produce the pattern of features $F_1, F_2, \dots, F_n$ in a light sensitive material, e.g., a photoresist, on the resist recording plate **360**. In some embodiments, the resist can be used as the surface **12** of the master **10**. As disclosed herein, other techniques, such as electron beam lithography on electron sensitive material and ion beam lithography on ion sensitive material can also be used.

In some embodiments, the method **300** can further include adding on the master **10** features corresponding to holographic elements on the optical product **10'**. For example, an optical recording (e.g., a planar optical recording) for the holographic elements can be superimposed onto the master **10** to add the holographic elements on the master **10**. As another example, in some embodiments, the data file **340** can include features corresponding to holographic elements on the optical product **10'**. In other embodiments, a separate data file comprising the features of intensity corresponding to holographic elements on the optical product **10'** can be provided. Manufacturing the master **10** can be based at least in part on the data file **340** including features corresponding to non-holographic elements and on the data file including features corresponding to holographic elements on. In some such embodiments, the data file **340** including the features corresponding to non-holographic elements and the data file including the features corresponding to holographic elements can be used sequentially or simultaneously to manufacture the master **10**. In some other embodiments, a needle, such as from an atomic force microscope, can be used to produce the features corresponding to the holographic elements on the optical product **10'**. Other methods can be employed to add holographic features or elements.

FIG. **2C** illustrates yet another example method that can be used to determine the pattern of the features $F_1, F_2, \dots, F_n$ on the surface **12** of the master **10**. The method **400** shown in FIG. **2C** is similar to the method **300** shown in FIG. **2B** except that a normal map **415** can be provided instead of the input image **310**. The normal map **415** can be inputted into the main program **425** of the processor **430** to produce the data file **440**.

FIG. **3A** illustrates an example 2D data file **540** in accordance with certain embodiments disclosed herein. The data file **540** can include a plurality of portions $p_1, p_2, \dots, p_n$. In some embodiments, the plurality of portions $p_1, p_2, \dots, p_n$ can form a single cell (e.g., a mono-cell). In other embodiments, as shown in FIG. **3A**, the plurality of portions $p_1, p_2, \dots, p_n$ can form a plurality of cells. In various embodiments, the portions $p_1, p_2, \dots, p_n$ can form a pixelated surface corresponding to the portions $P_1, P_2, \dots, P_n$ of the

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surface **12** of the master **10**. For example, as shown in FIG. **3A**, the portions $p_1, p_2, \dots, p_n$ can include a plurality of rows and columns.

As also shown in FIG. **3A**, in some embodiments, borders **13'** can surround at least part of the portions $p_1, p_2, \dots, p_n$. The borders **13'** can substantially surround a portion p_n or can surround just part of a portion p_n . As with the master **10**, the size and shape of the portions $p_1, p_2, \dots, p_n$ on the data file **540** are not particularly limited. Some of the portions $p_1, p_2, \dots, p_n$ can comprise a symmetrical shape. For example, the symmetrical shape can include a rectangle, a square, a rhombus, an equilateral triangle, an isosceles triangle, a regular polygon (e.g., a regular pentagon, a regular hexagon, a regular octagon), etc. The shape can also include curvature, e.g., a circle, an ellipse, etc. In other embodiments, some of the portions $p_1, p_2, \dots, p_n$ can comprise a non-symmetrical shape, e.g., a non-rotationally symmetrical shape, and/or an irregular shape. For example, FIG. **3B** illustrates an example embodiment of a data file **545** with irregularly shaped portions $p_1, p_2, \dots, p_n$. In some embodiments, some of the portions $p_1, p_2, \dots, p_n$ can have a shape that is substantially the same as other portions $p_1, p_2, \dots, p_n$. In other embodiments, e.g., as shown in FIG. **3B**, some of the portions $p_1, p_2, \dots, p_n$ can have a shape that is different from other portions $p_1, p_2, \dots, p_n$.

As with the master **10**, the arrangement of the portions $p_1, p_2, \dots, p_n$ in the data file **540** is not particularly limited. For example, whether with or without borders, whether symmetrically shaped or non-symmetrically shaped, or whether regularly or irregularly shaped, the portions $p_1, p_2, \dots, p_n$ can form a periodic array. For example, in FIG. **3A**, the portions $p_1, p_2, \dots, p_n$ form a periodic array. In other embodiments, whether with or without borders, whether symmetrically shaped or non-symmetrically shaped, or whether regularly or irregularly shaped, the portions $p_1, p_2, \dots, p_n$ can form an aperiodic array. For example, in FIG. **3B**, the portions $p_1, p_2, \dots, p_n$ form an aperiodic array. In yet other embodiments, the portions $p_1, p_2, \dots, p_n$ can form a combination of periodic and aperiodic arrays.

With continued reference to FIG. **3A**, each portion p_n can include features $f_1, f_2, \dots, f_n$ that correspond to features $F_1, F_2, \dots, F_n$ on the surface **12** of the master **10**. Portion p_a has a single feature f_1 , while portion p_b has multiple features f_n . The features $f_1, f_2, \dots, f_n$ of the data file **540** can include features of intensity (varying dark and light lines). In some embodiments, the intensity can correlate to the height of a feature on the surface **S** of the 3D object **50**.

In various embodiments, a lateral distance between two features can be defined in some embodiments as a pitch. In some embodiments, the pitch between features within a portion p_n can be substantially the same within the portion p_n . For example, in various embodiments, in portion p_1 of the portions $p_1, p_2, \dots, p_n$, the feature f_1 can comprise a plurality of features that form a periodic array such that the pitch is substantially the same within portion p_1 . In addition, in some embodiments, the features $f_1, f_2, \dots, f_n$ among multiple portions $p_1, p_2, \dots, p_n$ can form a periodic array such that the pitch is substantially the same among multiple portions $p_1, p_2, \dots, p_n$.

In other embodiments, the features can form an aperiodic array such that the pitch may be different among multiple portions $p_1, p_2, \dots, p_n$. However, although the pitch may be different for different portions $p_1, p_2, \dots, p_n$, in some embodiments, the pitch can be slowly varying (e.g., less than 15% change per lateral distance, less than 12% change per lateral distance, less than 10% change per lateral distance, less than 8% change per lateral distance, less than 5%

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change per lateral distance, less than 3% change per lateral distance, or less than 1% change per lateral distance) among the portions $p_1, p_2, \dots, p_n$. In some embodiments, the pitch may uniformly change across multiple portions $p_1, p_2, \dots, p_n$.

In other embodiments, the features could be chirped within a portion p_n such that the pitch may be different within the portion p_n . In some such embodiments, the pitch within the portion p_n may slowly vary (e.g., less than 15% change per lateral distance, less than 12% change per lateral distance, less than 10% change per lateral distance, less than 8% change per lateral distance, less than 5% change per lateral distance, less than 3% change per lateral distance, or less than 1% change per lateral distance).

FIG. 3A shows an example data file 540 with linear features where the pitch is substantially uniform within a portion p_n , and FIG. 3B shows an example data file 545 with curved features where the pitch is substantially uniform within a portion p_n . FIG. 3A is also an example of features having a pitch that slowly changes (e.g., less than 10% change per lateral distance) across multiple portions $p_1, p_2, \dots, p_n$.

In various embodiments, each feature of intensity can include a slope. Various embodiments can advantageously have a uniform gradient (e.g., uniform slope) within each portion p_n such that the gradient is a single value (e.g., a single polar angle θ_n) at the corresponding point S_n on the surface S of the 3D object 50. The gradient in the features $f_1, f_2, \dots, f_n$ can correlate to an inclination of the surface S of the 3D object 50 at the corresponding point $S_1, S_2, \dots, S_n$. In other embodiments, the feature f_n within a portion p_n includes a plurality of features, and the features within the portion p_n may have more than one gradient (e.g., different slopes). In such embodiments, the average gradient (e.g., average slope) of the features within the portion p_n can correlate to the inclination of the surface S of the 3D object 50 at the corresponding point S_n .

Various embodiments can also advantageously have a uniform orientation within each portion p_n such that the orientation is a single value (e.g., a single azimuth angle ϕ_n) at the corresponding point S_n on the surface S of the 3D object 50. In various embodiments, the orientation of features $f_1, f_2, \dots, f_n$ can correlate to an orientation of the surface S of the 3D object 50 at the corresponding point $S_1, S_2, \dots, S_n$. In other embodiments, the feature f_n within a portion p_n includes a plurality of features, and the features within the portion p_n may have more than one orientation (e.g., different orientations). In such embodiments, the average orientation of the features within the portion p_n can correlate to the orientation of the surface S of the 3D object 50 at the corresponding point S_n . Furthermore, the orientation of the features within and among the portions $p_1, p_2, \dots, p_n$ can slowly vary (e.g., less than 15% change per lateral distance, less than 12% change per lateral distance, less than 10% change per lateral distance, less than 8% change per lateral distance, less than 5% change per lateral distance, less than 3% change per lateral distance, or less than 1% change per lateral distance) within and among the portions $p_1, p_2, \dots, p_n$.

In some embodiments, where a feature f_1 includes multiple features within a portion, the features can appear discontinuous with other features within the portion. In some embodiments where the surface 12 of the master 10 is pixelated (e.g., having a plurality of cells), the features $f_1, f_2, \dots, f_n$ can appear discontinuous with features in surrounding adjacent portions. Based on pixel or cell size and/or tolerances in creating the data file 540, some embodi-

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ments may include random discontinuities with substantially no (relatively little if any) negative impact in image reproduction. Such discontinuity can reduce iridescence. In other embodiments, the portions $p_1, p_2, \dots, p_n$ can form a single cell or a mono-cell. In some such embodiments, the features $f_1, f_2, \dots, f_n$ can appear continuous and smoothly varying depending on the shape. In other such embodiments, the features $f_1, f_2, \dots, f_n$ can appear discontinuous due to discontinuities in the 3D object 50.

In some embodiments, as shown in FIG. 3C, the features $f_1, f_2, \dots, f_n$ can comprise linear features corresponding to a substantially smooth region of the surface S of the 3D object 50. The features $f_1, f_2, \dots, f_n$ can be used to produce linear features $F_1, F_2, \dots, F_n$ on the surface 12 of the master 10. The features $f_1, f_2, \dots, f_n$ can also be used to produce non-linear features $F_1, F_2, \dots, F_n$ on the surface 12 of the master 10. In some embodiments, features $f_1, f_2, \dots, f_n$ that are linear can be used to correspond to a curved region of the surface S of the 3D object 50. In some such embodiments, linear features $f_1, f_2, \dots, f_n$ in the data file can be used to represent a curved region by using a piecewise approximation function.

As shown in FIG. 3D, in some embodiments, although linear features $f_1, f_2, \dots, f_n$ in the data file can correspond to a substantially smooth region of the surface S of the 3D object 50, non-linear features on the master 10 (e.g., curved facets shown in left profile) can be used. As described herein, in some such embodiments, non-linear features on the master 10 can be used to produce elements $E_1, E_2, \dots, E_n$ on an optical product 10' that can appear smooth because the corresponding features on the optical product 10' can be relatively small (e.g., between 1 μm and 100 μm , between 1 μm and 75 μm , between 1 μm and 50 μm , or between 1 μm and 25 μm).

As the features $f_1, f_2, \dots, f_n$ of the data file 540 correspond to aspects of the surface S of the 3D object 50, the features $f_1, f_2, \dots, f_n$ of the data file 540 can be used to produce the features $F_1, F_2, \dots, F_n$ on the surface 12 of the master 10. As described herein, the features $F_1, F_2, \dots, F_n$ on the surface 12 of the master 10 can be used to fabricate the elements $E_1, E_2, \dots, E_n$ on the surface 12' of the optical product 10'. As described herein, in various embodiments, the elements $E_1, E_2, \dots, E_n$ on the optical product 10' can be non-holographic. For example, the elements $E_1, E_2, \dots, E_n$ do not need to rely on holography to render a 3D image 50' of the 3D object 50.

FIG. 4A is another example 2D data file 640 prepared in accordance with certain embodiments described herein. The data file 640 was generated by the normal map 650 shown in FIG. 4B. As an example, the lower left portion 645 of the data file 640 represents the center of the hemispherical object 655 in the lower left portion of the normal map 650. The data file 640 was used to generate the features $F_1, F_2, \dots, F_n$ on the surface 12 of a master 10, which was used to fabricate the elements $E_1, E_2, \dots, E_n$ on the surface 12' of an optical product 10'. The optical product 10' was configured, when illuminated, to reproduce by reflected light, the 3D image 650' shown in FIG. 4C.

In certain embodiments, an optical product 10' is also disclosed herein. As described herein, the optical product 10' can be configured, when illuminated, to reproduce by reflected light, a 3D image 50' of at least a part of a 3D object 50. As shown in FIG. 1A, similar to the master 10, the optical product 10' can include a surface 12' comprising a plurality of portions $P'_1, P'_2, \dots, P'_n$. Each portion P'_n can correspond to a point S_n on a surface S of the 3D object 50. Each portion P'_n can comprise features, e.g., non-holographic elements $E_1, E_2, \dots, E_n$. In certain embodiments, the non-holographic elements $E_1, E_2, \dots, E_n$ can be configured

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to produce at least part of the 3D image **50'** without relying on diffraction. In various embodiments, the portions $P'_1, P'_2, \dots, P'_n$ can form a single cell (e.g., a mono-cell). In other embodiments, the portions $P'_1, P'_2, \dots, P'_n$ can form a plurality of cells. Each portion P'_n can form a cell of the plurality of cells. The optical product **10'** can include borders surrounding at least part of the portions $P'_1, P'_2, \dots, P'_n$.

A gradient (e.g., uniform slope or average slope) in the non-holographic features $E_1, E_2, \dots, E_n$ can correlate to an inclination of the surface **S** of the 3D object **50** at the corresponding point $S_1, S_2, \dots, S_n$. In addition, the orientation (e.g., uniform orientation or average orientation) of the non-holographic features $E_1, E_2, \dots, E_n$ can correlate to an orientation of the surface **S** of the 3D object **50** at the corresponding point $S_1, S_2, \dots, S_n$.

Furthermore, since the master **10** can be used to fabricate an optical product **10'**, aspects disclosed herein with reference to the master **10** can apply to certain embodiments of the optical product **10'**. For example, disclosure with respect to the shapes (e.g., symmetrical, non-symmetrical, irregular, curved, etc.) and arrangements (e.g., periodic, aperiodic, etc.) of the portions $P_1, P_2, \dots, P_n$ for the master **10** can apply to the shapes and arrangements of the portions $P'_1, P'_2, \dots, P'_n$ of the optical product **10'**. As another example, disclosure with respect to the features $F_1, F_2, \dots, F_n$ (e.g., linear, curved, periodic, aperiodic, slowly varying, continuous, discontinuous, non-sinusoidal, etc.) for the master **10** can apply to the features $E_1, E_2, \dots, E_n$ of the optical product **10'**. Furthermore, as described herein with respect to the master and the method of manufacturing the master, the optical product **10'** of certain embodiments can further comprise features corresponding to holographic features.

In addition, small features can be imbedded in the optical product **10'** that do not contribute to the formation of the image. Such imbedded features can be used in authenticity and security applications. Furthermore, as described herein, certain embodiments can incorporate intentional variations within one or more portions $P'_1, P'_2, \dots, P'_n$ of the optical product **10'** for security applications.

The terms "about" and "substantially" as used herein represent an amount equal to or close to the stated amount (e.g., an amount that still performs a desired function or achieves a desired result). For example, unless otherwise stated, the terms "about" and "substantially" may refer to an amount that is within (e.g., above or below) 10% of, within (e.g., above or below) 5% of, within (e.g., above or below) 1% of, within (e.g., above or below) 0.1% of, or within (e.g., above or below) 0.01% of the stated amount.

Various embodiments of the present invention have been described herein. Although this invention has been described with reference to these specific embodiments, the descriptions are intended to be illustrative of the invention and are not intended to be limiting. Various modifications and applications may occur to those skilled in the art without departing from the true spirit and scope of the invention.

What is claimed is:

1. An optical product configured, when illuminated, to reproduce by reflected light, an image that appears 3D of at least a part of a 3D object, said optical product comprising:

a first surface; and

a second surface opposite said first surface, said second surface comprising a plurality of portions, each portion corresponding to a point on a surface of said 3D object, each portion comprising one or more non-holographic features configured to produce at least part of said image without relying on diffraction (1) at viewing angles through about 20 degrees to about 160 degrees

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relative to a plane of the optical product as the optical product is tilted and (2) at viewing angles through about 20 degrees to about 90 degrees relative to the plane of the optical product as the optical product is rotated at least throughout the range of about 90 degrees in the plane of the optical product, at least one of said one or more non-holographic features comprising a curved feature with a reflective coating such that the optical product, when illuminated, reproduces by reflected light, the image that appears 3D,

wherein for individual ones of the portions, a gradient in said non-holographic features correlates to a surface normal of said surface of said 3D object at said corresponding point,

wherein for individual ones of the portions, an orientation of said non-holographic features correlates to an orientation of said surface of said 3D object at said corresponding point, and

wherein the portions are configured to mix a plurality of colors together to form white light.

2. The optical product of claim 1, wherein the viewing angles are through about 15 degrees to about 165 degrees relative to the plane of the optical product as the optical product is tilted.

3. The optical product of claim 2, wherein the viewing angles are through about 10 degrees to about 170 degrees relative to the plane of the optical product as the optical product is tilted.

4. The optical product of claim 3, wherein the viewing angles are through about 5 degrees to about 175 degrees relative to the plane of the optical product as the optical product is tilted.

5. The optical product of claim 4, wherein the viewing angles are through about 0 degrees to about 180 degrees relative to the plane of the optical product as the optical product is tilted.

6. The optical product of claim 1, wherein the viewing angles are through about 15 degrees to about 90 degrees relative to the plane of the optical product as the optical product is rotated at least throughout the range of about 90 degrees in the plane of the optical product.

7. The optical product of claim 6, wherein the viewing angles are through about 10 degrees to about 90 degrees relative to the plane of the optical product as the optical product is rotated at least throughout the range of about 90 degrees in the plane of the optical product.

8. The optical product of claim 7, wherein the viewing angles are through about 5 degrees to about 90 degrees relative to the plane of the optical product as the optical product is rotated at least throughout the range of about 90 degrees in the plane of the optical product.

9. The optical product of claim 8, wherein the viewing angles are through about 0 degrees to about 90 degrees relative to the plane of the optical product as the optical product is rotated at least throughout the range of about 90 degrees in the plane of the optical product.

10. The optical product of claim 1, wherein said optical product is configured to provide authenticity verification on an item for security.

11. The optical product of claim 10, wherein said item is currency, a credit card, a debit card, a passport, a driver's license, an identification card, a document, a tamper evident container or packaging, or a bottle of pharmaceuticals.

12. The optical product of claim 10, wherein the optical product is an embedded feature, a laminated feature, a hot stamp feature, windowed thread feature, or a transparent window feature.

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13. The optical product of claim 1, wherein said 3D object comprises an irregularly shaped object.

14. The optical product of claim 1, wherein said 3D object comprises one or more alphanumeric characters.

15. The optical product of claim 1, wherein said non-holographic features comprise facets.

16. The optical product of claim 15, wherein said non-holographic features comprise linear or curved facets.

17. The optical product of claim 15, wherein said non-holographic features comprise saw tooth shaped features.

18. The optical product of claim 1, wherein said non-holographic features reproduce said image by specularly reflecting light.

19. The optical product of claim 1, wherein said non-holographic features with less steep slopes are configured to reflect light toward an observer's eye, and wherein said non-holographic features with steeper slopes are configured to reflect light away from the observer's eye.

20. The optical product of claim 1, wherein said image is not scaled up in size.

21. The optical product of claim 1, wherein said first surface opposite said second surface is planar.

22. The optical product of claim 1, wherein said optical product is a thin film.

23. The optical product of claim 1, wherein said second surface has a shape different from said 3D object.

24. The optical product of claim 1, wherein said portions form at least a 4×4 array of rows and columns.

25. The optical product of claim 1, wherein said portions comprise from 10 to 20 portions.

26. The optical product of claim 25, wherein a majority of said portions comprises non-holographic features with discontinuities.

27. The optical product of claim 1, wherein a majority of said portions comprises non-holographic features with discontinuities.

28. The optical product of claim 1, wherein said portions are defined by borders.

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29. The optical product of claim 28, wherein said portions are defined by linear borders.

30. The optical product of claim 1, wherein a majority of said portions comprise features discontinuous with features in surrounding adjacent portions.

31. The optical product of claim 1, wherein a majority of said features are discontinuous at linear boundaries between adjacent portions.

32. The optical product of claim 1, wherein said portions comprise non-holographic features with discontinuities corresponding to a continuous region of said 3D object.

33. The optical product of claim 1, wherein said one or more non-holographic features are configured to produce at least part of said image without relying on diffraction at viewing angles through about 20 degrees to about 90 degrees relative to the plane of the optical product as the optical product is rotated at least throughout the range of about 180 degrees in the plane of the optical product.

34. The optical product of claim 1, wherein said one or more non-holographic features are configured to produce at least part of said image without relying on diffraction at viewing angles through about 20 degrees to about 90 degrees relative to the plane of the optical product as the optical product is rotated at least throughout the range of about 270 degrees in the plane of the optical product.

35. The optical product of claim 1, wherein said one or more non-holographic features are configured to produce at least part of said image without relying on diffraction at viewing angles through about 20 degrees to about 90 degrees relative to the plane of the optical product as the optical product is rotated at least throughout the range of about 360 degrees in the plane of the optical product.

36. The optical product of claim 1, wherein said second surface further comprises holographic features.

37. The optical product of claim 1, wherein the portions have a length and width between 35 μm and 55 μm .

38. The optical product of claim 37, wherein the portions have a length and width between 40 μm and 50 μm .

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