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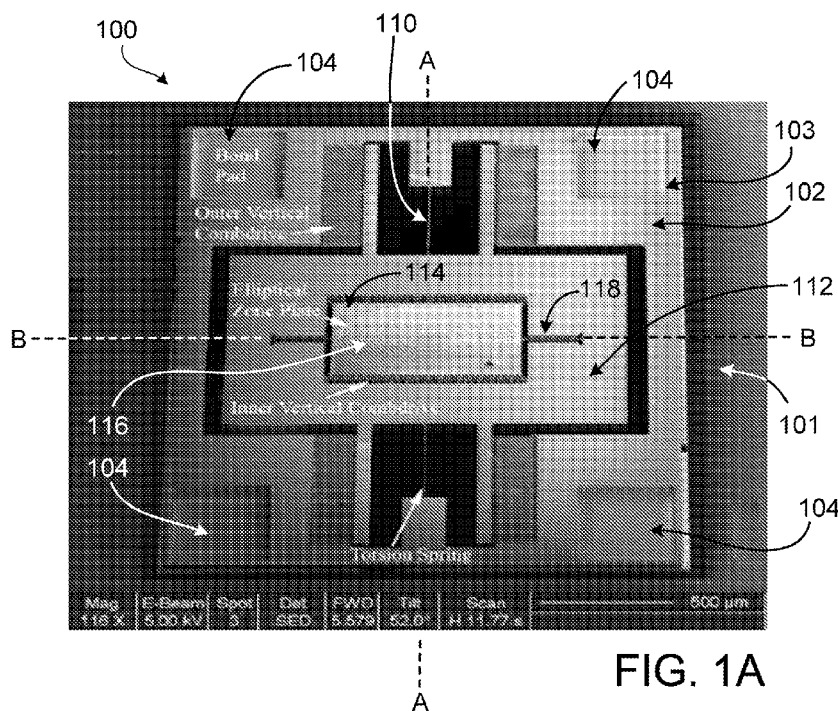


FIG. 1A

[Continued on next page]



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OPTICAL SCANNING DEVICES

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 61/052,527, filed May 12, 2008, which is incorporated by reference in its entirety as part of this application.

BACKGROUND

Optical imaging and optical communications are important tools in the medical and communication fields.

SUMMARY

Provided are optical scanning devices comprising a Fresnel Zone Plate Objective (FZPO). The scanning devices can be positioned in endoscopes for use in medical applications. The scanning devices can also be used in optical communications systems.

DESCRIPTION OF DRAWINGS

Figures 1A-C are scanning electron micrographs of an example scanning device.

Figures 2A-F are schematic illustrations showing a cross sectional view of an example fabrication process for the scanning device shown in Figure 1.

Figure 3 is a schematic diagram illustrating an example optical imaging system for use with the scanning device shown in Figure 1.

Figure 4 is a schematic diagram illustrating example design parameters for a scanning binary-phase reflective Elliptical Fresnel Zone Plate (EZP). θ is the off-axis illumination angle of wavelength λ , θ_s the micromirror scan angle, w and w_f are the incident and focused beam waists, and f is the focal length of the EZP with n zones.

Figures 5A and B are graphs showing micromirror operating characteristics. Figure 5(A) shows frequency response characteristics (Applied voltage= $20.0 + 20.0\sin(\omega t)$ V). Figure 5(B) shows static deflection characteristics on driving one comb bank on each axis.

Figure 6 is a map of diameter of the focused spot (in microns) created by an EZP with 8mm focal length for 635nm illumination at 45° nominal incidence as function of optical angular deflection of the micromirror.

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Figure 7 is schematic illustration of a transmission-mode imaging system.

Figures 8A-D are images of Mylar transparencies produced using the example system shown in Figure 7. Figures 8A and B show image calibration: (A) Image of number 100 (transparent) in opaque background, and (B) Image of sample using Olympus (Center Valley, PA) BX51 confocal microscope. Figures C and D show images of longhorn symbol and text “TEXAS” using the device (C), and using an Olympus (Center Valley, PA) BX51 confocal microscope. Scale Bar: 250µm.

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Figures 9A-C are images of a USAF1951 resolution target using a laser-scanning reflectance confocal device shown schematically in Figure 3. Images of groups of elements from different parts of the target are depicted in (A)-(B). Field of view is 1mm × 0.35mm, and resolution is ~15µm. (C) Image of the target using an Olympus (Center Valley, PA) BX51 confocal microscope.

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Figure 10 is a schematic illustration of a 1xN optical switch realized using two-axis scanning micromirror with a monolithically integrated Fresnel lens objective (FZPO).

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Figure 11 is a schematic illustration of a the Littrow configuration external cavity wavelength swept laser system.

DETAILED DESCRIPTION

Figure 1A is a scanning electron micrograph (SEM) of a example scanning device 100. The scanning device 100 comprises a peripheral support frame 101 having a plurality of silicon layers. A first silicon layer 102 has a upper surface visible in Figure 1A, and a bottom surface that overlies the top surface of a second silicon layer 104. At least a portion of the first silicon layer can be removed to expose portions of the second silicon layer 104. The

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underlying second silicon layer 104 can be electrically accessed thorough apertures 103 in the first silicon layer 102.

The first silicon layer 102 can be in electrical communication with portions of the scanning device 100, and can provide a grounding function for the device. Thus, the first
5 silicon layer 102 can function as a electrical ground layer of the device. Moreover, portions of the second silicon layer 104, including those that are exposed through apertures 103 in the first silicon layer, can receive electrical voltage from a voltage source in operative communication with the second silicon layer 104.

The scanning device 100, can further comprise a gimbal structure comprising a
10 peripheral portion 112 and a interior portion 114. Both portions have an upper surface visible in Figure 1A and an opposed bottom surface. The portions can be fabricated from silicon. The peripheral portion 112 and interior portion 114 together allow for two axis rotation for portions of the scanning device. The interior portion 114 is operatively attached to the peripheral portion 112 with an attachment link 118. For example, the attachment link can be
15 a torsion spring or rod that stores energy when the peripheral and interior portions are forcefully rotated relative to each other. Portions or all of the interior portion 114 can be reflective and serve as a mirror type surface.

The stored energy can be released to move the peripheral and interior portions towards a neutral position when the rotational force is removed or reduced. Similarly, an
20 attachment link 110 can operatively attach the peripheral portion 114 to the peripheral support frame 101. The attachment link 110 can be a torsion spring or rod that stores energy when the peripheral portion 112 is forcefully rotated relative to the frame 101. The stored energy can be released to move the peripheral portion towards a neutral position when the rotational force is removed or reduced. The attachment link 110 can be operatively
25 positioned along an axis A perpendicular to the axis B of attachment link 118. The attachment link 118 allows rotation about axis B and attachment link 110 allows rotation about axis A. The peripheral portion 112 can be scanned using rotation about each axis A and the interior portion 114 can be scanned using rotation about axis B.

The rotation about axis A and axis B can be powered by voltage supplied through
30 electrical communication with a portion or portions of layer 104. If the attachment links are torsion springs, the rotation can be forced against the springs and energy can be stored in each spring. When the rotational power is removed or is reduced about a given axis, the

respective springs return to a lower energy state causing the respective gimbal to return to a neutral position relative to the given axis of rotation.

The axes of the gimbal structure are optionally perpendicular to each other. However, the axes can also be configured in a non-perpendicular orientation. For example, the gimbal structure could comprise two torsion rods or springs aligned along the same direction, or any orientation between perpendicular and aligned in the same direction. In the example configuration where the torsion springs are aligned along the same direction, rotation about either torsion rod causes deflection of a light beam in the same direction. This configuration can be used to achieve very large deflection angles, although the scanning becomes one-dimensional. In configurations where the angle between torsion rods lies between 0 and 90 degrees, rotation about one torsion rod deflects the beam by some amount along a direction perpendicular to the orientation of the second torsion rod, and by some amount along the direction of the second torsion rod, rotation about the two axes are not be decoupled. In another configuration, a 360 degree rotational surface structure can be used with a corresponding circular support frame design. The rotational surface structure can be mirrored. In this case there is not a gimbal structure having a peripheral and interior portion, but the rotational surface can be used to scan reflected or transmitted light. Thus an example scanning device and system can comprise a gimbal or other rotating surface structure capable or scanning reflected or light as described herein.

A Fresnel zone plate objective (FZPO) 116 can be patterned on the upper surface of the interior portion 114. An example FZPO is an elliptical zone plate objective (EZP). The FZPO 116 can be used to concentrate or focus light into a small volume. Light projected onto the FZPO 116 can be reflected and focused or transmitted and focused. The combination of rotation about axis A and axis B allows light that contacts the FZPO 116 to be focused and scanned about each axis. The FZPO 116 focuses the contacting light as the peripheral and interior portions are scanned about the two axes. The integration of the FZPO 116 onto the interior portion 114 allows for focusing without a separate focusing element or objective. The scanning device 100 integrates the focusing element, the FZPO 116 with the interior portion 114. For example, without the FZPO, light reflected from the surface of the gimbal would not be focused and a separate focusing element positioned between the gimbal reflecting surface and the target would be used.

The scanning device 100 provides a surface with an integrated FZPO that is scanable about axes A and B. The FZPO can be transmissive or reflective. A reflective scanning

device reflects focused incident light from the integrated FZPO/gimbal surface and a transmissive scanning device allows light to pass through the FZPO and gimbal to be focused.

The scanning device, whether transmissive or reflective, can be operatively positioned in an endoscope. Such an endoscope can be used for medical procedures. In the case of a transmissive device, a light is passed through the FZPO and onto the target tissue. In the reflective configuration, light is directed onto the FZPO surface and the light, or a portion thereof, is reflected onto the target tissue. The scanning device 100 can also be used in non-endoscope applications. For example, the scanning device can be used in optical communication applications. In light of different wavelengths, each wavelength can carry a different amount of information that is different from the other wavelength. The scanning device can be used to segregate light of different wavelengths. For example, the device can be used to direct and send information comprising light of different wavelengths along an optical fiber. The scanning device 100 can be used to segregate the light of different wavelengths and turn them into different fibers. In this aspect, the scanning device functions analogously to a switch. The ability to distinguish different wavelengths of light is a physical property of the FZPO based on principles of diffraction. This means that different light wavelengths would be directed into different positions of space automatically without scanning. The addition of scanning, however, allows a greater degree of multiplexing.

Using the physical properties of the FZPO, different wavelengths of light can be automatically assigned to different positions of space. For example, a linear array of optical fibers can be placed at appropriate positions of space and different wavelengths of light emanating from the light source can be assigned to different optical fibers. Such a distribution can be referred to as wavelength division multiplexing, and can be performed without mechanical scanning based on the properties of the FZPO. When mechanical scanning is performed about an axis orthogonal to the direction along which wavelength dispersion occurs (due to the FZPO), and the single-dimensional array of optical fibers is replaced by a two-dimensional array of fibers, then each single wavelength of light can be directed to one of several optical fibers in an array oriented orthogonal to the direction of wavelength dispersion. The fiber used can depend on the rotation angle at the specific instant of time. Such a distribution can be referred to as joint time-wavelength division multiplexing.

Figure 1B is a SEM showing a portion of underside the scanning device 100. A portion of the peripheral support frame 101 was removed to allow movement of the peripheral and interior portions about axis A and axis B. The peripheral support frame comprises a plurality of layers including the first silicon layer 102, the second silicon layer 104, and a lower support layer 111. Each silicon layer, for example first layer 102 and second layer 104, can be separated by a layer of silicon dioxide to provide an electric insulator.

Figure 1C is a SEM showing features of the actuation mechanism of the scanning device 100. Actuator mechanisms are positioned between the peripheral support frame 101 and the peripheral portion 112 and between the peripheral portion 112 and interior portion 114. When a voltage is applied to the device, for example to the second silicon layer 104, the actuator mechanisms can cause rotation of the peripheral and interior portions about axis A and axis B. A voltage can be applied at a variety of locations to power the actuator mechanisms.

An example actuator is a comb-drive type actuator. Figure 1A, 1B, and 1C show views of an example comb-drive actuator mechanism. The comb-drives are linear motors that utilize electrostatic forces that act between two silicon combs. The electrostatic forces are created when a voltage is applied between the combs causing them to attract. The actuator mechanism can comprise at least one rotor and a stator for the interior and peripheral portions. Each rotor comprises a comb element having a spine portion 106 and a plurality of finger portions 107 attached to the spine 106. Each stator also has a plurality of finger portions 105 that can interlace with the finger portions of the rotor. When a voltage is applied it causes movement of the rotor and rotation of the peripheral and interior portions about axis A and axis B.

Figure 2A-F are schematic illustrations showing a cross sectional view of the fabrication of an example scanning device 100. A silicon on insulator (SOI) wafer 200 is provided that comprises an upper silicon layer 204, an insulator of silicon dioxide 201, and a lower layer of silicon 202. Other insulator materials can also be used. Features can be patterned in the upper silicon layer 204 as shown in Figure 2A. These features correspond to portions of the stator of the scanning device 100.

After the upper silicon layer is patterned as shown in Figure 2A, another silicon wafer 206 can be bonded to the patterned upper silicon layer 204 with an insulating material layer 205, for example, silicon dioxide. The bonding process can be fusion bonding. Any method

of bonding, can be used to bond the silicon to the silicon dioxide. For example, heat can be applied over time to bond the silicon dioxide and the silicon. The silicon layer 206 can be ground and polished so that it has a desired thickness and the appropriate surface smoothness. The layer thickness determines the mechanical resonant frequencies of the modes of vibration of the device, and also determines the amount torque exerted on the rotatable portions of the device for a given actuation voltage applied at the bond pads 104 of the device. The desired thickness to which the layer is ground can be determined based on engineering design of these quantities. The desired smoothness of the device can depend on the application. For optical applications where the surface behaves as a mirror, the root mean square (RMS) surface roughness can be less than 1/10th of the wavelength of light illuminating the mirror (for example, for 1310 nanometer wavelength, the RMS surface roughness can be less than 131 nanometers to prevent significant optical aberrations).

Features of the Fresnel Zone plate objective, or FZPO are patterned onto 206, which is shown in Figure 2C as 208. For example, Reactive Ion Etching (RIE) can be used to pattern the FZPO. In Figure 2D a chemical deposition of silicon dioxide 210 is made onto the surface of 206 and 208. As shown in Figure 2E, the applied silicon dioxide 210 match the features of the upper layer 206 and lower layer 204. The pattern that exists in the silicon dioxide 210 is then extended through the silicon layers 206 and 204. This process provides the features of the stators, rotors and the peripheral support frame. Figure 2F shows removal of a portion of the silicon layer 202. The portion of 202 removed substantially underlies the peripheral and interior portions, stators and rotors allow for rotational movement of the peripheral and interior portions along axis A and B while still allowing for support of the device at the periphery. Thus, Figure 2F schematically shows features of the scanning device 100 corresponding to Figures 1A-1C and resulting from the fabrication steps shown in Figures 2A-2F. The upper surface of the FZPO can be coated with a material to improve its reflectivity. For example, the upper surface of the FZPO can be coated with a metal layer.

Figure 3 is a schematic illustration of an example imaging system 300 for use with the example scanning device 100. The system comprises the scanner 100, which can be positioned in an endoscope such that a sample 302, for example tissue, can be imaged or monitored. The scanning device 100 can be in operative communication with a computer. The computer can monitor the position of the scanner and can determine the voltage applied to the scanner to control the scanning movements about axis A and axis B. The same or a separate computer in operative communication with the computer can comprise an image

acquisition module for rendering and/or manipulating an image captured using the endoscope device. The computer can comprise a driver 345 programmed to control the scanner such that it scans a regular pattern. For example, the scanner can scan a rectangular or other geometric area. Portions of the system can be disposed within an endoscope. For example, the scanning device 100 can be disposed within the tip of an endoscope, or otherwise to direct light and receive light from a target.

A laser module 304 can be used as a source of light for the imaging system. The laser module 304 produces light of one particular wavelength, for example 635nm, and of a particular polarization. The light from the laser module 304 is guided using a fiber optic cable through a collimator 308 to produce a beam of light that has a constant width as it travels in space. The light from the collimator 308 is directed through a walk off polarizer 312. The light traveling from the collimator 308 through the walk off polarizer 312 does not have its polarization affected. Light passing through the walk off polarizer 312 passes through a second collimator and passes along a fiber optic cable 316. The fiber optic cable 316 maintains the polarization of the light such that the polarization state of the light that enters the cable 316 is the same as the polarization of the light that exits it. The light is directed into a pigtailed collimator 318 that re-collimates the beam and makes it a beam having a predetermined diameter. Before light enters a quarter-wave plate (QWP) 320, the light is linearly polarized. The QWP 320 modulates the light so that it is circularly polarized. The circularly polarized light is deflected about 90 degrees downwards using a stationary mirror 322. The polarization state is not affected by the interaction with the stationary mirror. The deflected light contacts the scanning device 100 and is simultaneously scanned and focused across the target 302. A small percentage of the focused light scanned across the target 302 is reflected back to the scanner. The backscattered light maintains circular polarization back to the QWP 320. Once the backscattered light crosses 320 backwards, light again becomes linearly polarized. The light continues to move back through 318, 316, and 314 which maintain the polarization. The light traveling backwards through the collimator 314 contacts the walk off polarizer 312 and the walk off polarizer takes the polarized light and shifts it upwards by some distance. The shifted light alone can be separated and directed into a spatial filter 338. The spatially filtered light is transmitted into an avalanche photodiode 340 that converts the optical signal into an electrical signal. The electrical signal is transmitted to the computer for processing and image formation.

As shown in Figure 10, further provided is an optical switching system 1000 comprising an input optical fiber 1002. The system further comprises a peripheral portion pivotable about a first axis C and a interior portion having a surface and pivotable about a second axis D perpendicular to the first axis. A Fresnel zone plate objective (FZPO) is patterned on the surface of the interior portion. The input optical fiber directs light onto the FZPO and the FZPO reflects and focuses the light directed thereon. An actuator system is provided for pivoting the first and interior portions about the first and second axes. A plurality of output optical fibers 1006 are positioned to receive the focused light reflected from the FZPO and the pivoting of the first and interior portions selectively directs the focused light into an output optical fiber of the plurality.

As shown in Figure 11, also provided is an optical scanning device 1100 comprising a micromirror 1102 surface and a linear diffraction grating pattern patterned on the micromirror surface. The micromirror surface and the linear diffraction grating pattern are rotatable about an axis E.

Examples

Example 1

Coherent illumination incident on the micromirror surface at an angle to the mirror normal can be concentrated at a wavelength-dependent focal distance by an Elliptical Zone Plate Objective (EZP) (Figure 4) designed according to equation (1):

$$\left(\frac{x}{a_n \cos \theta} \right)^2 + \left(\frac{y - b_n}{a_n} \right)^2 = 1, \text{ where} \quad (1)$$

$$a_n = \frac{\sqrt{n\lambda \left(f \cos^2 \theta + \frac{n\lambda}{4} \right)}}{\cos^2 \theta} \text{ and } b_n = \frac{n\lambda \sin \theta}{2 \cos^2 \theta}$$

θ is the off-axis illumination angle about the x-axis with respect to the micromirror normal, λ is the illumination wavelength, f is the focal distance, and a_n and $a_n \cos(\theta)$ are the semi-major and semi-minor axes of the elliptical boundary of the nth zone of the EZP.

Degradation in focal spot size (indicated as w_f in Figure 4) due to changing illumination angle θ (by micromirror rotation) and wavelength are negligible for optical path difference deviation at the zone boundaries of less than $\lambda/4$ from nominal value. Therefore, the EZP can be fabricated for a given focal spot size under maximum rotation angle to prevent aberrations using the following design constraints:

Spherical Aberration: $n \approx \sqrt{2f / \lambda}$ (2)

Chromatic Aberration: $n \approx \lambda / \Delta\lambda$ (3)

Off-Axis Aberration: $\alpha \approx (3n)^{-1/2}$ (for small n) (4)

These conditions can restrict the maximum number of EZP zones and micromirror scan angle (indicated as θ_s in Figure 4), and can be used to determine the number of resolvable points in the image or the numerical aperture of the EZP. Variation of focal distance with wavelength provide a new mechanism for 3-D imaging through axial scan.

The micromirror was actuated by staggered vertical comb drives fabricated by a comb self-alignment process in bonded double-SOI wafers. Coarse features of the stator were etched by Deep Reactive Ion Etching (DRIE) into 25 μ m thick SOI <100> device layer (Figure 2). Device fabrication process sequence included: (a) DRIE of coarse features in to SOI device layer; (b) Bond oxidized wafer, grind/polish; (c) Pattern binary-phase modulation elements of zone plate into micromirror surface; (d) Chemical vapor deposit silicon dioxide and pattern with exact micromirror features; (e) DRIE-Oxide RIE-DRIE sequence to create self-aligned actuators; (f) Backside DRIE to release micromirror, and oxide RIE on both sides to remove protective oxide.

An oxidized <100> wafer was fusion bonded on top of the patterned wafer, and ground down to 25 μ m thickness with <50nm surface roughness to form the micromirror surface. Features of the elliptical zone plate objectives were patterned on the surface to quarter-wavelength depth. Exact features of the actuators, aligned to the lower layer features, were etched into deposited silicon dioxide. A first Deep Reactive Ion Etch (DRIE) transferred the features present in the silicon dioxide to the upper layer of the device. Reactive Ion Etch (RIE) of the silicon dioxide removed the exposed regions of the intermediate layer of silicon dioxide between the two silicon layers. A subsequent DRIE trimmed the features present in the lower silicon layer to match the features in the upper silicon layer. This process was termed self-alignment, and was used for robust, stable operation of the device, as

misalignment between the stator features in the lower layer of silicon and the rotor features in the upper layer of silicon can cause stiction between the combs present in the two layers.

Backside substrate DRIE and oxide RIE on both sides released the mirror and removed remaining protective oxide. Scanning electron micrographs of the fabricated device are presented in Figures 1A-C. The SEM images of the fabricated device show: (a) Top view showing the EZP, vertical comb drives, torsion springs, and bond pads for electrical connection; (b) Backside view showing DRIE trench with vertical sidewalls to release the scanning micromirror; (c) Close-in view of vertical combdrive.

Scanning EZPs designed for 635nm (1310nm) wavelength with focal lengths of 7mm (8mm) and off-axis illumination angles of 20° (45°) were fabricated on micromirrors of size 500 μ m $\times$ 700 μ m. The FZPOs were made of size to fully cover the mirror surface, but can be made smaller. A larger FZPO (i.e., one with a greater number of zones in it) focuses the light into a smaller volume than one with fewer zones, if both FZPOs are designed for the same wavelength and focal length. A larger mirror allows the patterning of a larger FZPO with enhanced focusing ability. Two-axis beam scanning was obtained by mounting the micromirror by torsion rods within a gimbal, which was suspended by torsion rods aligned in the orthogonal direction. Rotation about each axis was driven by two sets of staggered vertical comb drives. This configuration led to two-axis angular scanning about a single pivot point at the center of the micromirror, which reduced optical field distortions.

Frequency response characteristics (Figure 5A) of the micromirror were tested by applying voltage of $20.0+20.0\sin(\omega t)$ volts and varying the sinusoidal frequency. The micromirror exhibited resonant out-of-plane rotation at 2280Hz and 383Hz for the inner and outer axes respectively. The static voltage deflection characteristics (Figure 5B) were determined by applying a DC voltage to one comb drive on each axis. Static voltage deflection of $\sim 9^\circ$ (optical) was measured on application of 110 volts on both axes. A raster scan pattern was used for point-by-point image formation, employing resonant frequency operation of the inner axis for fast line scan, and non-resonant operation of outer-axis for frame scan.

Size of the focused spot of an EZP designed with an 8mm focal length for 635nm illumination at 45° was profiled against micromirror rotation angle by measuring the far-field angular beam divergence (θ) of the Gaussian beam, and calculating the focused beam waist (w_f) using the formula:

$$\theta \approx \frac{2\lambda}{\pi w_f} \quad (5)$$

The measured focused spot size showed little degradation (Figure 6) for micromirror scanning angles up to 10° (optical) about both axes.

Transmission Barcode Imaging using EZP Micromirror:

Image-formation capabilities of the device were demonstrated using a transmission-mode system, depicted in Figure 7. A sample with spatially-varying transmission was placed in the focal plane of a scanning EZP, and transmitted light was concentrated into a photodetector using two collection lenses. Mylar transparencies printed with longhorn logos and numbers were imaged (Figure 8) using the system at 5 frames/second. Comparison with images obtained from an Olympus BX51 Microscope (Center Valley, PA) using 10X objective indicated an estimated field of view of 1mm × 0.35mm at approximately 15μm resolution.

EZP Micromirror-Based Reflectance Confocal Imaging:

The devices were then incorporated into a portable bench-top single-fiber laser-scanning reflectance confocal microscope (Figure 3). Figure 3 is a schematic illustration showing a single-fiber laser-scanning reflectance confocal microscope incorporating the micromirror with monolithically integrated EZP.

Polarized light from a 635nm semiconductor laser diode was launched into a single-mode polarization-maintaining fiber, aligned to the fiber slow axis. After collimation into a beam matched to the size of the EZP, the linearly polarized light was converted into circularly polarized light by a quarter-wave plate (QWP) before being simultaneously focused and scanned across the sample by our device. Reflected light from the sample maintains some component of circularly polarized light, which was converted into light linearly polarized along the fiber fast axis, orthogonal to the incident illumination. This allowed the walk-off polarizer to separate the sample reflection from laser illumination and direct it to an avalanche photodetector. Images using this system of a USAF1951 resolution target are depicted in Figure 9. The field of view was 1mm × 0.35mm and lateral resolution of 15μm were estimated based on calculating the line width of the resolvable features in the resolution target images.

Novel monolithic integration of reflective binary-phase-modulation elements on two-axis Microelectromechanical system (MEMS) scanning micromirrors was demonstrated for simultaneous beam scanning and focusing in a compact single-chip solution. This approach

can eliminate the need for focusing optics in a microendoscope catheter. Elliptical zone plates integrated on two-axis self-aligned staggered vertical comb driven micromirror, incorporated into a laser-scanning reflectance confocal microscope experiment, demonstrated cellular-level resolution without complex multi-element assembly. MEMS technologies were used to provide distal beam deflection for image formation in microendoscopes. Vertical combdrive micromirrors provided the large rotational torque, deflection angles and mirror surface quality for laser-scanned imaging systems. A micromachined Fresnel zone plate objective was monolithically integrated directly on the surface of the micromirror via patterning of reflective binary-phase-modulation elements.

Example 2

1xN Optical Switch for Optical Fiber Communication

Optical data communication networks have grown in transmission capacity and sophistication to accommodate the increasing demands on the internet. Wavelength and time-division multiplexed optical networks switches are an important component in optic-fiber communication. MEMS technologies demonstrate the ability to integrate electrical, mechanical and optical elements on a single chip, and are well suited to building wavelength division multiplexed WDM components.

A scanning device with monolithically integrated Fresnel lens system is used as a 1xN optical switch. An example scanning device for this application is schematically illustrated in Figure 10. Figure 10 schematically illustrates a 1xN optical switch realized using two-axis scanning micromirror with monolithically integrated Fresnel lens objective (FZPO). Light diverging while exiting from the input optical fiber is incident on the surface of the scanning micromirror, which is patterned with reflective phase modulation elements to make a FZPO. In this particular instance, the pattern on the scanning micromirror is designed to behave as a Fresnel zone plate, which concentrates light into a small volume (at the beam focus). Rotation of the scanning micromirror about two axes (about a single pivot point) allows lateral scan of the focused beam. An output array of optical fiber is operatively positioned at the focal plane of the scanning Fresnel lens. The output fiber into which the incoming beam is directed is selected by setting the rotation angle of the micromirror about the two rotation axes.

Example 3

External Cavity Wavelength Swept Laser

Laser sources whose output wavelength can be tuned are extremely important in Wavelength Division Multiplexed (WDM) optical communication systems and in optical imaging techniques such as swept-source optical coherence tomography (SS-OCT). The Littrow configuration is a well-known and efficient method of obtaining a swept wavelength laser with large tuning range and narrow laser line width. A schematic for the Littrow configuration external cavity wavelength swept laser is shown in Figure 11.

A scanning micromirror (rotation about only one axis) with mirror surface patterned with linear diffraction grating pattern serves as the wavelength-selecting element in the Littrow configuration external cavity wavelength-swept laser. In Figure 11, the laser diode amplifies a broad spectrum of wavelengths. Light exiting the laser diode is incident on a diffraction grating, which is rotated about its central axis in order to change the angle of incidence of the light illuminating it. Light incident on the grating is either reflected off the grating as if it were a mirror (zeroth order diffraction), or diffracted at a wavelength-dependent angle (first and higher diffraction orders). First-order diffraction is strong while other orders are typically very weak and can be neglected. The different wavelengths of light incident on the grating are diffracted at different angles. There is a single wavelength of light, whose diffraction angle equals the incidence angle, i.e., it retraces its path back directly into the laser diode. Therefore, a laser cavity is formed only for that particular wavelength, and therefore laser operation is restricted to that particular wavelength. By rotating the diffraction grating, the wavelength for which lasing operation occurs can be varied. Thus, a wavelength-swept laser can be obtained by continuously varying the rotation angle of the diffraction grating. The scanning micromirror with monolithically integrated diffraction grating performs this function efficiently.

WHAT IS CLAIMED IS:

1. A optical scanning device, comprising:
 - a) a gimbal structure comprising a peripheral portion pivotable about a first axis and an interior portion having a mirrored surface and pivotable about a second axis;
 - b) a Fresnel zone plate objective (FZPO), wherein the FZPO is patterned on the mirrored surface of the interior portion; and
 - c) an actuator system for pivoting the peripheral and interior portions about the first and second axes.
2. The optical scanning device of claim 1, wherein the first axis is perpendicular to the second axis.
3. The optical scanning device of claim 1, further comprising a light source configured to supply light to the FZPO.
4. The optical scanning device of claim 3, wherein the FZPO is configured to focus the supplied light on a distant target.
5. The optical scanning device of claim 4, wherein the actuator system is configured to pivot the peripheral portion and interior portion to scan the focused light across the distant target.
6. The optical scanning device of claim 3, wherein the FZPO is configured to focus light incident on the mirrored surface.
7. An endoscope comprising the optical scanning device of claim 1.
8. An optical communication system comprising the optical scanning device of claim 1.
9. The optical communication system of claim 8, wherein the optical scanning device is configured to segregate and direct light of different wavelengths to wavelength specific targets.

10. A optical scanning device, comprising:
 - a) a gimbal structure comprising a peripheral portion pivotable about a first axis and an interior portion having a surface and pivotable about a second axis;
 - b) a Fresnel zone plate objective (FZPO), wherein the FZPO is patterned on the surface of the interior portion; and
 - c) an actuator system for pivoting the peripheral portion and the interior portion about the first and second axes.
11. The optical scanning device of claim 10, wherein the first axis is perpendicular to the second axis.
12. The optical scanning device of claim 10, further comprising a light source configured to supply light to the FZPO.
13. The optical scanning device of claim 12, wherein the FZPO and interior portion are configured to allow transmission of the supplied light therethrough, and wherein the FZPO is configured to focus the transmitted light on a distant target.
14. The optical scanning device of claim 13, wherein the actuator system is configured to pivot the peripheral portion and interior portion to scan the focused light across the distant target.
15. An endoscope comprising the optical scanning device of claim 10.
16. An optical scanning device, comprising:
 - a) a micromirror surface; and
 - b) a FZPO patterned on the micromirror surface, wherein the micromirror surface and the FZPO are rotatable about a first axis and about a second axis.
17. The optical scanning device of claim 16, wherein the first axis is perpendicular to the second axis.
18. An endoscope comprising the optical scanning device of claim 16.

19. An optical scanning device, comprising a micro FZPO configured to rotate about a first axis and about a second axis.
20. The optical scanning device of claim 19, wherein the first axis is perpendicular to the second axis.
21. An endoscope comprising the optical scanning device of claim 19.
22. The optical scanning device of claim 19, wherein the micro FZPO is sized for operative positioning within a microendoscope.
23. An optical scanning device, comprising:
 - a) a micromirror surface; and
 - b) a linear diffraction grating pattern patterned on the micromirror surface, wherein the micromirror surface and the linear diffraction grating pattern are rotatable about an axis.
24. A optical switching system, comprising:
 - a) an input optical fiber;
 - b) a gimbal structure comprising a peripheral portion pivotable about a first axis and an interior portion having a surface and pivotable about a second axis;
 - d) a Fresnel zone plate objective (FZPO), wherein the FZPO is patterned on the surface of the interior portion, wherein the input optical fiber directs light onto the FZPO, and wherein the FZPO reflects and focuses the light directed thereon;
 - e) an actuator system for pivoting the peripheral portion and interior portion about the first and second axes; and
 - f) a plurality of output optical fibers positioned to receive the focused light reflected from the FZPO, wherein the pivoting of the peripheral and interior portions selectively directs the focused light into a predetermined output optical fiber of the plurality.

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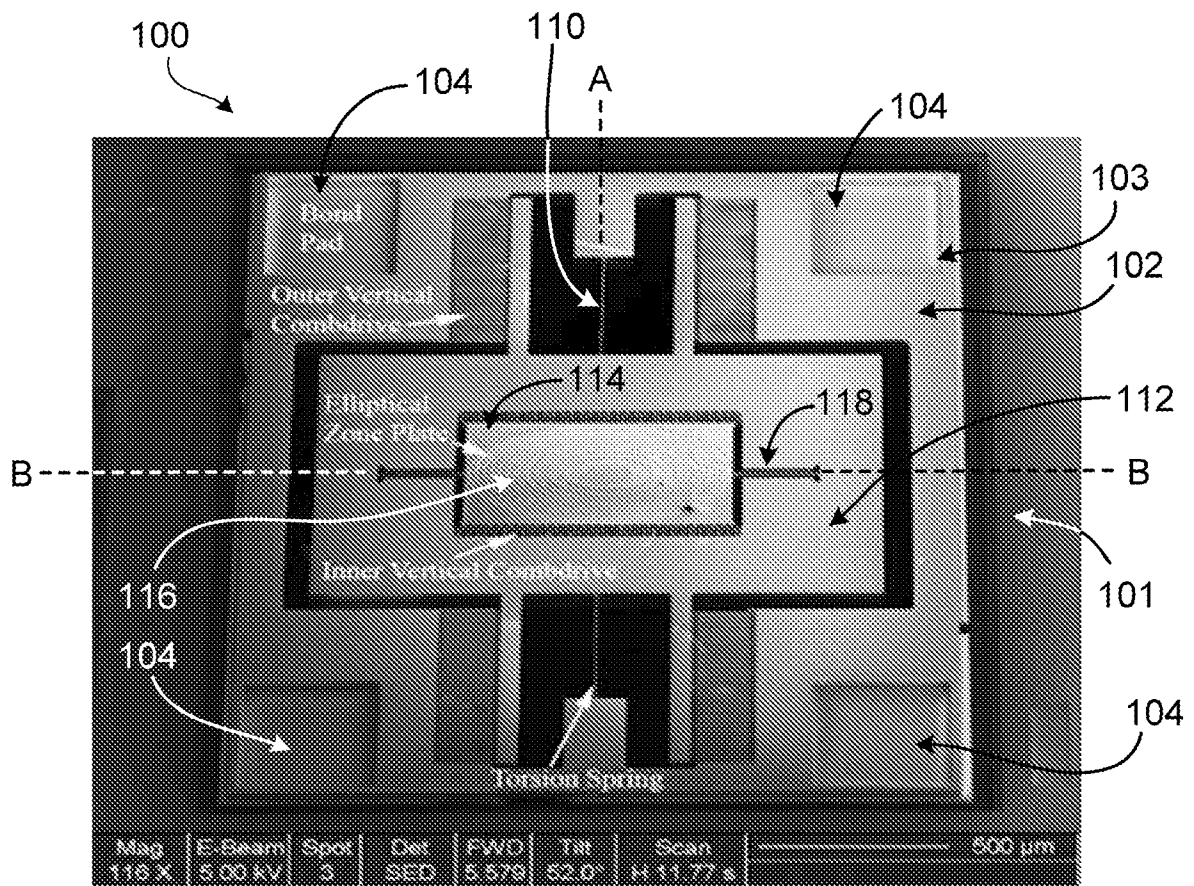


FIG. 1A

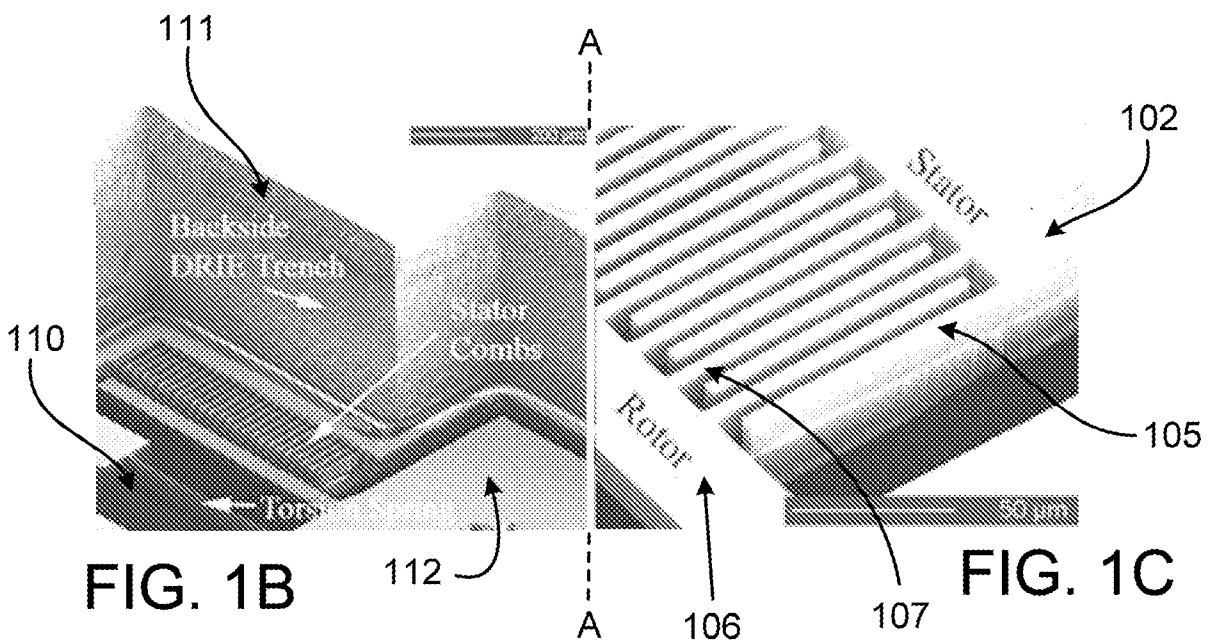


FIG. 1B

FIG. 1C

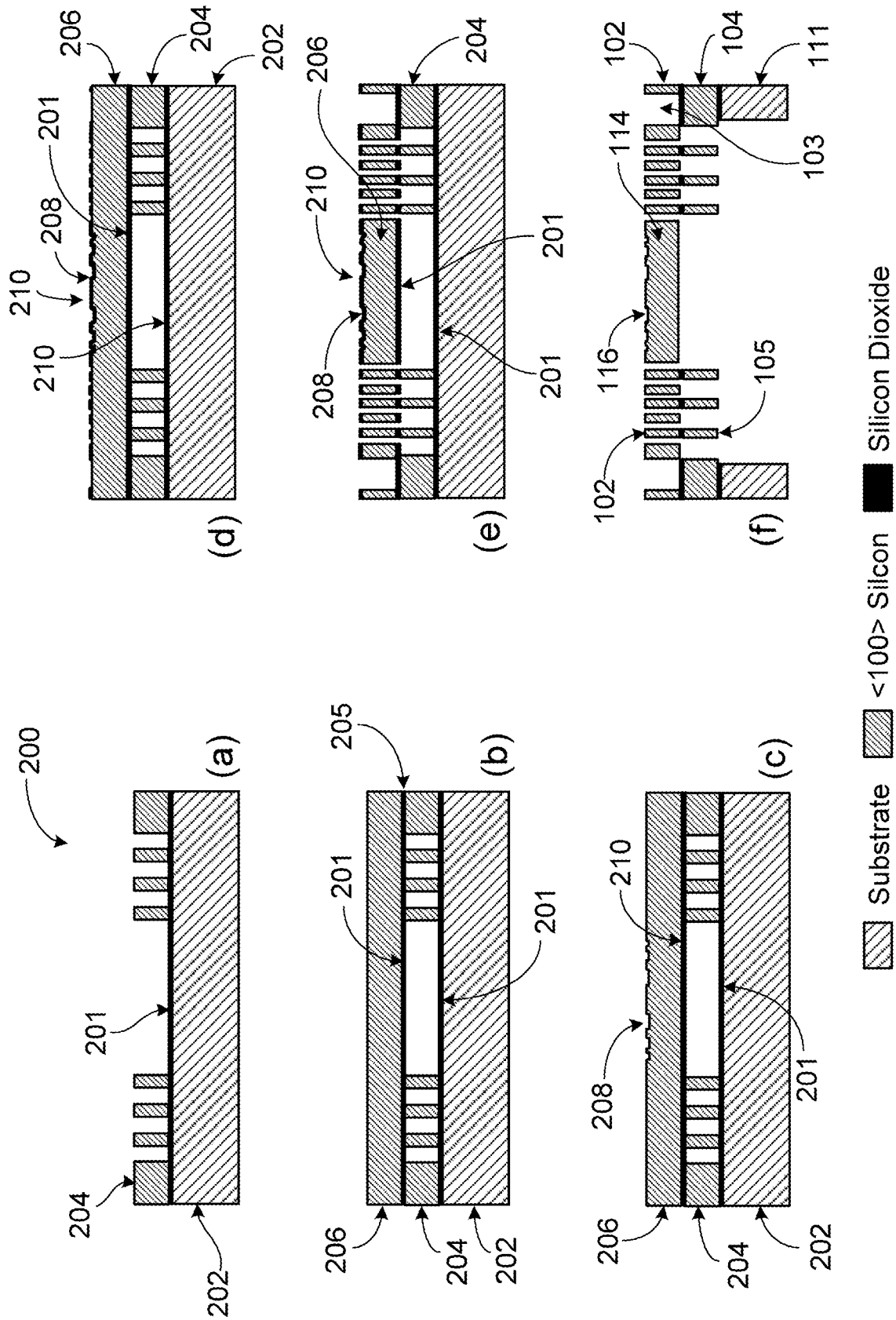


FIG. 2

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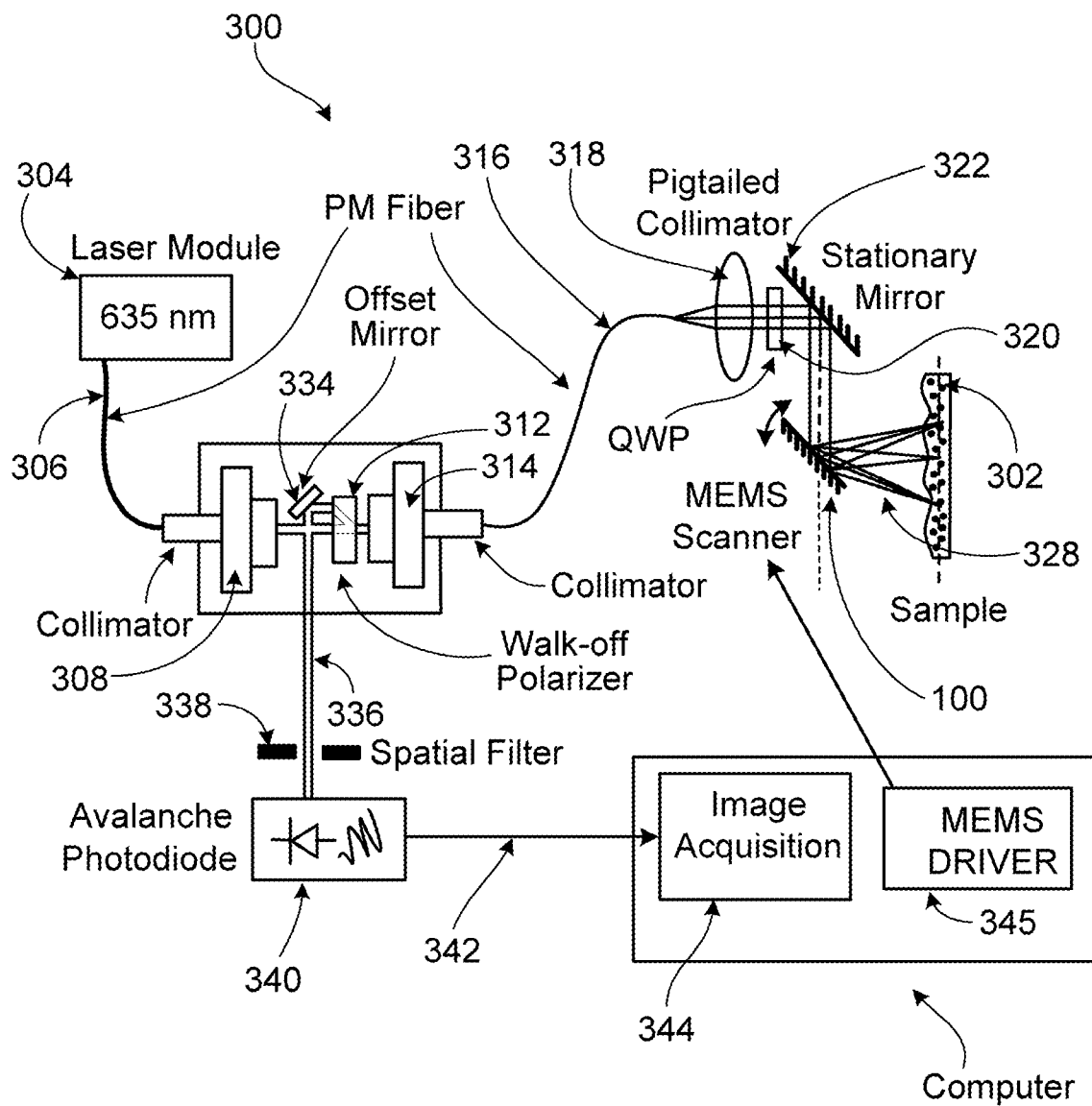


FIG. 3

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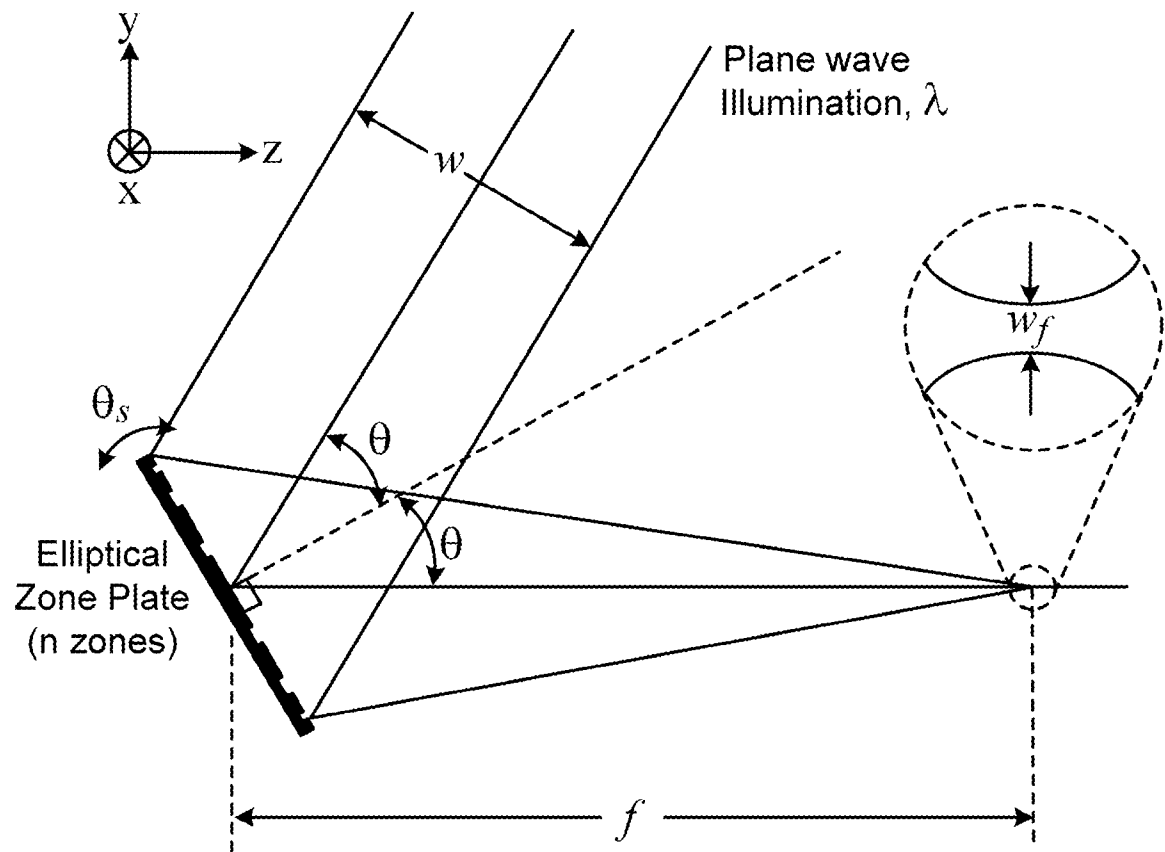


FIG. 4

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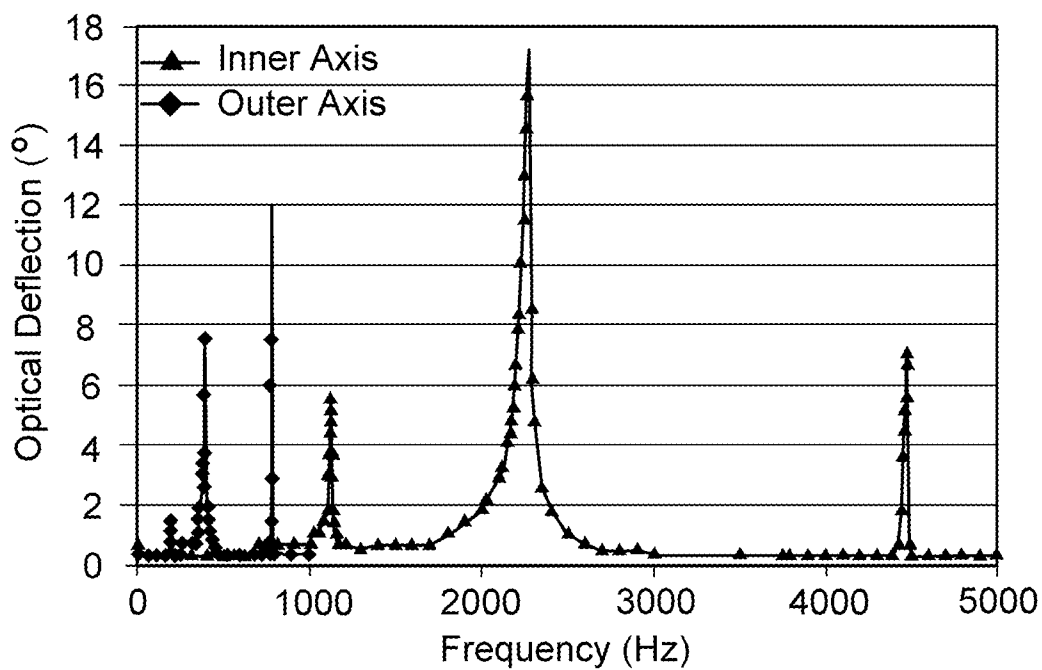


FIG. 5A

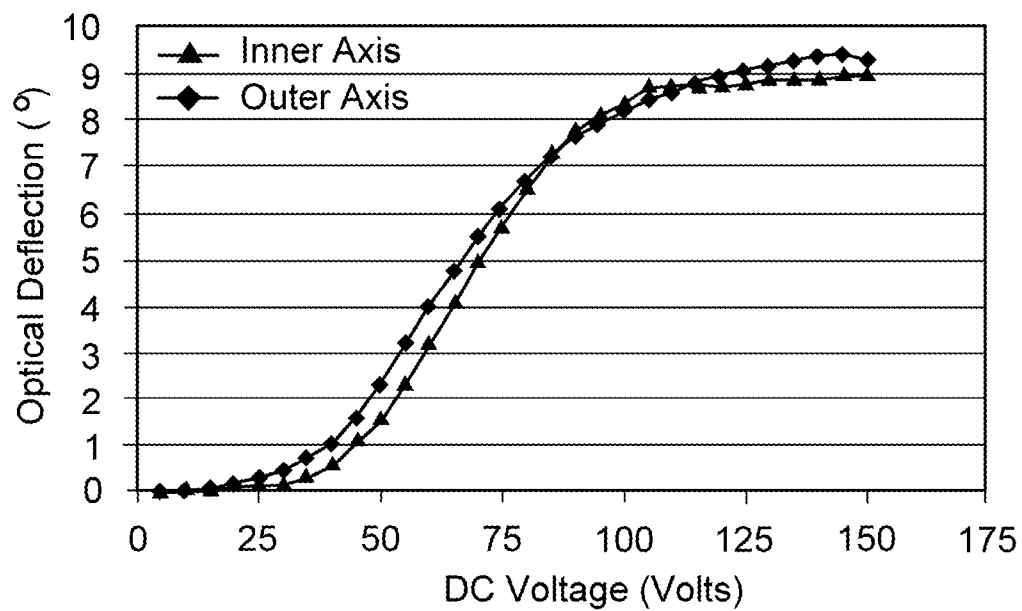
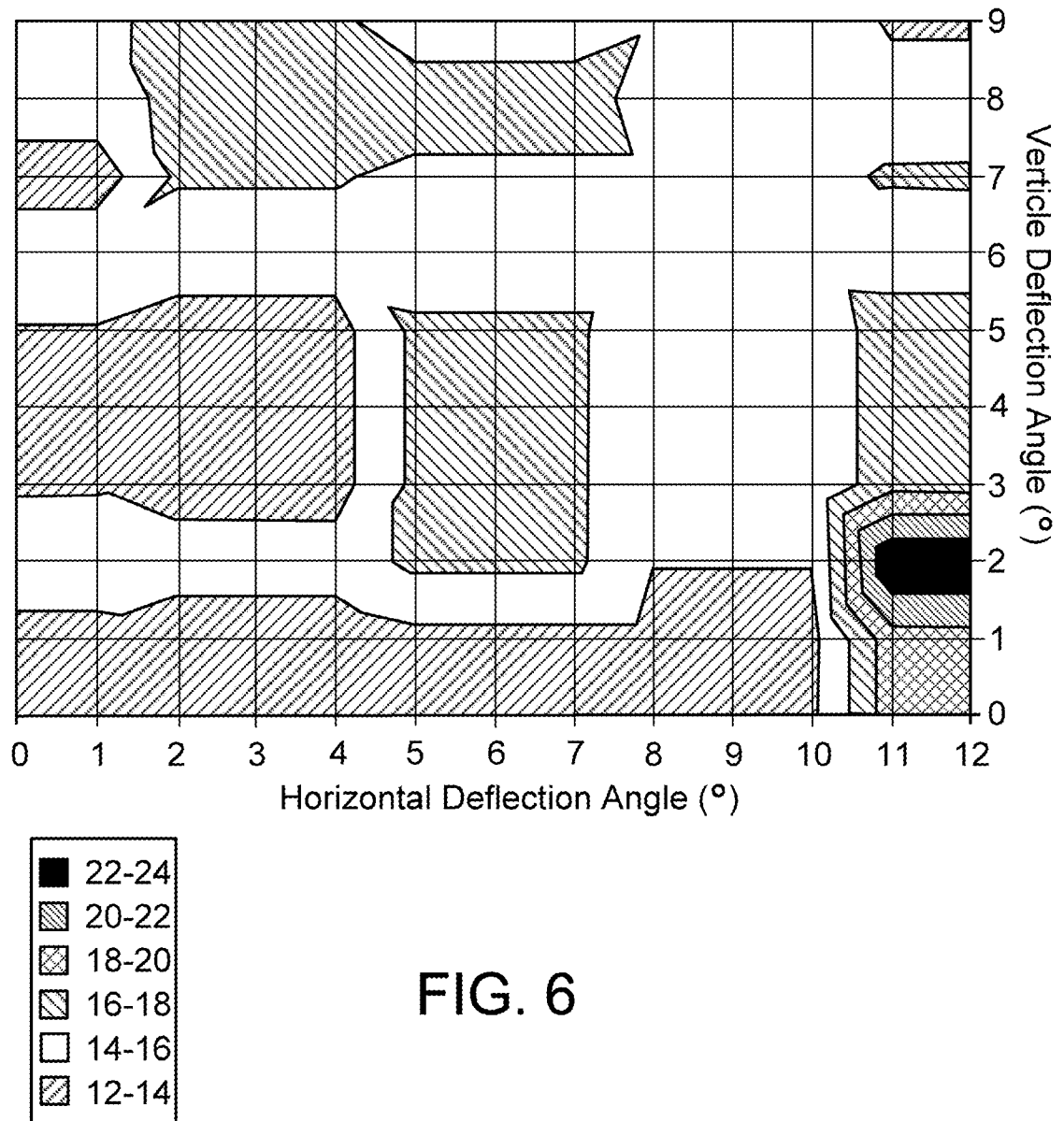


FIG. 5B

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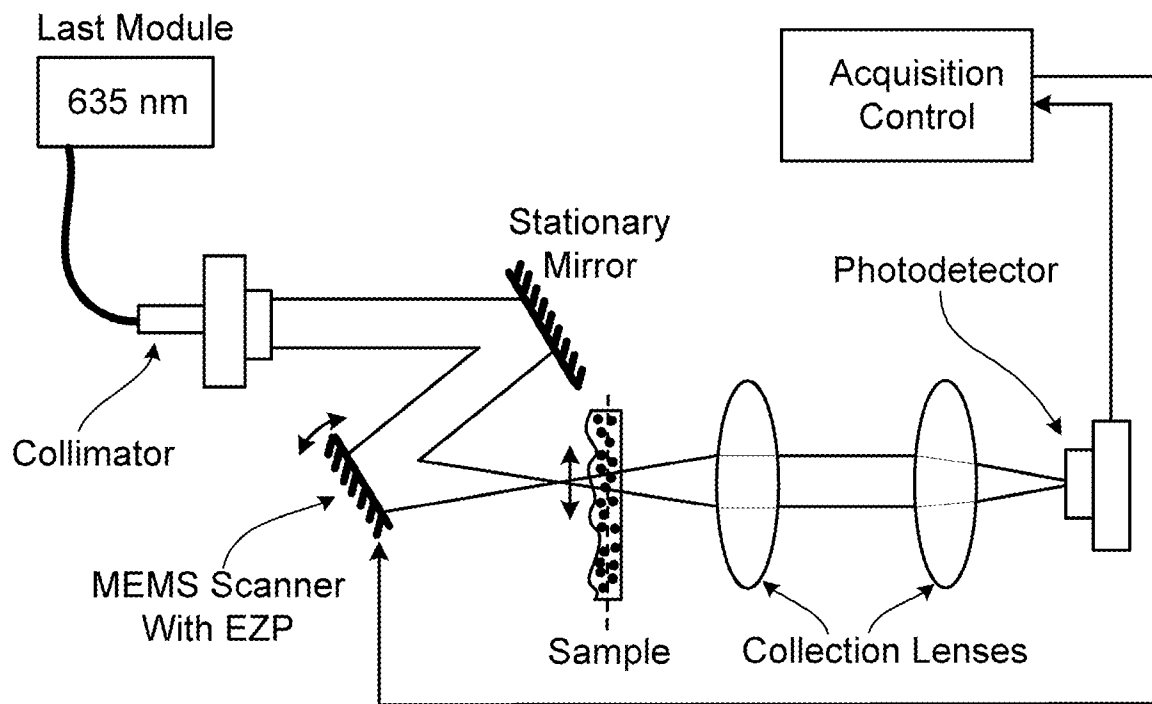


FIG. 7

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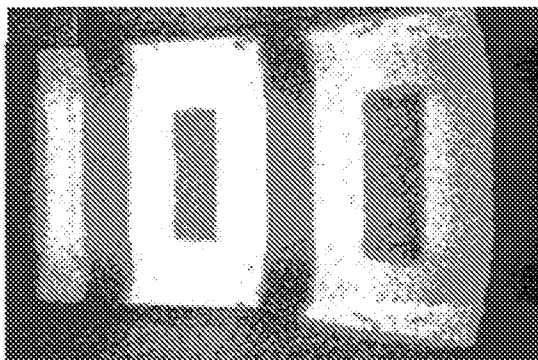


FIG. 8A

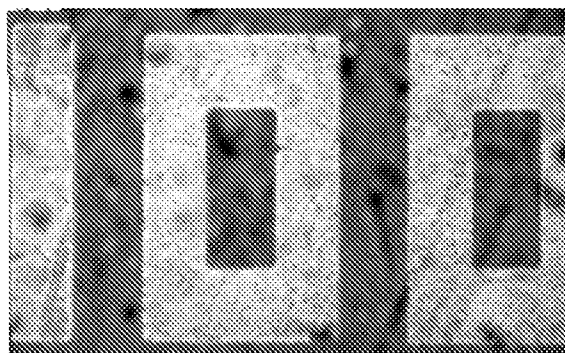


FIG. 8B

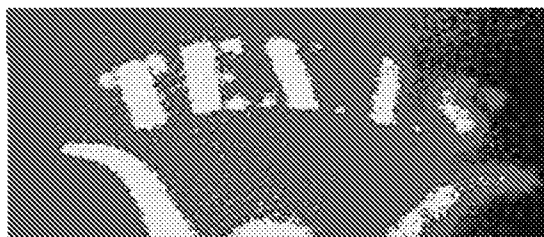


FIG. 8C

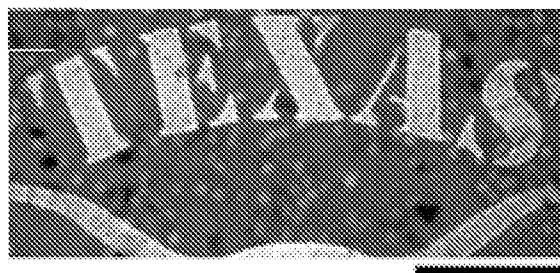


FIG. 8D

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FIG. 9A

FIG. 9B

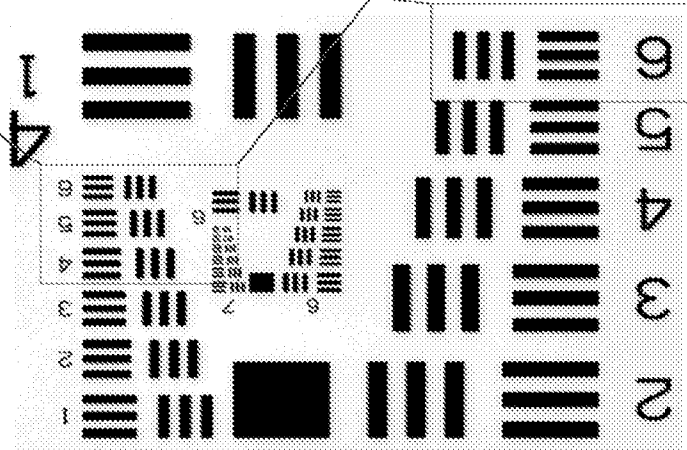


FIG. 9C

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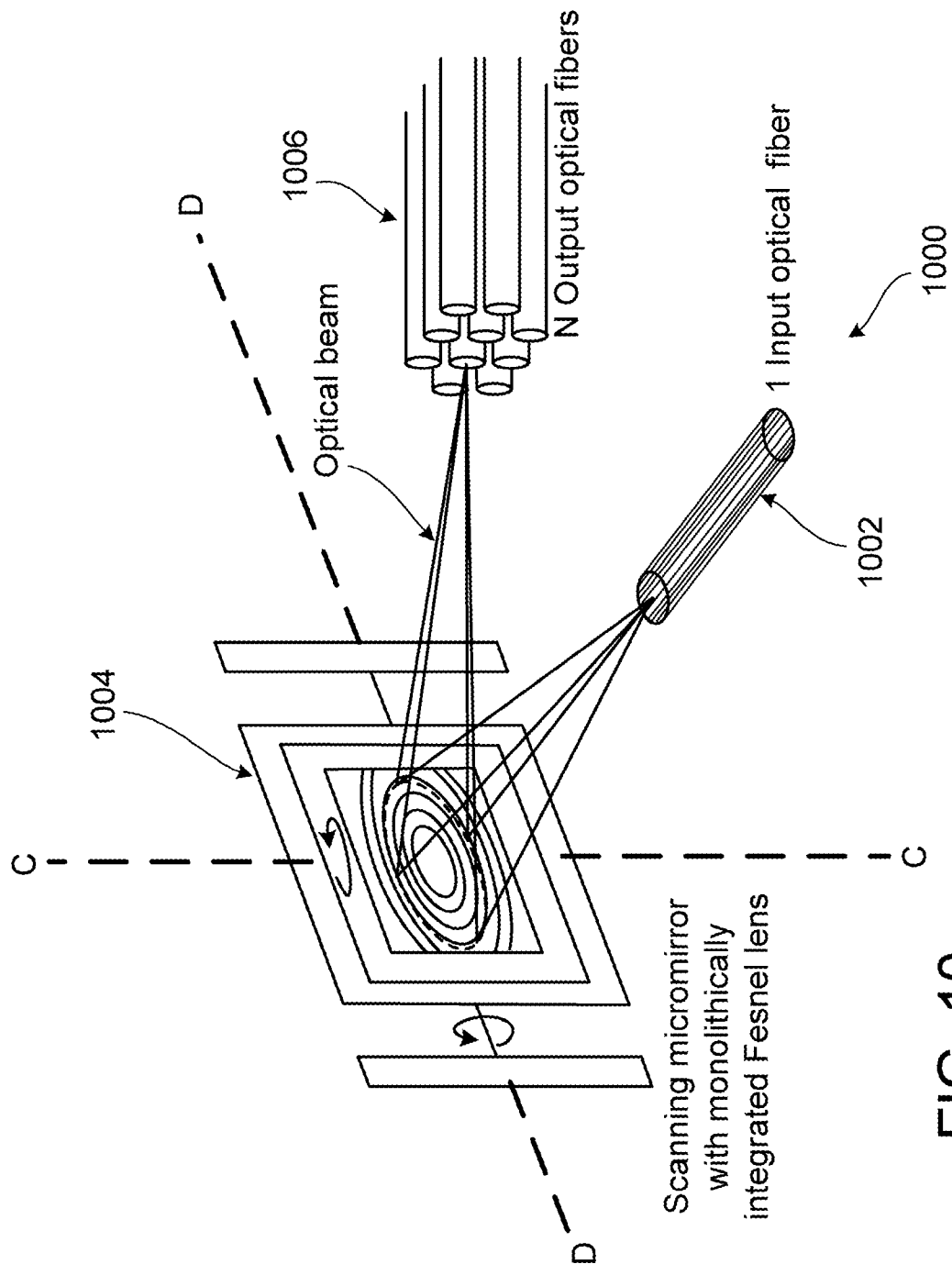


FIG. 10

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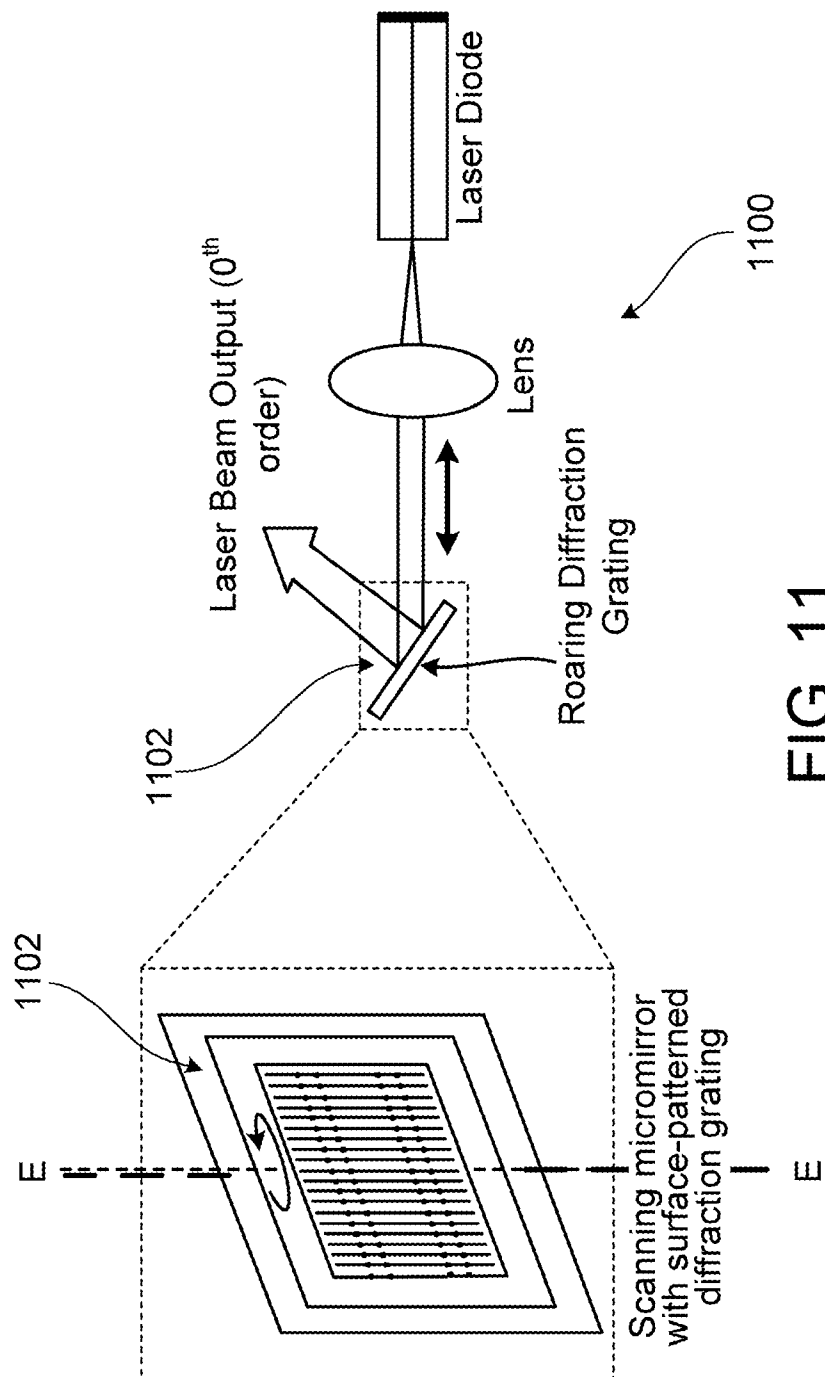


FIG. 11