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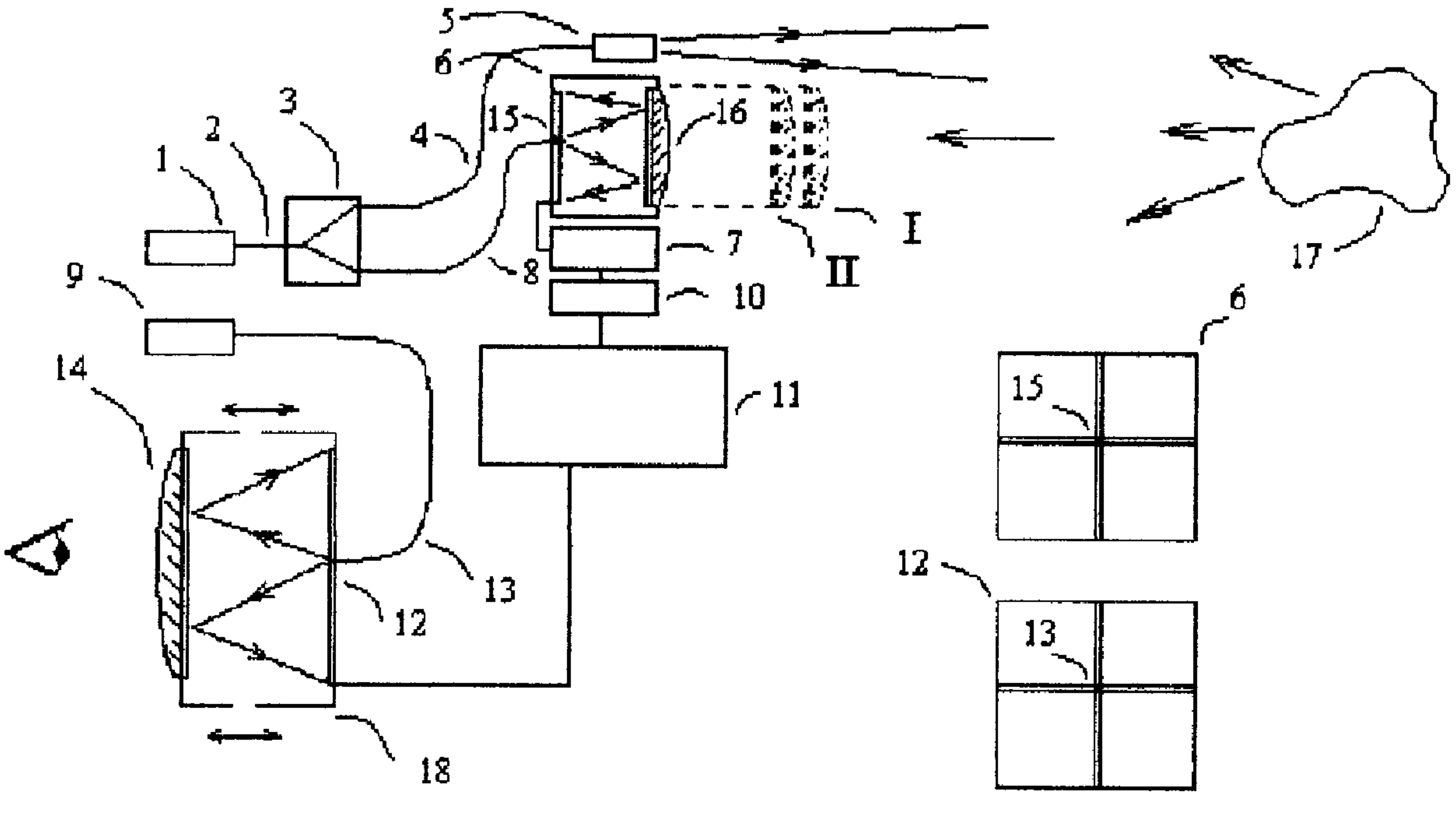
(54) Titre : SYSTEME D'HOLOGRAPHIE NUMERIQUE POUR L'ENREGISTREMENT ET LA RECONSTRUCTION D'HOLOGRAMMES TRAITES PAR ORDINATEUR

(54) Title: DIGITAL HOLOGRAPHY (DH) SYSTEM FOR RECORDING AND RECONSTRUCTION OF COMPUTER-PROCESSED HOLOGRAM



(57) **Abrégé/Abstract:**

A method and apparatus for monochrome or color digital holography (DH), which utilizes fiber-optical (FO) technology to illuminate object and reconstruct 3-D object's visible-light image taken in any wavelength or computer-simulated is disclosed. Acousto-optical filter together with a multi-line laser are further used for color holography.

ABSTRACT

A method and apparatus for monochrome or color digital holography (DH), which utilizes fiber-optical (FO) technology to illuminate object and reconstruct 3-D object's visible-light image taken in any wavelength or computer-simulated is disclosed. Acousto-optical filter together with a multi-line laser are further used for color holography.

Digital holography (DH) system for recording and reconstruction of computer-processed hologram

DESCRIPTION

FIELD OF THE INVENTION

[Para 1]

The present invention relates to a holography system for a real-time reconstruction of a three-dimensional image of an object. More particularly, it related to digital holography, wherein a hologram is registered by a matrix of photo sensors and reconstructed by LCD screen. Also, it relates to computer-processed and computer-simulated holography systems.

DESCRIPTION OF THE RELATED ART

[Para 2]

It is known, that conventional holography systems using a high-resolution photographic film (or plate) illuminated by a reference light wave and scattering of said light wave from an object (object light wave). The result of interference of these waves is registered on the photographic film as a hologram. When the hologram is illuminated by incident reference light wave, the object light wave is reproduced and 3-D image of an object is reconstructed.

[Para 3]

Particularly, because the photographic technique requires the film developing, this hologram can not reconstruct real-time images. Moreover, photographic technique does not allow creating dynamic images and such holograms can not be re-writable; and to store such holograms in computer memory or electronically transmit them, digitization of each photographically-made hologram is requires. Also, wavelengths, which can be registered on a photographic film, are restricted from long wavelengths by near infrared (about 1.1 microns) that does not allow registering middle and far infrared.

[Para 4]

As the option, theoretically, it is possible to utilize high-resolution CCD matrix instead of photographic film. This CCD camera connected to ADT allows taking pictures in real time and store it in computer memory. Also, reproduction of the object can be made by means of high-resolution LCD screen illuminated by the reference light, wherein said LCD screen is reproduces the hologram taken by said CCD camera.

[Para 5]

US Patent No 5515183 issued to Hashimoto describes such real-time holography system including a matrix liquid crystal display and a CCD camera that converts object light wave and reference light wave into a video signal. US patent No 6078392 issued to Thomas, US patent No 7038787 issued to Price and US Patent No 7471609 issued to Tateishi, et al. describe holography system utilizing CCD camera and ADT converter to digitize holograms. Utilization of computer for data processing can allow processing digitized holograms to increasing hologram resolution and terminate noise. US Patents No 5347375 and No 5668648 issued to Saito and Canadian Patents CA2687364 and CA 2588738 issued to Schwerdtner describe computerized system for hologram processing that utilizes an interpolation processor to increase density of processed hologram.

[Para 6]

Also, holograms can be artificially created by means of computer. US patents No 4778262 and No 5194971 and Canadian Patent CA200819 issued to Haines describe the system using computer-generated hologram that can be printed to form a hologram element. US patent No 7675680 issued to Hamano describe the system producing a computer-generated hologram, wherein LCD display is used to reconstruct such holograms. US Patent No 7193754 issued to Borgsmuller, et al. describes methodic of preparation and recording of such computer-generated holograms. Also, digital holography allows image scaling. For example, US Patent No 3756683 issued to Smith describes the method of image scaling by means of hologram transforming.

[Para 7]

Utilization of an array of receivers, which operate in non-visible part of spectrum or, even, non-electromagnetic media, to obtain the digital hologram allows transforming, for example, acoustical hologram taken by sonar array into 3-D visible image. US Patent No 5214581 issued to Rhodes, et al. describes the X-ray micro-holography system that takes image by means of two-dimensional X-ray detector array. US Patent No 4415996 issued to Maynard, et al. describes a system holographically generating visual representations of acoustical characteristics of sound sources that transforms acoustical image into visible one. US Patent No 4314739 describes method for conversion of one wavelength into different wavelength by means of a hologram in which the synthetic hologram representing in visible light the image of an object illuminated by a radiant energy is generated. US Patent No 3633407 issued to Whitman, US Patent No 3745812 issued to Korpel, US Patent No 3879989 issued to Brenden and US Patent No 4284324 issued to Hugnard, et al. describe the systems for acoustic imaginary that transform acoustic image into visible one. In these systems acoustic holograms created in physical substances are directly illuminated by visible coherent light so creating 3-D images representing this acoustic image. All of mentioned systems are analog ones that do not use any receiver array, computer processing and transformation of acoustic hologram on LCD screen.

[Para 8]

Such conversion of waves has inherited disadvantages, such as linear scaling of reconstructed holograms. Because the reconstruction wave is different from the reference wave, the reconstructed wave gets converted in relation to the recorded wave. So scale of reconstructed object becomes different unless the hologram, the object and the wavelength all are scaled linearly by the same factor. Thus, the reconstructed object gets distorted throughout its depth unless said factor is chosen equal to ratio of a reconstruction wavelength to a recording wavelength.

[Para 9]

Also, optical systems used in all mentioned patents are complicated ones containing numerous spatial elements that require mutual maintenance and alignment. Utilization of single-mode optical fiber proposed in the present invention can significantly minimize size of the system; it contains fiber-optical elements and does not require permanent maintenance and alignment. Moreover, output of single-mode optical fiber is an ideal point source producing spherical wave.

[Para 10]

Thus, above-mentioned problems can be overcome by means of utilization:

- a fiber-optical lines connecting lasers to registration and reconstruction cameras,
- a 2D receiver array together with ADT, which digitizes result of interference of object and reference waves of any nature on array's surface so creating synthesized hologram,
- a computer processing, rendering and scaling this hologram,

- a LCD screen illuminated by visible reference light that is properly scaled to represent in visible light the 3-D image taken in different wavelength or by radiant energy (such as acoustic waves).

[Para 11]

Also, today's color holography faces some limitations and problems. The first methods for recording color holograms were established in the early 1960s. Leith and Upatnieks proposed multicolor wavefront reconstruction and Denisyuk introduced the single-beam reflection holography technique which is most suitable for recording color holograms today. It requires thick film that works as wavelength-sensitive interference filter reconstructing an image in its colors without any additional parasite images. Even though this technology is well-developed one, it can not be utilized in systems having 2-dimensioned matrix as a registration media. To overcome this problem, the system employing multi-color laser together with acousto-optical filter is proposed by the author of the present invention.

[Para 12]

Moreover, resolution of existing CCD cameras and IR matrixes is not enough to reconstruct the object in details that causes losing part of information about the object. For example, resolution of photo planes used for holography can reach up to 5,000 elements per millimeter, whereas the best resolution of CCD cameras is about 700 elements per millimeter.

[Para 13]

There were some attempts to increase said resolution to achieve super-resolution. One of such approach is to increase numerical aperture (NA) of the optical system. Several strategies have been defined and different approaches have been tested to increase NA of the optical system in order to get super-resolution. Most of these methods are aimed at increasing synthetically the NA of the light sensor to get super-resolution. Massig et al.

(J. H. Massig, "Digital off-axis holography with a synthetic aperture," Opt. Lett. 27, 2179-2181 (2002)) increased the NA by recording nine holograms with a CCD camera moved to different positions and by recombining them in a single synthetic digital hologram. Alexandrov et al. (*Sergey A. Alexandrov, Timothy R. Hillman, Thomas Gutzler, and David D. Sampson, "Synthetic Aperture Fourier Holographic Optical Microscopy," Phys. Rev. Lett. 97, 168102 (2006))* tried to break the diffraction limit by rotating the sample and recording a digital hologram for each position in order to capture the diffraction field from different directions.

[Para 14]

A different approach was proposed by Kuznetsova et al. *(Y. Kuznetsova, A. Neumann, and S. R. Brueck, "Imaging interferometric microscopy-approaching the linear systems limits of optical resolution," Opt. Express 15, 6651-6663 (2007))*, who rotated the sample in respect to the optical axis in order to re-direct the rays scattered at wider angles into the aperture of the optical system, thus going beyond its diffraction limit. Mico et al. *(Vicente Mico, Zeev Zalevsky, Pascuala García-Martínez, and Javier García, "Superresolved imaging in digital holography by superposition of tilted wavefronts, " Appl. Opt. 45, 822-828 (2006))* proposed and demonstrated a method for enhancing the resolution of the aperture limited imaging systems based on the use of tilted illumination and common-path interferometerical recording. Martínez et al. (*L. Martínez-León and B. Javidi, "Synthetic aperture single-exposure on-axis digital holography," Opt. Express 16, 161-169 (2008))* translated the camera by a few microns in order to increase both the spatial resolution and the sampling in the recoding process. Synthetic-aperture utilized on-axis digital heterodyne holography by LeClerc et al. (*F. Le Clerc, M. Gross, and L. Collot , "Synthetic-aperture experiment in the visible with on-axis digital heterodyne holography," Opt. Lett. 26, 1550-1552 (2001))*, whereas a combination of aperture synthesis and phase-shifting DH was developed by Binet et al. (*Renaud Binet, Joseph Colineau, and Jean-Claude Lehureau, "Short-Range Synthetic Aperture Imaging at 633 nm by Digital Holography," Appl. Opt. 41, 4775-4782 (2002)*)

[Para 15]

Analysis of the methods shown below reveals that all of them require complicated optical system containing large moving elements (particularly, the mentioned Martinez's system requires micron-shifting whole camera about the object). This problem can be overcome by means of utilization of fiber-optical lines having movable output that shifts light source about the matrix. This technology is one of object of in the present invention.

SUMMARY OF THE INVENTION

[Para 16]

The present invention deals with a method and apparatus for monochrome or color digital holography (DH), wherein its holographic image is taken by 2-D matrix and further processed to remove noise, increase hologram density and represent reconstructed image in variable scale. The apparatus utilizes fiber-optical (FO) technology to illuminate object and reconstruct object's image. Acousto-optical filter together with a multi-line laser are further used for color holography.

[Para 17]

DESCRIPTION OF THE DRAWINGS

FIG. 1 depicts scheme of the apparatus of the Preferable Embodiment.

FIG. 2 depicts scheme of the apparatus of the second embodiment - simplified version of the Preferred Embodiment.

FIG. 3 depict scheme of the apparatus of the third embodiment incorporating AO filter.

FIG. 4 depict scheme of the apparatus of the fourth embodiment incorporating hologram shifting mechanism.

FIG. 5 illustrates hologram shifting about the matrix.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT OF THE INVENTION - INLINE/FOURIER HOLOGRAPHIC APPARATUS UTILIZING FIBER-OPTICAL LINES

[Para 18]

All objects (physical bodies) are selfradiating, so they emit IR radiation with wavelength depending on the body temperature. Therefore, bodies heated up to 300 C emits in 3-micron wavelength, wherein 20 C bodies emit in 10-micron wavelength according to Planck's Law. Also all physical bodies consist of scattering elements, so, illuminating such bodies by radiation of any wavelength, it is possible to obtain 2-D optical image, 3-D holographic image and Fourier Transform of the object in this irradiating wavelength. Combining such information about the body allows complete optical reconstruction of this body including its 3-D surface temperature distribution.

[Para 19]

The scheme of the apparatus is depicted in FIG. 1.

The holographic apparatus of the present invention employs single-mode fiber-optical lines 4, 8 and 13 (see FIG. 1), which outputs operate as point sources of inline holography. Movable lenses 16 and 14 allow taking Fourier hologram when matrix 15 and LCD screen 12 are in focal plane of these lenses.

[Para 20]

Registration part of the apparatus comprises FO laser 1 optically connected (pigtailed) to FO single-mode line 2, FO splitter 3 having a single input and two outputs, which input is optically connected to said FO laser 1 via FO single-mode line 2, and two said outputs are optically connected to two single-mode FO lines (FO lines 4 and 8) so dividing laser radiation in two ways. The FO line 4 is optically connected to graded-index FO collimator 5 illuminating an object 17, and the FO line 8 carrying reference light is connected to registration camera 6.

Optionally, the collimator 5 can be removed from the scheme; in this case the object 17 is illuminated by a point source which is output of FO line 4.

[Para 21]

The registration camera 6 comprises 2-dimesional matrix of photo-sensitive elements 15 (it can contain 4 electrically connected matrixes as depicted in FIG. 1) and plane-convex lens 16, wherein the plane surface of the lens 16 has semi-reflecting coating. The lens 16 can be shifted in the position I or II that allows taking picture of the image or Fourier hologram on the matrix 15. The FO line 8 enters the camera 6 in the middle of the IR matrix 15, where said matrix 15 has an opening. Information recorded from the matrix 15 is digitized by ADT 7 and transmitted to computer 11 via USB port 10.

[Para 22]

The registration part works as follows: FO laser 1 emits IR radiation; the FO splitter 3 divides the radiation in two ways. The first portion of the radiation is transmitted by FO line 4 to FO collimator 5 illuminating the object 17. Light scattered from the object 17 enters the registration camera 6 via lens 16, whereas the reference light is emitted from the 9-micron end of FO line 8 as a spherical wave (end of 9-micron-core single-mode optical fiber works as a point light source); said reference light is reflected from semi-reflected surface of the lens 16 and, together with said scattered light illuminates the matrix 15.

Superposition of said scattered and reference light creates hologram on the 2-dimensional matrix15. The analog hologram appeared on the matrix 15 is further digitized by Analog-to Digital-Transformer (ADT) 7 and transmitted to the computer 11 via USB port 10. To take the Fourier hologram of the object, the lens 16 is moved in position II that is on the focal distance from the matrix 15; and to take the picture of the object (self-radiated or illuminated by some light), the laser 1 is shut off and the lens 16 is moved in position I. These data, also, are digitized by ADT 7 and transmitted to the computer 11 via USB port 10. The computer 11 processes said data to scale hologram and display processed hologram on a LCD screen of the registration camera 18 of the apparatus.

[Para 23]

The image reconstruction part of the apparatus operates as follows:

The hologram image is reconstructed by means of the camera 18 containing reflecting LCD screen 12 and movable plane-convex lens 14, which plane surface has semi-reflected coating. The laser 9 optically coupled to single-mode FO line 13 emits visible light, such as green or red. End of the FO line 13 enters the camera through opening in the screen 19 (it can contain 4 electrically connected LCD screens as depicted in FIG. 1). It emits a spherical wave, which is reflected from semi-reflected plane surface of lens 14 and illuminates LCD screen 12 so reconstructing 3-D image of the object 17 that is observed through lens 14. The scale of reconstructed image is adjustable by means of computer software.

[Para 24]

Radiation emitted by the laser 1 can be IR FO standard one (1550 nm); so all elements of the scheme are standard FO ones. Also, it can be any required wavelength, such as visible one, UV or IR (with wavelength up to 10,000 nm). In this case, FO line has to be specially mage from material transparent for this wavelength and the matrix 15 has to be sensitive to this wavelengths. Also, said FO laser has to emit linearly-polarized radiation; and FO lines and its elements (such as FO splitter 3) have to be polarization-maintaining ones.

[Para 25]

Additionally, picture of the object can be taken in its self-radiating wavelength and deep processing of data obtained from inline hologram, Fourier hologram and picture of the object allows complete optical reconstruction of this object including its 3-D surface temperature distribution.

SECOND EMBODIMENT OF THE PRESENT INVENTION

[Para 26]

The scheme of the apparatus of this embodiment is depicted in FIG. 2.

This scheme simplified version of the scheme of the Preferred Embodiment is depicted in FIG. 1. This scheme operates as inline holography. Here, the part of reference wave passes through window 161 having semi-transparent coating and illuminates an object 17. The light scattered from the object 17 - the object wave - passes through the window 161 backward so superposing on matrix 15 with the reference wave reflected from semi-reflecting surface of window 161. This scheme does not require additional light source (FO line 4 and FO collimator 5 on FIG. 1). Reconstruction of the image is performed by the spherical wave emitted by the end 20 of optical fiber 13 passing through transparent LCD 12.

THIRD EMBODIMENT OF THE PRESENT INVENTION UTILIZING MULTI-WAVELENGTH SOURCE AND ACOUSTO-OPTICAL FILTERS

[Para 27]

The scheme of the apparatus of this embodiment is depicted in FIG. 3.

This scheme is the multi-color version of the scheme of the Preferred Embodiment depicted in FIG. 1 that additionally comprises second FO splitter 31 and acousto-optical (AO) filter 14.

[Para 28]

In 60-th Denisyuk introduced the single-beam reflection holography technique which is most suitable for recording color holograms today. It requires thick film that works as wavelength-sensitive interference filter reconstructing an image in its colors without any additional parasite images. Even though this technology is well-developed one, it can not be utilized in systems having 2-dimensioned matrix as a registration media. To overcome this problem, the system employing multi-color laser together with acousto-optical filter is proposed by the author of the present invention.

[Para 29]

To obtain multi-color hologram, the present embodiment comprises multi-line laser 1, wherein said lines are switched by means of AO filter 14. This AO filter can be spatial one optically coupled to FO lines 33 and 34, or FO one based on controllable FO Bragg grating. The scheme of spatial filter is shown on FIG. 3. It contains two collimators - input 141 and output 143 - optically coupled with FO lines 33 and 34 and AO cell 142 electrically connected to AO controller 32.

[Para 30]

The apparatus operates as follows:

The laser 1 optically coupled with FO line 33 emits a number of lines having different wavelength. AO filter controlled by AO controller 32 and computer 11 sequentially extracts each line and transmit it to the FO splitter 31 via FO line 34. The splitter 31 divides said light in two ways. One portion of the light is transmitted to the FO splitter 3 via FO line 2, whereas another portion of light, which is used as a reference light for reconstruction of the image, is transmitted to the camera 18 via FO line 13 so illuminating the LCD screen 12. The first portion of light passed the FO splitter 31 is also divided by the FO splitter 3 in two portions. The first one running in FO line 4, which is optically connected to graded-index FO collimator 5, illuminates an object 17. The second one running in FO line 8, which is connected to registration camera 6, is the reference light illuminating the matrix 15. The registration camera 6 comprises 2-dimesional IR matrix 15 (it can contain 4 electrically connected matrixes as depicted in FIG. 1) and plane-convex lens 16, wherein the plane surface of the lens 16 has semi-reflecting coating. The light scattered from the object 17 enters the registration camera 6 and superposes with the spherical reference wave coming from the end of FO line 8 and reflected from plane surface of the lens 16. The signal acquired by the matrix 15 is further digitized by the ADT 33 and enters the computer 11 via USB port 10; the computer 11 collects data obtained for each wavelength in its memory.

[Para 31]

Reconstruction of the image in color is performed by means of sequentially switched wavelengths emitted by the same laser 1. In this case, the portion of light of the specific wavelength is transmitted from the FO splitter 31 to the camera 18 via FO line 13, reflected from semi-reflecting surface of lens 24, reflected from LCD screen 18 on which hologram taken in this specific wavelength is displayed; and reconstructed image is observed through lens 24. The computer 11 processes data from the matrix 15, controls wavelength switching and creates scaled digital hologram of the object 17 that is displayed on LCD screen 12. Thus, image of the object 17 is sequentially reconstructed in different wavelengths. Also, movable lenses 16 and 24 allow performing inline and Fourier holography in the same way as described in the Preferred Embodiment.

[Para 32]

The wavelength of radiation emitted by the laser 1 can be in any waveband including visible, IR and UF ones. In the first case, this system allows creating color image of the object 17, which can be reconstructed in real time or recorded in computer's memory.

FOURTH EMBODIMENT OF THE PRESENT INVENTION - TWO-DIRECTIONAL SHIFTING OF FO LINE OUTPUT ABOUT MATRIX

[Para 33]

It is known, that hologram resolution depends on resolution of photo plate or matrix. Resolution of existing matrixes is limited (even for the most advanced CCD matrix) by 200 - 300 cells per millimeter, whereas photosensitive materials provide about 1,000 - 5,000 pixel per millimeter. The formula for required resolution of the recording element (matrix or photo plate) is: $\nu = 2/\lambda \times \sin(\beta/2 + \alpha/4 - \gamma/4 + \phi/4)$ [1],

where ν - required resolution (number of elements per micron), λ - wavelength (microns), γ - angular aperture of optical fiber 8, β - angle between axis of output of optical fiber 8 (see FIG. 1 - 3) and the line connecting output of optical fiber 8 to center of the object 17, α - angular size of the matrix 15 visible from the center of the object 17, and ϕ - angular size of the object 17 visible from the center of the matrix 15.

Formula [1] allows brief evaluating the necessary resolution of the matrix 15. For the scheme depicted in FIG. 2, the angle between axis of output of optical fiber 8 and the line connecting output of optical fiber 8 to center of the object 17 is equal to zero ($\beta = 0$). Angular aperture γ of single-mode optic fiber is about 28 arc degrees. Assume that matrix consists of four matrixes 30 x 30 mm each (total size 60 x 60 mm) and operates at $\lambda = 0.5$ microns (green light). Also assume that the object size is 250 mm and distance between object 17 and matrix 15 is 380 mm (distance on which the beam illuminates whole 250-mm object). Thus, the angles are follows: $\alpha = 8$ arc degrees and $\phi = 38$ arc degrees. In this case the required resolution of the matrix will be $v = 0.31$ (element/micron), so required size of matrix cells has to be about 3.2 microns. The cell size of the best conventional CCD matrix (for example, Hasselblad and SONY professional digital cameras) is about 7 microns, that is two times larger than the required one, but newest CCD matrix (for example, ICX681SQW image sensor from SONY) has cell size of about 1.45 microns that is enough for holography in visible light at the condition when the angle between axis of output of optical fiber (angle β) is equal to zero or small. In some cases it is necessary to have some angle between axis of output of optical fiber and the line connecting output of optical fiber to center of the object (angle β in formula [1]). In this case, for example for $\beta = 10$ arc degrees, the resolution v will be 0.66 elements per micron (cell size of 1.5 micron), and for $\beta = 20$, the resolution v will be about 1 element per micron (so cell size is 1 micron). Therefore, the resolution of existing CCD matrix is not enough to fully reconstruct the image in sharpest details.

[Para 34]

Also, for UV and X-ray holography required resolution will be proportionally higher and required size of the cell can not be achieved by today's matrix technology. Therefore, quality of such holograms will be limited by density of photo-sensitive cells of this matrix. To increase said resolution it is necessary to make the photo-sensitive elements significantly smaller, or use interpolation technology that artificially fills hologram pattern between said photo-sensitive elements. The last solution allows diminishing hologram noise caused by discrete photo-sensitive element, but can not significantly increase hologram resolution.

There is another solution that uses programmable mechanical shifting the hologram (or any image) on the matrix 16. In this case, shifting the image on some predictable distance changes the integral volume of power accepted by single photo-sensitive element (cell). So, interpolation of EMF (or resistance of photo-resist cells) based on algorithm of computer tomography allows significantly increasing resolution of the matrix. In this case, the computer 11 is processing the data obtained in the process of said shifting.

[Para 35]

To achieve this, the matrix 15 can be mechanically shifted in X and Y directions; but It is much easy to shift in X and Y output end of the FO line 8, which is proposed in this embodiment of the present invention. Therefore, linear shifting of the end of the FO line 8 provides the same shifting of the image on the matrix 15.

[Para 36]

Shifting mechanism of the present embodiment is depicted in FIG. 4, whereas the rest of the scheme of this embodiment is the similar to one depicted in FIG. 1 - 3. The shifting mechanism comprises holder 42 of optical fiber 8, precession micro-step linear motors 43 and 44 controlled by the processor 11, and spring 45. The micro-step motors 43 and 44 shift output of optical fiber 8 in X and Y according to the program written in memory of the processor 11. The spring 45 supports the holder 42. The micro-step motors 43 and 44 provide steps as small as 0.3 - 0.5 microns and the full dismissal is equal to size of matrix's cell.

[Para 37]

The laser 1 of this embodiment can be continuous wave (CW) or pulse one. In the case of short pulse laser, it can be activated each time when the step motors 43 and 44 shift the output end of the FO line 8 on specific distance according to schedule written in the memory of the computer 11. Series of holograms obtained for different position of the output end of the FO line 8 are further stored in memory of the processor 11.

[Para 38]

This solution allows about 10 times increasing the resolution by means of processing a number of images of the hologram that are sequentially shifted in X and Y directions about the matrix 15. In this case, signal received from any single cell is processed separately and, after this, all signals are merged in a single high-resolution holographic image. Therefore, amplitudes of the optical signal detected by each cell of the matrix 15 are changed while the output end of the FO line 8 is shifted. This process is illustrated on FIG. 4. Here, the hologram is shifted from position I to position III. The electrical signal appeared on each cell is proportional to integral of the power of optical signal affecting said cell:

$$U_{cell} = k \iint P_{(x,y)}\, dxdy \qquad [2],$$

Where: P - power of optical signal, k - coefficient of cell efficiency (volt/watt). The integral is taken from x_1 to x_2 and from y_1 to y_2, wherein x and y - coordinates of cell borders. When the hologram (picture) is shifted, coordinates of the cell borders (in the coordinate system of the hologram) are shifted too and become: $x'_1 = x_1 + \Delta x$, $x'_2 = x_2 + \Delta x$, $y'_1 = y_1 + \Delta y$, $y'_2 = y_2 + \Delta y$; where Δx and Δy - linear shift of hologram (picture) about the matrix. Further processing of shifted signals utilizes algorithm of tomogram processing; but, unlike conventional 3-D tomography when the image recorder rotates about the object, here the image recorder (matrix 15) is linearly moving about the hologram sequentially taking picture of the hologram, wherein coordinates x_1, x_2 and y_1, y_2 become the moving borders.

IMAGE RECONSTRUCTION

[Para 39]

Schemes of holographic devices depicted in FIG. 1 - 4 introduce elements, which reconstruct the image. They include laser 9, FO line 13, LCD screen 12 and lens with semi-reflected coating 14. The embodiments shown on FIG 3 for image reconstruction utilizes the same laser 1 that operates as a reference and object source.

According to holography theory, a linear enlargement of the reconstructed object is described by the formula:

$M = \mu/m \times Z_r/Z_o$ [3],

where $\mu = \lambda_r/\lambda_o$; λ_r - wavelength of reconstructing light, λ_o - wavelength of reference light,

$m = L_r/L_o$; L_r - size of reconstructed object, L_o - size of original object,

Z_r/Z_o - ratio of distances of the reconstructed object and the original object about the hologram (reconstructing and original).

Therefore, if wavelengths are the same, size of hologram is the same and distances still the same, the reconstructed object is not magnified. Also, if $\mu = 1$, size of the reconstructing hologram is m time larger than original one, to achieve the same linear dimensions of the reconstructed object ratios m and Z_r/Z_o have to be: $m = Z_r/Z_o$.

To reconstruct image from high-resolution hologram obtained from the shifting technique - the object of the fourth embodiment of the present invention - it is necessary to use high-resolution LCD screen, wherein size of each element should not to exceed 3 - 4 microns and the screen should have size of 600 x 600 mm.

Thus, for 600-mm LCD screen 12 (reconstructing hologram), the distance from reconstructing light source 20 - the end of FO line 13 - to LCD screen 12 (see FIG. 1 and 2) - has to be 3,800 mm according to formula [3]; in this case the reconstructed object will have the same size as the original one.

Also, to magnify the reconstructed image, it is need to change the ratio Z_r/Z_o. So, if the distance from reconstruction source to LCD screen is 7,600 mm, it will magnify reconstructed image twice (see formula [3]).

[Para 40]

Moreover, it is possible to transform holographic image taken in IR wavelength in visible one. In this case, the reconstruction source has to emit coherent visible light. So, if IR wavelength in which the initial hologram was taken is 3 microns, and reconstruction wavelength is 0.5 micron, magnification of reconstructed image will be determined by formula [3]:

$M = \mu/m \times Z_r/Z_o$.

As an example, if $\mu = 3/0.5 = 6$, $m = 10$ (60-mm matrix and 600 mm LCD screen), $Z_r/Z_o = 10$ (380 mm from matrix 15 to the object 17, and 3,800 mm from LCD screen 12 to output of FO line 13), the magnification of the reconstructed image will be about six times.

[Para 41]

The matrix 15 of all embodiments of the present invention can be high-resolution CCD one (for visible and near IR light) or made of photo resist elements, such as PbS or PbSe (up to 3-micron-wavelength IR) or CdHgTe (up to 10-micron-wavelength IR). In these cases, required resolution of the matrix can be evaluated by the formula [1], and the size of the reconstructed image - by the formula [3].

DIGITAL HOLOGRAM PROCESSING

[Para 42]

Digitizing of the hologram requires its transformation in a table containing a number of digital discrete values taken from each pixel of the holographic image (for the system depicted in FIG. 4 - taken from each cell of the matrix 15). Old-style holograms taken on photo plates were digitized by means of optical-electronic reader, that record and digitize the photo plate transparency of 2-dimensional hologram image divided by net on N (horizontal) x M (vertical) square pixels.

[Para 43]

Each said square pixel has coordinates (X_1, Y_1), (X_1, Y_2), (X_2, Y_1) and (X_2, Y_2); so the optical signal taken from such pixel is its integral (median) value determined by the formula [2] and such representation of initial analog hologram can only be approximate one.

On another hand, the Sampling Theorem (Nyquist-Kotelnikov Theorem) posts: if the function has spectrum limited by spatial frequency of f_0, it can be represented by pixels (cells) separated by distance of $\Delta x = 1/2f_0$ [4], wherein the value of the optical signal taken from each cell can be represented by the signal applied to the knots (X_i, Y_i) of said net. So, if the cell has dimensions of p_0 x q_0, the net can be substituted by 2-dimensional field of said spots (knots), wherein total number of said spots is equal N x M, so the image can be represented by numerical N x M table (matrix). Also, it means that sell size depends of spatial spectrum of the object. So, uniformly scattering large object that does not have any details can be represented by a single cell, whereas the object having more details can be represented by more complicated matrix. Because the hologram system of the present invention has to equally work for objects having different spatial frequency, the size and number of matrix's cells should be determined by the formula [1]. Such matrix allows fully utilizing all geometry features of the systems of the present invention to achieve the maximal resolution of the reconstructed object.

[Para 44]

Because hologram pattern appeared on the matrix 15 (see FIG. 1 - 4) has to be digitized for further storing and processing, ADT (position 7 on FIG. 1 - 3) is introduced in the schemes of all embodiments. Thus, this digital hologram is represented by the net (N x M table) of digital values of the optical signal taken by each cell of N x M-element matrix. Being reconstructed the object image will have (be limited by) spatial frequency (resolution) determined by the formula [4].

[Para 45]

As an example, the procedure of processing of Fourier hologram in simplified form is represented on FIG. 6.

After digitizing the digital hologram is represented by the N x M matrix of digital values of the optical signal taken by each cell. After this, knowing geometrical parameters of the optical system and CCD matrix, fast Fourier transformation is performed for rows and columns of the matrix, wherein, to simplifying the calculations, the matrix obtained from the first Fourier transformation is transponated (changed rows to columns) that allows using the same algorithm for the second Fourier transformation. As the result, transparency (or reflectivity) of the image-reconstructing LCD screen is obtained for each element (cell) of said LCD screen. So illuminating the LCD screen by the reference light as depicted in FIG. 1 and 3 allows reconstructing the 3-D image.

[Para 46]

In the case when the hologram is shifted about the CCD (the fourth embodiment of the present invention), interpolation procedure is additionally performed for each cell in each shifted position. To achieve the maximal resolution of the hologram of this embodiment the algorithm of computed tomography can be applied for each cell 112, 113, 114, etc. of the CCD matrix (position 15 on FIG. 4).

[Para 47]

To remove hologram noise caused by CCD matrix discrete cells (the image looks like to be observed through a net), Fourier transform of this net can be subtracted from Fourier transform of the image.

[Para 48]

Described above calculation procedure can be applied to computer-created Fourier hologram. The procedure of processing of such Fourier hologram in simplified form is represented on FIG. 7.

Here, the computer image created in graphic-designer software is transformed into N x M numerical matrix. After this, for pre-calculated geometrical parameters of simulated optical system and CCD matrix, fast Fourier transformation is performed for rows and columns of this N x M matrix. As the result, transparency (or reflectivity) of the image-reconstructing LCD screen is obtained for each element (cell) of said LCD screen. So illuminating the LCD screen by a reference light as depicted in FIG. 1 and 3 allows 3-D reconstruction of this computer-created image.

THE EMBODIMENT OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

[Claim 1]

The holographic apparatus comprising a registration part and an image reconstruction part, wherein:
said registration part comprises a single laser optically connected via a first single-mode FO line to an input of a single-mode FO splitter having a first output, a second output and a third output, wherein said first and second outputs are optically connected to a second and a third single-mode FO lines respectively; and an output of said second FO line and an output of said third FO line operate as two point sources of radiation, wherein said output of said second FO line - a first point source of radiation - emits an object wave and said output of said third FO line - a second point source of radiation - emits a reference wave, wherein obtained hologram - the result of interference of said object wave with said reference wave - is taken by a matrix of photo-sensitive cells; and data obtained from said matrix of photo-sensitive cells are digitized and numerically processed by a computer in a form a digital hologram that is displayed on a LCD screen of said image reconstruction part,
said image reconstruction part comprising said LCD screen illuminated by said reference wave coming from a third point source, which is an output of a fourth single-mode FO line optically connected to said third output of said FO splitter; wherein said first, second, third and fourth FO lines and said FO splitter are polarization-maintaining ones, and said single laser emits stable linearly-polarized radiation.

[Claim 2]

The holographic apparatus of Claim 1, wherein the registration part of Claim 1 additionally comprises a window having a semi-reflecting coating that, being illuminated by the reference light of Claim 1, reflects part of said reference light to the matrix of Claim 1, whereas another part of said light passed through said window illuminates an object as an object wave; therefore the FO splitter of Claim 1 has only two outputs and the second FO line of Claim 1 is eliminated from the scheme, wherein the first output of Claim 1 is connected to the third FO line of Claim 1 transmitting light to said registration part, and the second output of Claim 1 is connected to the fourth FO line of Claim 1 transmitting light to said registration part.

[Claim 3]

The holographic apparatus of Claim 1, wherein the registration part of Claim 1 additionally comprises a plane-convex lens placed on focal distance from the matrix of Claim 1, which plane surface faces the matrix of Claim 1 and has a semi-reflecting coating that, being illuminated by the reference light of Claim 1, reflects part of said reference light to the matrix of Claim 1, whereas another part of said light passed through said window illuminates an object as an object wave; therefore a hologram appeared on said matrix is a Fourier hologram.

[Claim 4]

The holographic apparatus of Claim 1, wherein the laser of Claim 1 is a multi-line one emitting radiation of different colors, and the registration part of Claim 1 additionally comprises acousto-optical filter which input is optically connected to said laser and output is optically connected to the first FO line of Claim 1, wherein said acousto-optical filter sequentially extracts a single line of specific color from said radiation emitted by said laser; so said radiation is spitted by the splitter of Claim 1 on three point sources of Claim 1, wherein the first source of Claim 1 illuminates an object as an object wave, the second source of Claim 1 works as a reference wave to create the hologram of Claim 1, and the third source of Claim 1 illuminates the LCD of Claim 1 in the image reconstruction part of Claim 1; so superposition of reconstructed images of said object taken in different wavelengths creates 3-D multi-color image of said object.

[Claim 5]

The holographic apparatus of Claim 1, wherein the output of said second FO line of Claim 1 that is the first point source of radiation of Claim1 is mechanically and programmable shifted by small steps in X and Y in the plane of the matrix of Claim 1; therefore a spherical wave emitted by said first point source of radiation of Claim1 is shifted about said matrix that allows increasing resolution of said matrix by means of computer tomography performed by said shifting for each individual cell of said matrix.

[Claim 6]

The holographic apparatus of Claim 1, wherein the laser of Claim 1 and the matrix of Claim 1 are the IR ones, wherein said holographic apparatus additionally comprises a visible-light laser optically connected to the fourth FO line of Claim 1, which output illuminates the LCD screen of Claim 1 by visible light; wherein the data obtained from the matrix of Claim 1 are processed by the computer of Claim 1 to display and scale a hologram of IR image of the object of Claim 1 in visible light on the LCD screen of Claim 1; therefore, the 3-D image of the object in visible light is reconstructed by means of illumination of said LCD screen by said visible light.

[Claim 7]

The holographic apparatus of Claim 1, wherein the digital hologram of Claim 1 is a computer-simulated one; and said digital hologram is displayed on a LCD screen of the image reconstruction part of Claim 1.

DRAWINGS

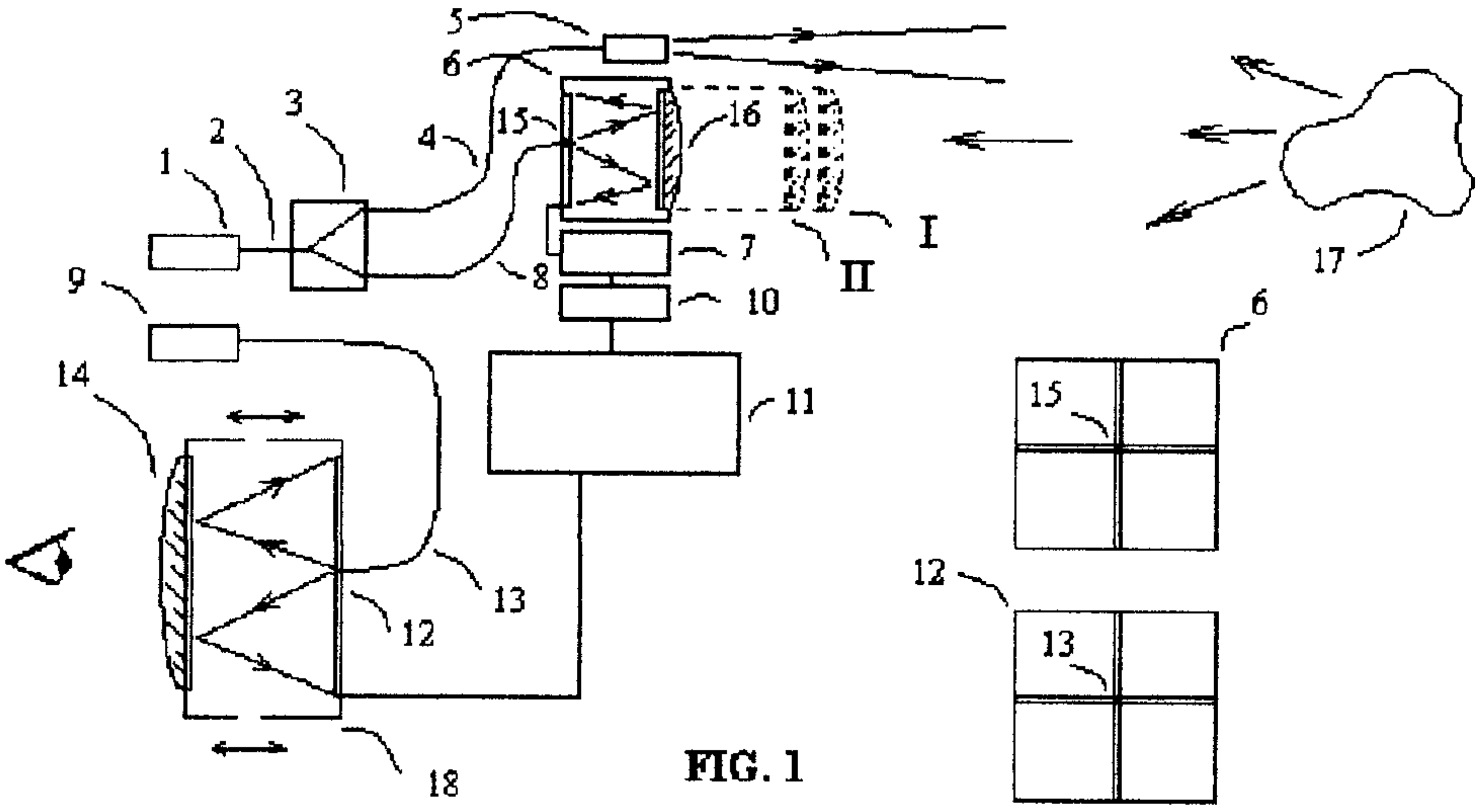


FIG. 1

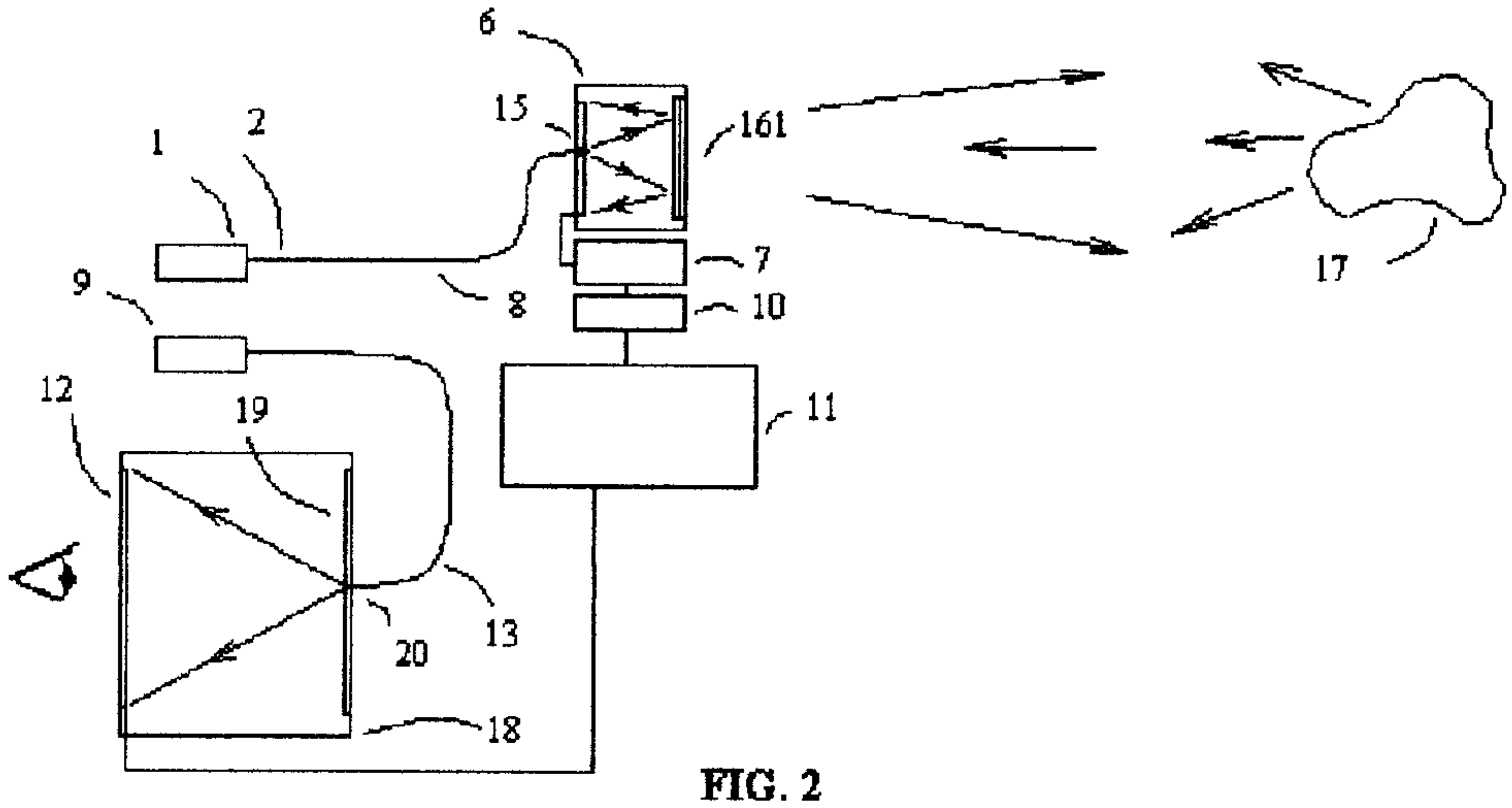


FIG. 2

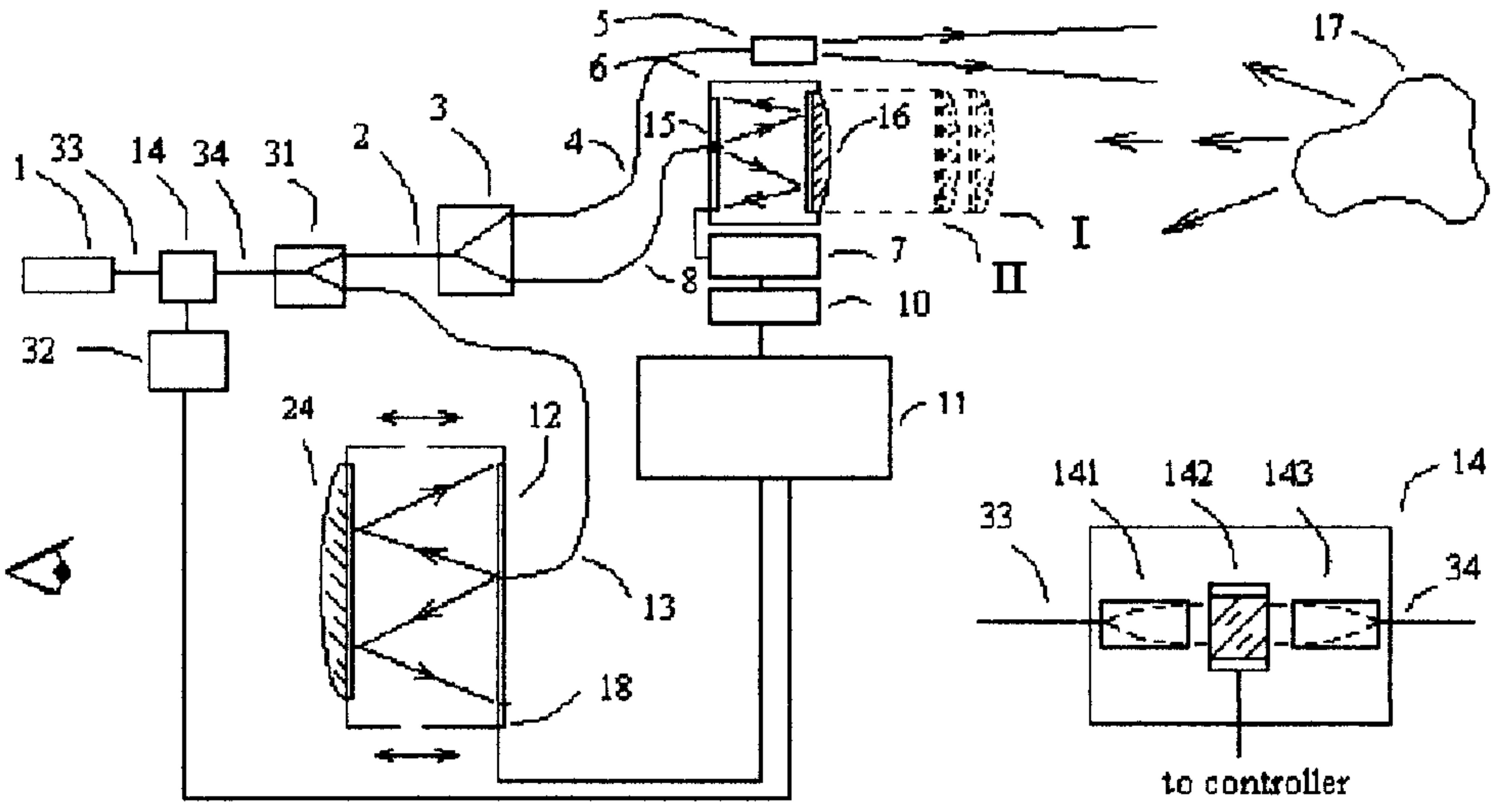


FIG. 3

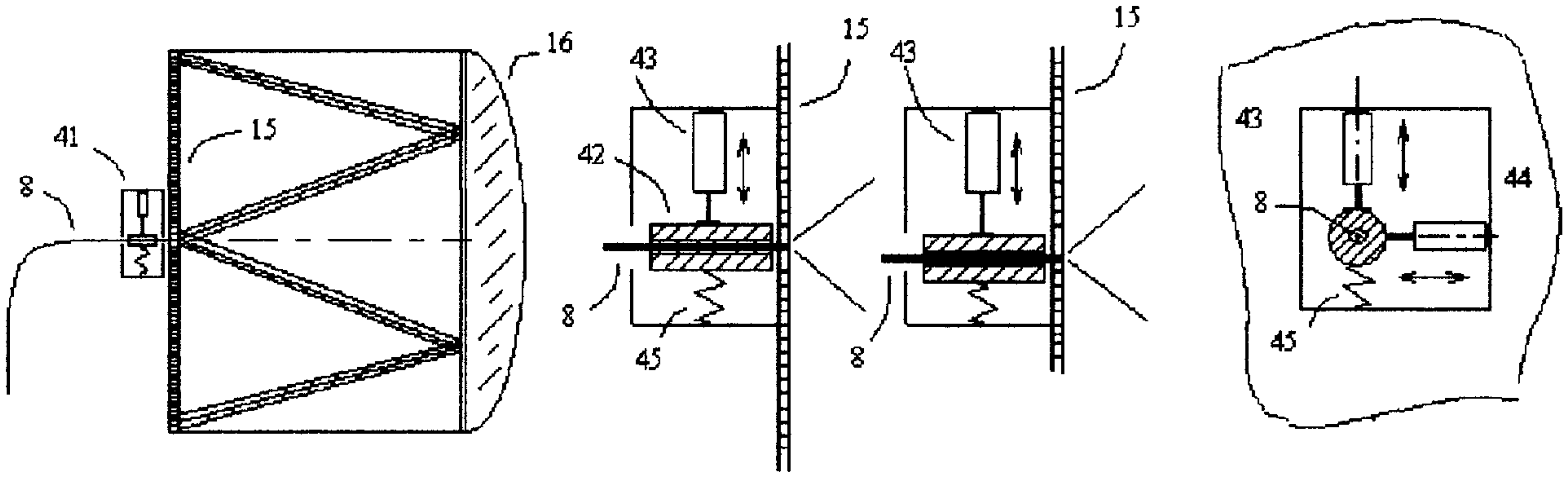


FIG. 4

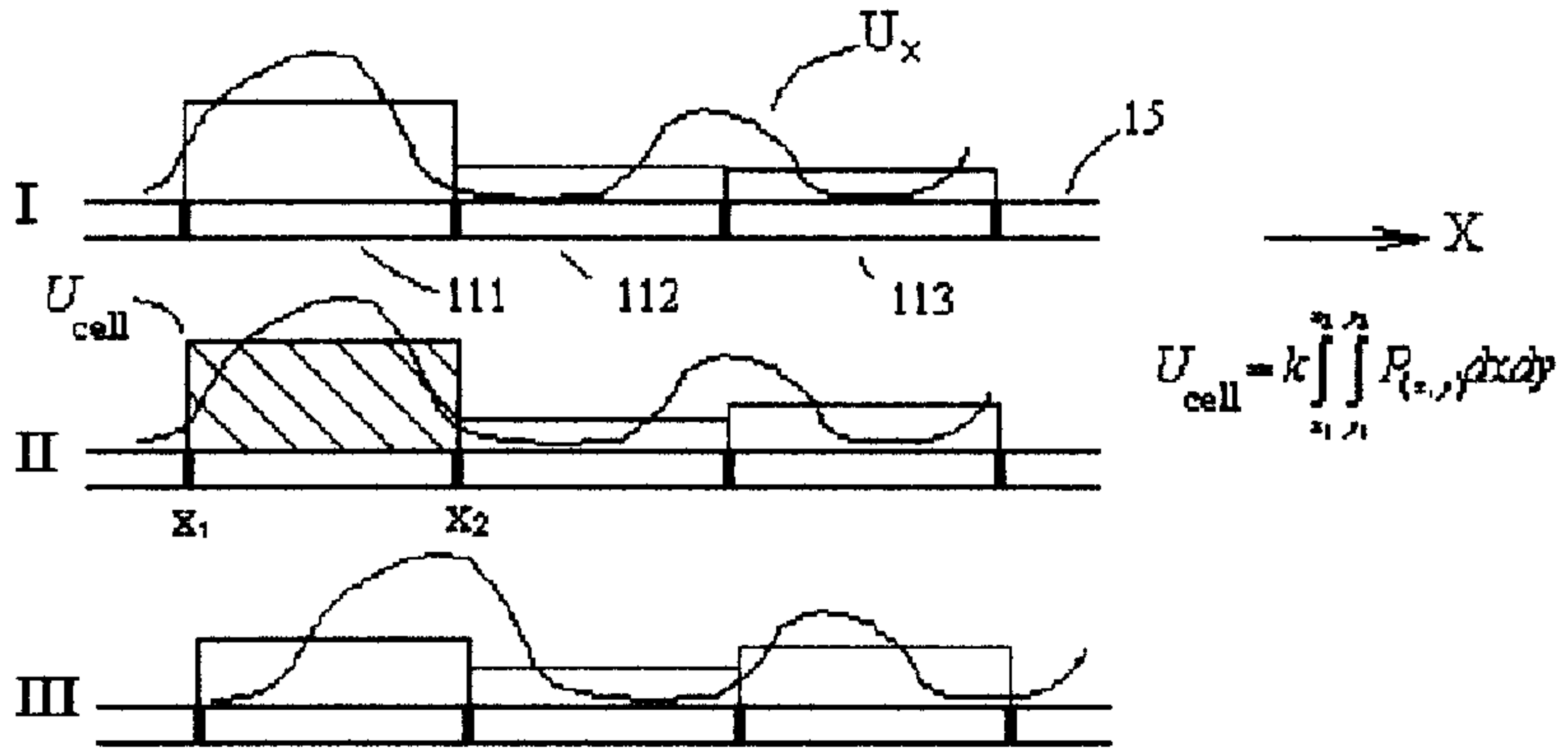


FIG. 5

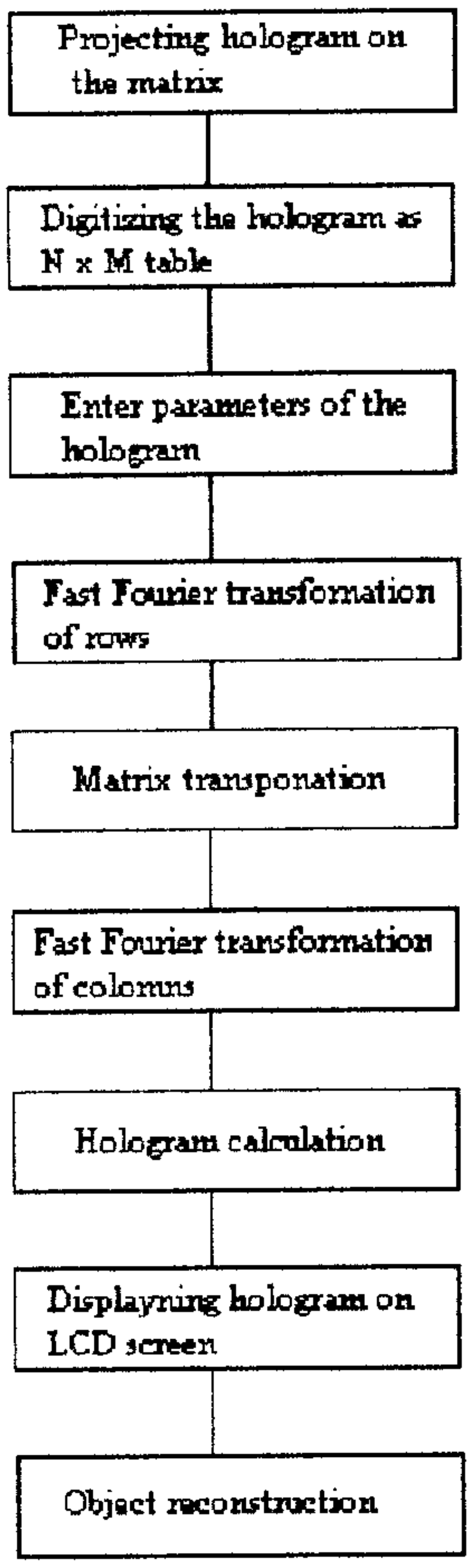

Projecting hologram on the matrix
Digitizing the hologram as N x M table
Enter parameters of the hologram
Fast Fourier transformation of rows
Matrix transponation
Fast Fourier transformation of columns
Hologram calculation
Displayning hologram on LCD screen
Object reconstruction

FIG. 6

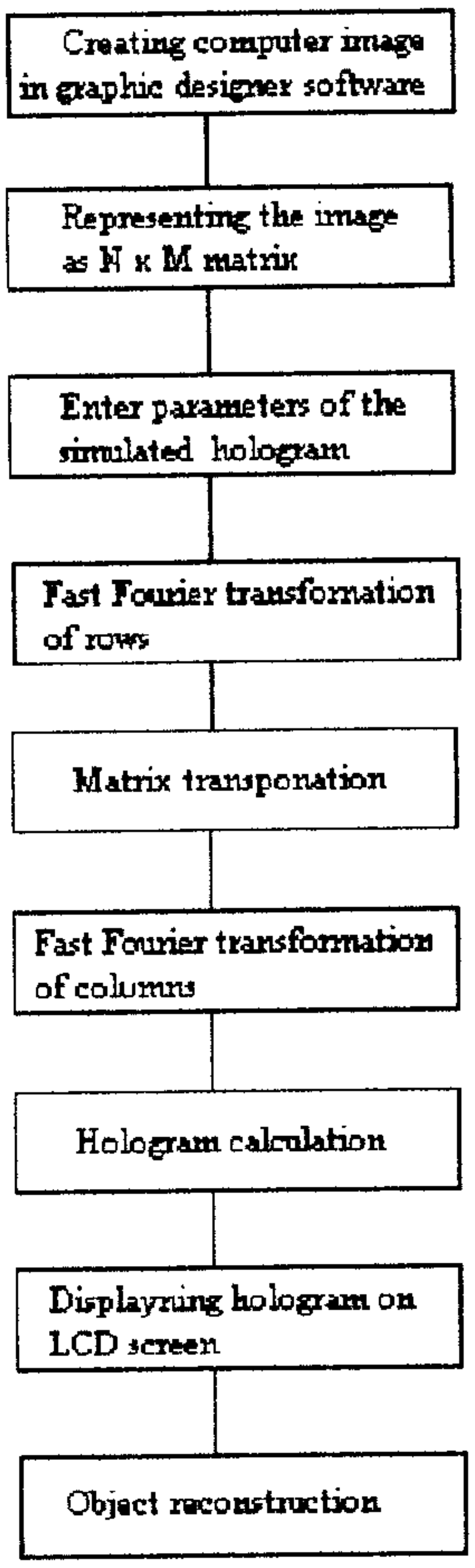
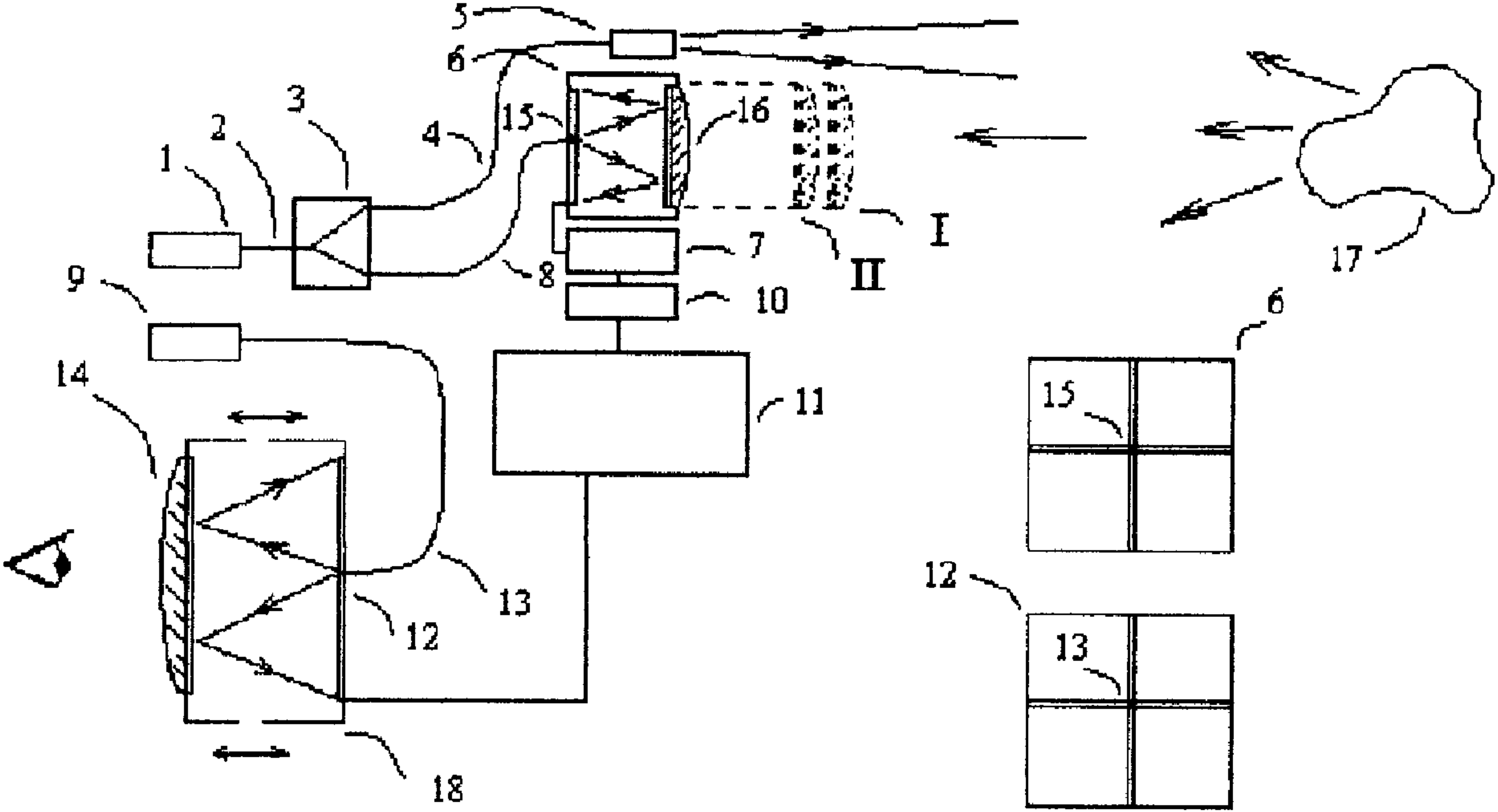

Creating computer image in graphic designer software
Representing the image as N x M matrix
Enter parameters of the simulated hologram
Fast Fourier transfomation of rows
Matrix transponation
Fast Fourier transformation of columns
Hologram calculation
Displayning hologram on LCD screen
Object reconstruction

FIG. 7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