(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
24 December 2014 (24.12.2014)

WIPO | PCT

(10) International Publication Number
WO 2014/204623 A1

(51) International Patent Classification:
G03H 1/02 (2006.01)

(21) International Application Number:
PCT/US2014/039737

(22) International Filing Date:
28 May 2014 (28.05.2014)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/837,728 21 June 2013 (21.06.2013) US

(71) Applicant: **UNIVERSITY OF SOUTH FLORIDA** [US/US]; 3802 Spectrum Blvd., Suite 100, Tampa, FL 33612 (US).

(72) Inventor: **KIM, Myung, K.**; 3802 Spectrum Blvd., Suite 100, Tampa, FL 33612 (US).

(74) Agents: **RISLEY, David, R.** et al.; Thomas | Horstemeyer, LLP., 400 Interstate North Parkway, Suite 1500, Atlanta, GA 30339 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,

[Continued on next page]

(54) Title: FULL-COLOR INCOHERENT DIGITAL HOLOGRAPHY

(57) Abstract: In one embodiment, a color holographic image is created by generating a separate complex hologram for each of multiple different colors of an object field illuminated with incoherent light, combining the separate complex holograms to obtain a color complex hologram, and generating a reconstructed color holographic image of the object field.

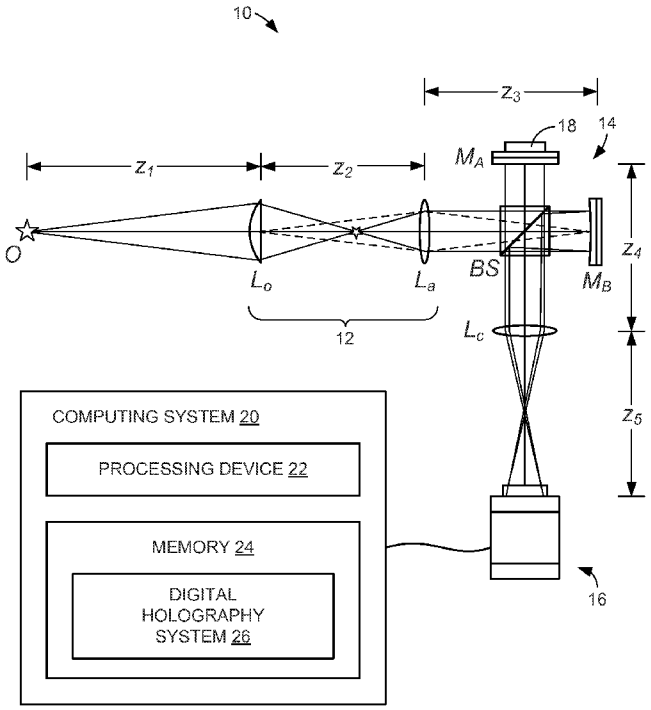


FIG. 1

WO 2014/204623 A1

EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

FULL-COLOR INCOHERENT DIGITAL HOLOGRAPHY

Cross-Reference to Related Application(s)

This application claims priority to co-pending U.S. Provisional Application serial number 61/837,728, filed June 21, 2013, which is hereby incorporated by reference herein in its entirety.

Background

While conventional photography records a two-dimensional projection of the intensity profile of an object onto a fixed plane, holography records enough information to enable recreation of the three-dimensional optical field emanating from an object, including both the amplitude and phase of the optical field. The three-dimensional recording is made possible by the interference of the object's optical field with a so-called reference field and therefore requires coherence between the two fields. In the original conception of holography, the reference was realized from a part of the illumination undisturbed by the object. The invention of the laser made it possible to provide the coherent reference field explicitly and with a high degree of freedom in the optical configurations. Three-dimensional holographic

images quickly captured the imagination of the general public and lead to a multitude of new technological applications. In such applications, coherence of the reference light was at the core of the holographic principle. Unfortunately, this has been a major impediment to a wider range of applications of holography because it requires special illumination sources, such as lasers, or significantly constraining the optical configurations.

Digital holography is an emergent imaging technology that has been made possible by advances in computing and image sensor technologies. Whereas photography is made faster and more convenient by the digital technologies, the digital implementation of holography has a more fundamental impact in new imaging modalities that have been impossible or impractical in analog versions. Once a hologram is acquired and stored in a computer as an array of complex numbers that represent the amplitude and phase of the optical fields, the hologram can be numerically manipulated in highly flexible and versatile manners.

While digital holography has been used in various scientific contexts, it has not been implemented to capture color images of scenes illuminated by incoherent light. If the requirement of coherent illumination can be removed, it would open doors to a wide range of new applications, including holography of scenes illuminated with ordinary light sources such as day light, room light, LEDs, etc. Holographic imaging could be effectively applied to all areas of common photography. Many areas of scientific imaging, from fluorescence microscopy to astronomical telescopy, that have been inaccessible to holography because of coherent illumination requirement, can now benefit from many powerful and versatile holographic imaging and processing techniques.

Brief Description of the Drawings

The present disclosure may be better understood with reference to the following figures. Matching reference numerals designate corresponding parts throughout the figures, which are not necessarily drawn to scale.

Fig. 1 is a schematic diagram of an embodiment of a color self-interference incoherent digital holography (CSIDH) system.

Fig. 2 is a flow diagram an embodiment of a method for performing CSIDH to generate a color digital holographic image.

Fig. 3A is an example CSIDH image of a toy boat under halogen lamp illumination.

Fig. 3B is an example CSIDH image of an outdoor scene under daylight illumination.

Fig. 4A is an example CSIDH image of a scene focused on distant buildings in the scene.

Fig. 4B is an example CSIDH image of the scene of Fig. 4A while focusing on a toy boat in the foreground.

Fig. 5A is an image of a flash light captured by a CCD camera.

Fig. 5B is a panel of images that show the amplitude of a complex hologram of the flash light for red, green, and blue channels.

Fig. 5C is a panel of images that show the phase of the complex hologram of the flash light for the red, green, and blue channels.

Fig. 5D is a panel of numerically focused images from the hologram of the flash light for the red, green, and blue channels.

Fig. 5E is a panel of full-color holographic images of the flash light focused at five distances (-40, -20, 0, +20, +40 mm) from the best focal distance in the hologram space, which was 30 mm.

Fig. 6A is a panel of images that show the amplitude and phase of a hologram of a toy

boat for the red channel.

Fig. 6B is a panel of numerically focused images from the hologram of the toy boat for the red, green, and blue channels.

Fig. 6B is a mobile phone camera image of the toy boat for comparison.

Fig. 6D is a full-color focused holographic image of the toy boat.

Fig 6E is a panel of full-color holographic images of the toy boat focused at five distances (-40, -20, 0, +20, +40 mm) from the best focal distance in the hologram space, which was 30 mm.

Fig. 7A is a panel of images that show the amplitude and phase of a holograph of an outdoor scene under clear daylight illumination for the red channel.

Fig. 7B is a panel of numerically focused images from the hologram of the outdoor scene for the red, green, and blue channels.

Fig. 7C is a mobile phone camera image of the outdoor scene for comparison.

Fig. 7D is a full-color focused holographic image of the outdoor scene.

Fig. 7E is a panel of full-color holographic images of the outdoor scene focused at five distances (-40, -20, 0, +20, +40 mm) from the best focal distance in the hologram space, which was 30 mm.

Detailed Description

As described above, digital holography has been applied to various scientific applications but has not been applied to other applications, such as capturing color holographic images of scenes illuminated by incoherent light. As described herein, three-dimensional, full-color images of objects under incoherent illumination can be obtained using a color digital holography technique. Color holographic images can be generated based on self-interference of two beam-split copies of the object's optical field with differential

curvatures. In some embodiments, the images can be captured using an apparatus comprising a beam-splitter, mirrors, a mirror actuator, lenses, and a color light sensor. No lasers or other special illuminations are required.

Described in the disclosure that follows are systems and methods for performing incoherent digital holography to produce full-color holograms of scenes illuminated by incoherent (e.g., natural) light. The systems and methods are based on self-interference with differential curvature. In some embodiments, two mirrors of different curvatures are used to generate two copies of the object field. Superposition of the two copies leads to Fresnel zone pattern interference from each source point. The spatial incoherence of the object points leads to rapid build-up of incoherent background, which is removed by dithering one of the two mirrors in the interferometer, as in phase-shifting digital holography. Several such phase-shifted interference patterns are acquired by a color digital sensor. For example, three RGB color channels can be extracted and separate complex holograms can be independently generated for each channel by arithmetically combining the several frames of each channel. The separate complex holograms can then be combined to form a color complex hologram that comprises three two-dimensional arrays of complex numbers. Numerical propagation can then be performed to any distance to reconstruct the object's optical field and generate a full-color holographic image of the object.

Fig. 1 illustrates an example color self-interference incoherent digital holography (CSIDH) system 10 that can be used to generate full-color holographic images in the manner summarized above. As shown in Fig. 1, the system 10 generally comprises an optical system 12, an interferometer 14, a color light sensor 16, and a computing system 20. In some embodiments, one or more of those components can be contained within an integrated digital holographic camera.

As shown in Fig. 1, the optical system 12 is represented by an objective lens L_o and a

relay lens L_a that together form an intermediate image in front of the interferometer 14. In some embodiments, the lenses L_o and L_a can have 25 cm and 10 cm focal lengths, respectively. While only these two lenses are shown in Fig. 1, it will be appreciated that the optical system 12 could comprise further lenses.

The interferometer 14 includes a beam splitter BS and two mirrors M_A and M_B. In the illustrated embodiment, mirror M_A is a planar mirror while M_B is a curved (concave) mirror. It is noted, however, that each mirror can be curved as long as they do not have the same curvature. In some embodiments, the mirror M_B has a focal length f_B of approximately 60 mm. The mirror M_A is mounted to a linear actuator 18, such as a piezoelectric actuator, that can adjust the position of the mirror along the optical axis for phase shifting (dithering). In some embodiments, the actuator 18 is capable of nanometer-scale adjustment of the mirror M_A.

The interferometer 14 further includes an imaging lens L_c that focuses the waves reflected by the mirrors M_A and M_B onto a color light sensor 16. In some embodiments, the lens L_c has a focal length of approximately 10 cm. The light sensor 16 can comprise a color charge-coupled device (CCD) or other color light detector. By way of example, the light sensor 16 can have 1024 x 768 pixels, a 4.76 x 3.57 mm sensor area, and 8-bit pixel depth. The three color channels of the sensor 16 can have sensitivity peaks near 620 nm, 540 nm, and 460 nm for the red, green, and blue channels, respectively. By way of example, the distances in Fig. 1 can be $z_2 \simeq 35$ cm, $z_3 = z_4 = z_5 \simeq 20$ cm.

During operation of the system 10, the objective lens L_o forms an intermediate image of the object field in front of the interferometer 14. The relay lens L_a is used to image the input pupil onto the mirrors M_A and M_B, achieving the requirement of $z' = 0$. The imaging lens L_c is used, in combination with L_o, to adjust the magnification and resolution of the system 10.

With further reference to Fig. 1, the computing system 20 generally comprises a processing device 22 and memory 24 (i.e., a non-transitory computer-readable medium) that stores digital holography system 26 that includes one or more algorithms (i.e., logic). As is described below, image data, such as color interference patterns captured by the sensor 16, can be provided to the computing system 20 for processing including the generation of full-color digital holograms of the object field.

Fig. 2 is a flow diagram that describes an example method of CSIDH using a system similar to that shown in Fig. 1. Beginning with block 30 of Fig. 2, light from an object field is received by an interferometer from an optical system. In some embodiments, the optical system an interferometer comprise part of a digital holographic camera. Turning to block 32, the light waves that are reflected by the mirrors of the interferometer are captured. In some embodiments, the waves can be reflected by a planar mirror M_A and a curved mirror M_B. In other embodiments, the waves can be reflected by a two curved mirrors having different radii of curvature, and therefore different focal lengths. Irrespective of the nature of the mirrors, the light reflected by the mirrors is captured by a color light sensor, such as a color CCD. The light waves can have been split by a beam splitter of the interferometer to provide copies of the waves to both mirrors. The light waves reflected by the mirrors interfere with each other and form an interference pattern, which can be captured by the color light sensor.

The interference can be used to generate interferograms of the object field. More particularly, the interference can be used to generate interferograms for each color of the color light sensor. These interferograms can be output from different channels of the color light sensor with each channel pertaining to a different color of the object field. For example, the sensor can output red interferograms, blue interferograms, and green interferograms. In such a case, a raw interferograms can be simultaneously generated for each color, as indicated in block 34.

With reference next to decision block 36, flow from this point depends upon whether further interferograms are to be obtained. Assuming that further interferograms are to be obtained, flow continues to block 38 and one of the mirrors (e.g., the planar mirror M_A) is displaced along the optical axis of the system for purposes of phase shifting. The distance that the mirror is displaced can be very small. By way of example, the mirror can be displaced approximately 1 to 650 nm. Such fine movement can be obtained using a precise actuator, such as a piezoelectric actuator.

Once the mirror M_A has been displaced, flow returns to block 30 and the above-described process is repeated so that further interferograms are generated. In some embodiments, a different number of interferograms can be obtained for different colors. For example, in some cases, eight interferograms can be obtained from the red channel, seven interferograms can be obtained from the green channel, and six interferograms can be obtained from the blue channel to account for the different wavelengths of the colors. In such a case, eight total exposures can be performed.

With reference again to decision block 36, once the desired number of interferograms has been obtained, flow continues to block 40 at which like-colored interferograms are combined to generate a separate complex hologram for each color channel. This process can be performed by a computing system, such as the computing system 20 shown in Fig. 1.

Once the complex holograms have been generated for each color channel, they can be combined to form a color complex hologram, as indicated in block 42. This also can be performed by the computing system. In some embodiments, the color complex hologram is represented as a separate amplitude and phase of the optical field.

At this point, numerical propagation can be performed to generate a color reconstructed holographic image, as indicated in block 44.

Two examples of CSIDH are presented in Fig. 3. In Fig. 3A, a toy boat and a die are illuminated with a miniature halogen lamp. Many of the details of the boat, including the masts and the net, are reproduced, although the high red content of illumination tends to give an orange-red overall appearance. Focusing on different parts of the structure has been observed when the reconstruction distance is varied. In Fig. 3B, the holographic camera was pointed at a scene outside a window in clear daylight. The red roof building is slightly out of focus, while the storage building with garage doors is in better focus. These structures were estimated to be at distances of about 1.0 and 0.5 km, respectively, and the field of view was about three degrees. To demonstrate the three-dimensional content of the holographic images, Fig. 4 shows another example of the daylight outdoor scene plus the toy boat placed in front of the window and illuminated with a halogen lamp. The two images were reconstructed at different distances from the same stored complex hologram. In Fig. 4A, the storage building is clearly in focus and the boat is out of focus. Conversely, in Fig. 4B, the boat is clearly in focus and the distant buildings are out of focus. Several additional images are presented below, including detailed sets of intermediate images generated at various steps of the holographic acquisition and processing.

Example procedures for acquiring and reconstructing holographic images using a system such as that shown in Fig. 1 will now be described with the example of a white LED flashlight in Fig. 5. In order to obtain interference, first the distances of the two mirrors M_A and M_B are matched, for example, using a single LED for better visibility. Fig. 5A shows an image of the six-LED flash light captured by the CCD sensor. When the phase-shifting piezo-mount is dithering, one can discern the existence of interference in the center area of the large circular haze, but with just six LEDs, the background is already large and the fringe visibility quite low. The bright spots on the upper left of Fig. 5A are the result of a stray reflection from the beam-splitter. They do not contribute to the interference or to the final holographic images. A ramp voltage is applied to the piezo-mount with sufficient amplitude to cover more than 2π of phase shift. The camera frame rate or the piezo ramp rate is adjusted so that N exposures are made over the 2π excursion. The complex hologram is calculated from the N intensity exposures I_n by $H = \sum_{n=0}^{N-1} I_n \exp(2\pi i n / N) / N$. A difficulty in phase-shifting for tri-color holography is the difference in wavelengths of the three color channels and, therefore, in the necessary piezo-shifts. Noting that the wavelength peaks of the CCD sensitivity has close to 620:540:460 $\approx$ 8:7:6 ratio, eight frames from a series of I_n are used to calculate the H_R for the red channel, and seven and six frames, respectively, are used for the green, and blue channels. The amplitude and phase of the complex holograms that were acquired for the red, green, and blue channels are respectively represented in the panels of Fig. 5B and Fig. 5C. These represent the starting optical field at the hologram plane. Numerical propagation to the image plane results in the image of the object for each channel. This is shown in the panel of Fig. 5D. These images can then be combined to form the full-color image, shown in the center of the panel of Fig. 5E. The image distance is given by a combination of the z distances and the focal lengths identified above in relation to Fig. 1. Numerical propagation

to a range of distances around the focal distance demonstrates the focusing property of the holographic image.

Further examples of CSIDH are presented in relation to Figs. 6 and 7. In Fig. 6, the object is a toy boat that is about 5 cm tall that was placed about 1 m from the front lens of the apparatus, under illumination of a miniature halogen lamp. A die was also present in front of the boat. The complex hologram for the red channel was acquired as described above and is shown in Fig. 6A. The numerically focused images for the three color channels are shown in the panel of Fig. 6B. These images were combined to form the RGB color image, which is shown in Fig. 6D. Many of the details of the boat, including the masts and the net, are reproduced. Focusing on different parts of the structure has been observed when reconstruction distance is varied. For comparison, a cell phone camera picture of the toy boat is shown in Fig. 6C. The red content of the halogen lamp gives the image an overall orange-red tint. As a rudimentary means of color balance, each color frame was multiplied by a factor to equalize the frame averages of the three channels. Also, all three channels were multiplied by a factor to maintain the overall brightness to a desired level. These were only performed for the purpose of adequate rendering of the final images. The panel of Fig. 6E shows the holographic image as focused at five distances -40, -20, 0, +20, +40 mm from the best focal distance in the hologram space, which was 30 mm. The center image of the panel of Fig. 6E is a copy of the image of Fig. 6D.

A similar set of figures is shown in Fig. 7, in which case the holographic camera was turned toward an outdoor scene visible through an office window. The day was clear and the camera was directed at an apartment building with red roof and a storage building with garage doors. The apartment building is slightly out of focus in the image of Fig. 7D, while the storage building is in better focus. These structures were estimated to be at distances of about 1.0 and 0.5 km, respectively, and the field of view was about three degrees.

The above disclosure demonstrates the feasibility of full-color natural light holographic three-dimensional imaging. As proof-of-principle examples, the images are not yet perfect and some of the technical issues can be mentioned. To avoid vignetting and to image a larger field of view, the interferometer can be configured more compactly, which should also improve the signal strength. The signal strength, however, should more directly increase with the bit depth of the CCD pixels, e.g., 12 bits instead of 8 bits, in order to extract weak interference fringes against large background. The lens and mirror systems were not presently optimized for best resolution. As with most color cameras, the color rendering is imperfect and subject to somewhat arbitrary adjustments, but the examples do clearly demonstrate the ability to distinguish different colors with plausible consistency. A more important issue for improving the chromatic and overall performance is in the phase shifting. In the above examples, the phase shifts were only approximate and rather inefficient for the three color channels. Still the overall performance of this early prototype appears quite robust against some of these deficiencies.

Using a simple optical apparatus including a beam splitter, a piezo-mounted plane mirror, a curved mirror, and a few lenses, together with a color light sensor and straightforward algorithms, three-dimensional holographic images are recorded and reconstructed under natural light illumination and with full color rendition. The simplicity of the principle suggests possible extensions in non-optical regions of the electromagnetic spectrum, such as in THz, x-ray, as well as electron holography, where the beam-splitter-plus-two-mirror interferometer may be replaced with half-transparent Fresnel zone plates for these wavelengths. Three or more of the zone plates can be fabricated for phase-shift acquisition. A more immediate application is a consumer-level holographic color camera in basically a point-and-shoot configuration. In this respect, this holographic camera can be compared with a system known as light-field camera, which is based on integral imaging

principle using a lenslet array placed in front of the CCD sensor. In comparison with a light-field camera, the holographic camera has no loss of resolution due to the lenslets and the computational load will be substantially lighter. Incoherent light holographic cameras, such as proposed here, have real potential to make holographic three-dimensional imaging as common as photography in all areas of imaging from microscopy to astronomy, as well as in engineering, artistic, and general public uses. More significantly, a large array of powerful holographic techniques developed for coherent imaging systems may now be applicable to incoherent imaging systems.

CLAIMS

Claimed are:

1. A method for generating a color holographic image, the method comprising:

generating a separate complex hologram for each of multiple different colors of an object field illuminated with incoherent light;

combining the separate complex holograms to obtain a color complex hologram; and

generating a reconstructed color holographic image of the object field.

2. The method of claim 1, further comprising capturing multiple phase-shifted interferograms of the object field for each color.

3. The method of claim 2, wherein capturing multiple phase-shifted interferograms of the object field comprises capturing the interferograms with a color light sensor.

4. The method of claim 2, wherein capturing phase-shifted interferograms comprises displacing a mirror along an optical axis of an interferometer to shift the phase of light reflected by the mirror.

5. The method of claim 4, wherein the interferometer comprises two mirrors that reflect light from the object field, wherein the mirrors having different radii of curvature.

6. The method of claim 2, wherein generating a separate complex hologram for each of multiple different colors comprises combining the multiple phase-shifted interferograms of the object field for each color.

7. The method of claim 1, wherein generating a reconstructed color holographic image comprises performing numerical propagation on the color complex hologram.

8. A non-transitory computer-readable medium that stores a digital holography system comprising:

logic configured to generate a separate complex hologram for each of several colors of an object field while the object is illuminated with incoherent light;

logic configured to combine the complex holograms to obtain a color complex hologram; and

logic configured to generate a reconstructed color holographic image of the object field.

9. The non-transitory computer-readable medium of claim 8, wherein the logic configured to generate a complex hologram is configured to combine multiple raw interferograms of the object field to generate the complex holograms.

10. The non-transitory computer-readable medium of claim 8, wherein the logic configured to generate a complex hologram is configured to combine multiple phase-shifted interferograms of the object field to generate the complex holograms.

11. The non-transitory computer-readable medium of claim 8, wherein the logic configured to generate a reconstructed color holographic image is configured to perform numerical propagation on the color complex hologram.

12. A system for generating color holographic images, the system comprising:

an optical system that collects incoherent light from an object field;

an interferometer that receives the light collected by the optical system, the interferometer including a first mirror, a second mirror, a beam splitter configured to send copies of the received light to each of the mirrors,

a color light sensor that receives light waves reflected by each of the mirrors of the interferometer and generates separate interferograms each of multiple different colors from the interfering light waves; and

a computing system that executes a digital holography system configured to receive the interferograms from the inteferometer and generate color holographic images of the object field based upon the interferograms.

13. The system of claim 12, wherein the mirrors have different radii of curvature.

14. The system of claim 13, wherein one of the mirrors is planar and the other mirror is curved.

15. The system of claim 12, wherein one of the mirrors is displaceable along an optical axis of the interferometer.

16. The system of claim 15, wherein the interferometer further comprises an actuator adapted to axially displace the first mirror along the optical axis.

17. The system of claim 16, wherein the actuator is a piezoelectric actuator.

18. The system of claim 12, wherein the color light sensor is a color charge-coupled device having separate red, green, and blue channels.

19. The system of claim 12, wherein the digital holography system is configured to combine the interferograms to form separate complex holograms for each color and then combine the separate complex holograms together to generate a color complex hologram.

20. The system of claim 19, wherein the digital holography system is further configured to perform numerical propagation on the color complex hologram to generate a color holographic image.

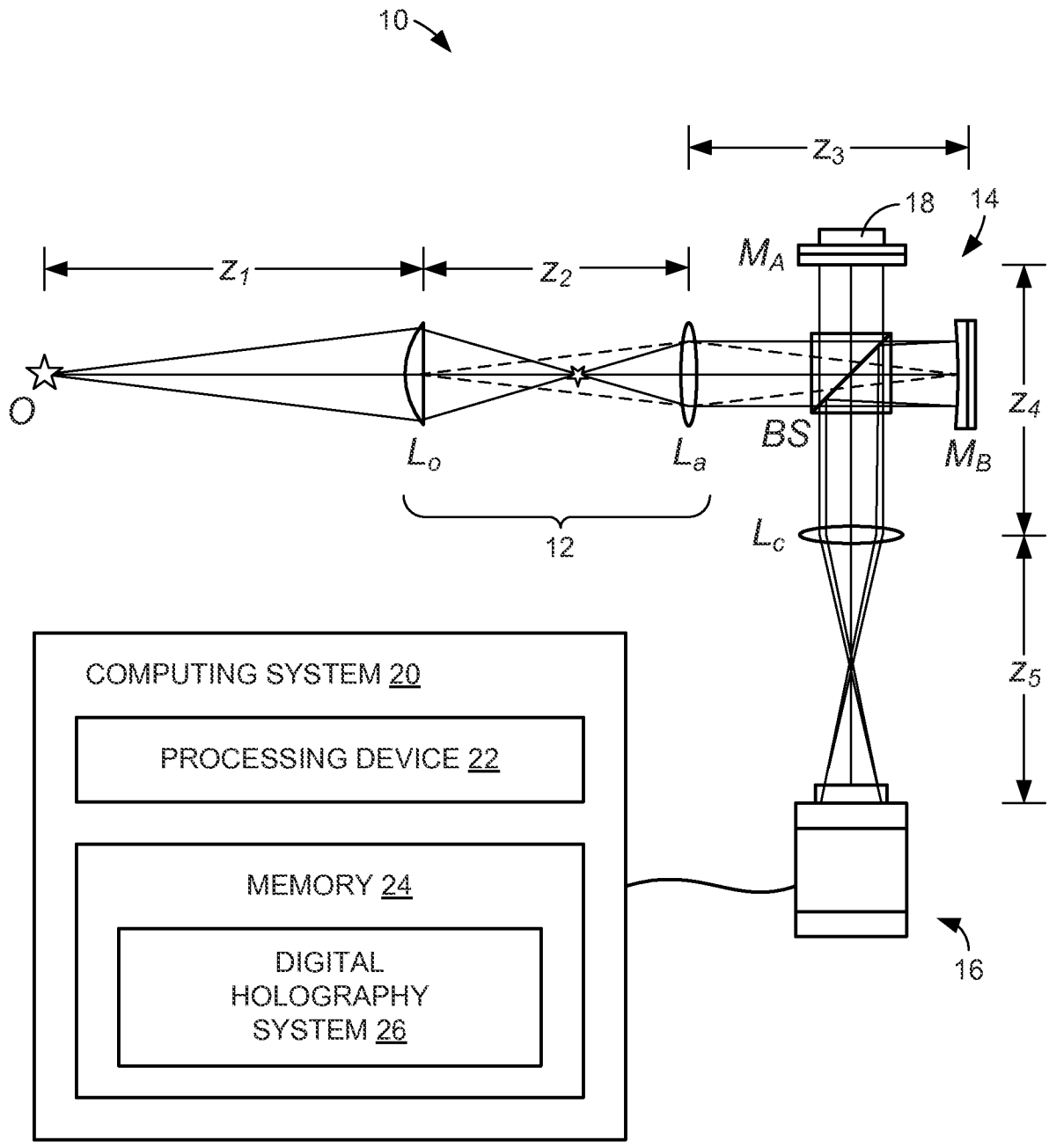

10
z_3
18
14
M_A
z_1
z_2
O
L_o
L_a
BS
M_B
z_4
12
L_c
z_5
COMPUTING SYSTEM 20
PROCESSING DEVICE 22
MEMORY 24
DIGITAL HOLOGRAPHY SYSTEM 26
16

FIG. 1

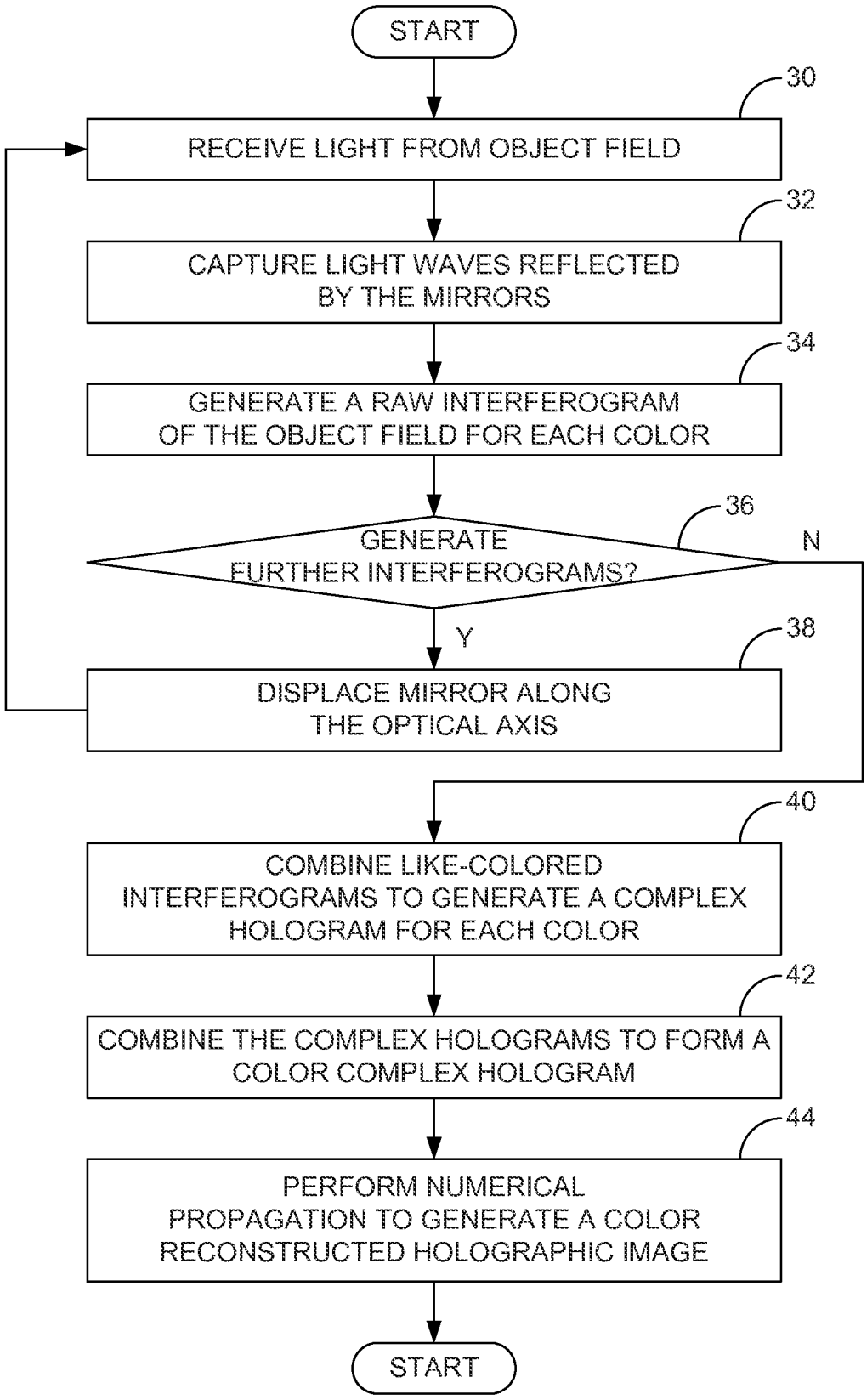

START
30
RECEIVE LIGHT FROM OBJECT FIELD
32
CAPTURE LIGHT WAVES REFLECTED BY THE MIRRORS
34
GENERATE A RAW INTERFEROGRAM OF THE OBJECT FIELD FOR EACH COLOR
36
GENERATE FURTHER INTERFEROGRAMS?
N
Y
38
DISPLACE MIRROR ALONG THE OPTICAL AXIS
40
COMBINE LIKE-COLORED INTERFEROGRAMS TO GENERATE A COMPLEX HOLOGRAM FOR EACH COLOR
42
COMBINE THE COMPLEX HOLOGRAMS TO FORM A COLOR COMPLEX HOLOGRAM
44
PERFORM NUMERICAL PROPAGATION TO GENERATE A COLOR RECONSTRUCTED HOLOGRAPHIC IMAGE
START

FIG. 2

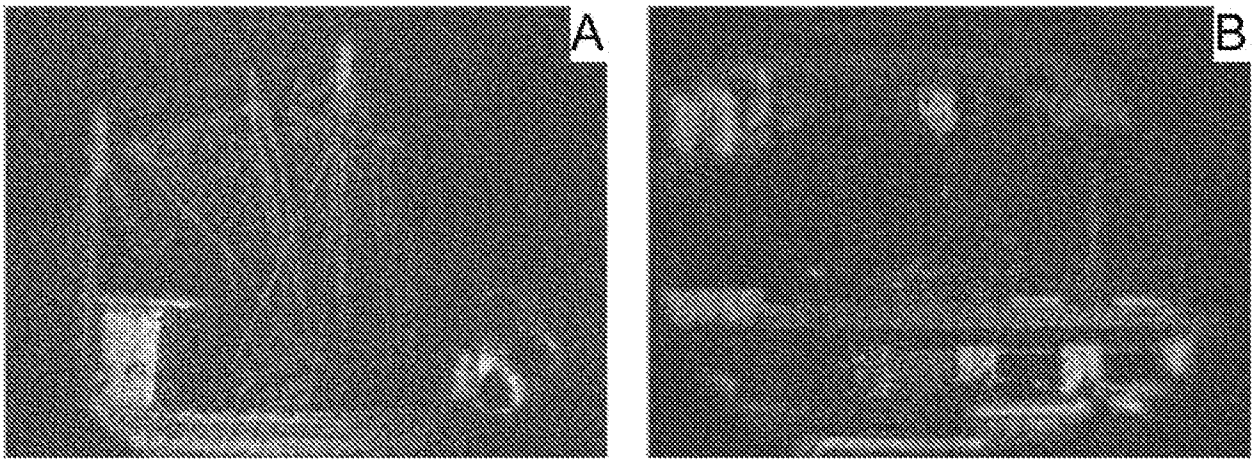


FIG. 3

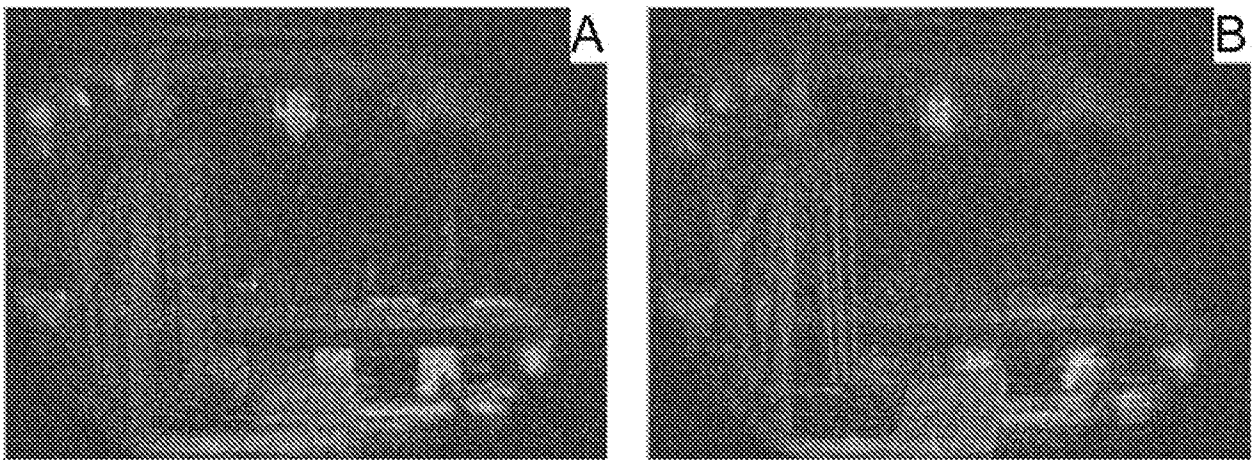


FIG. 4

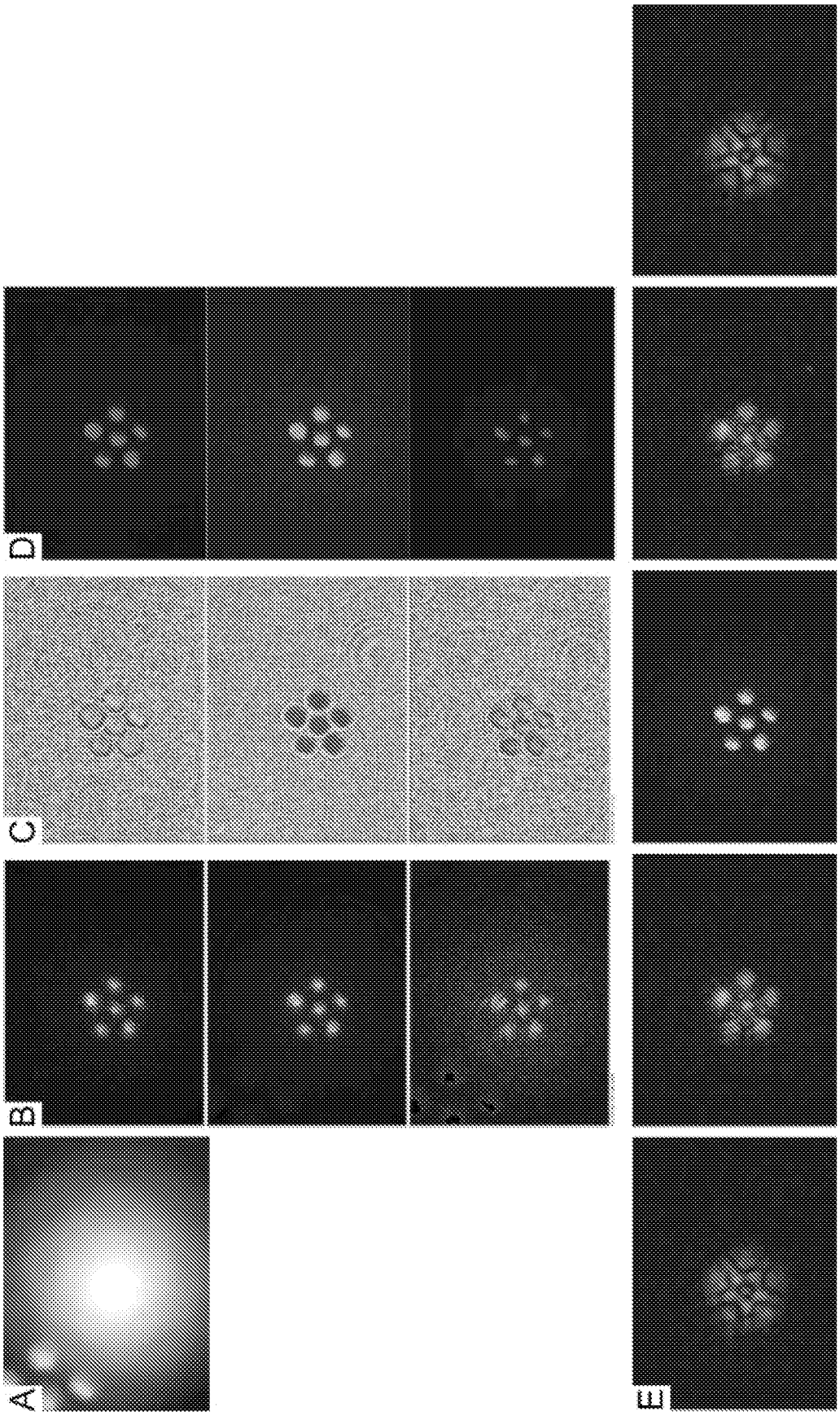


FIG. 5

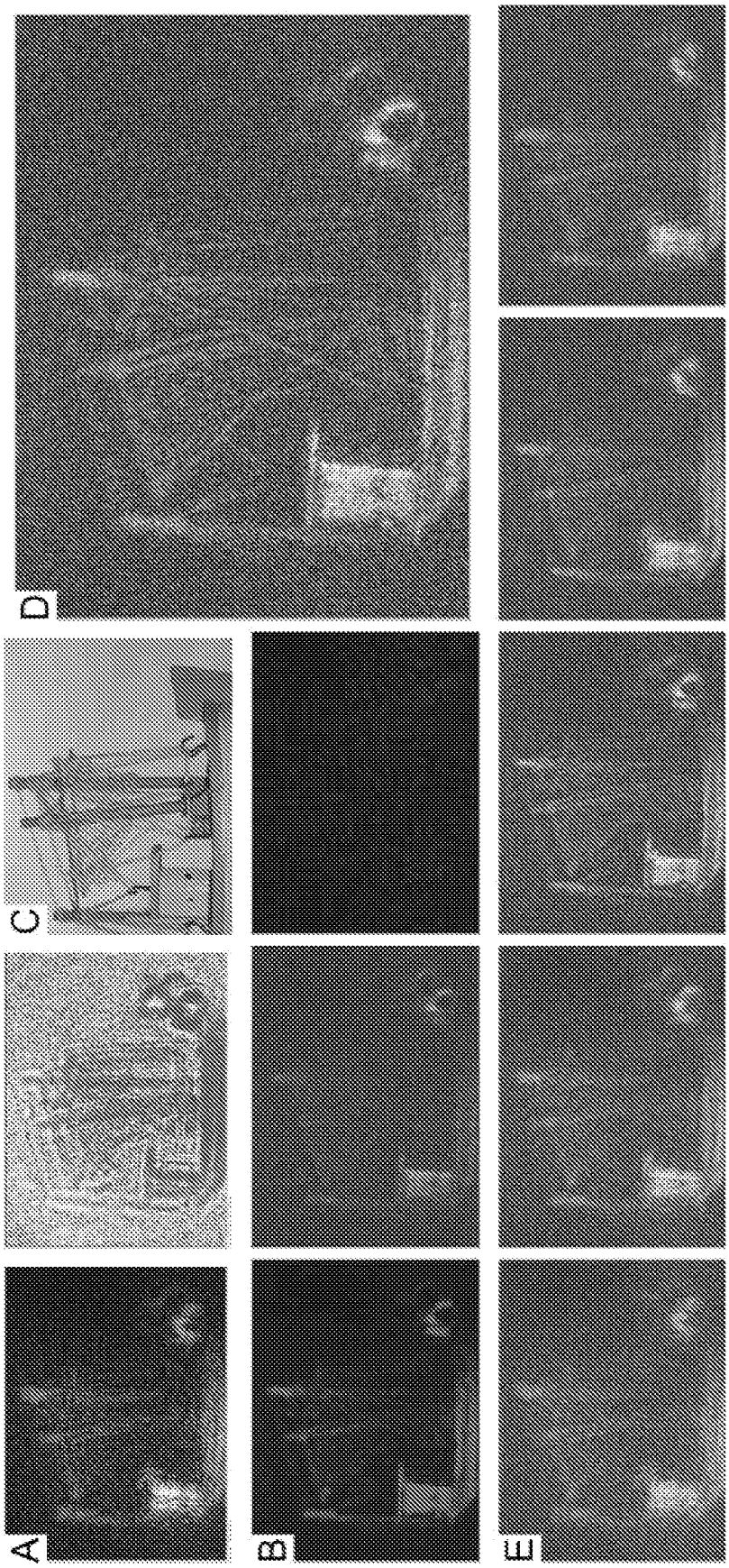


FIG. 6

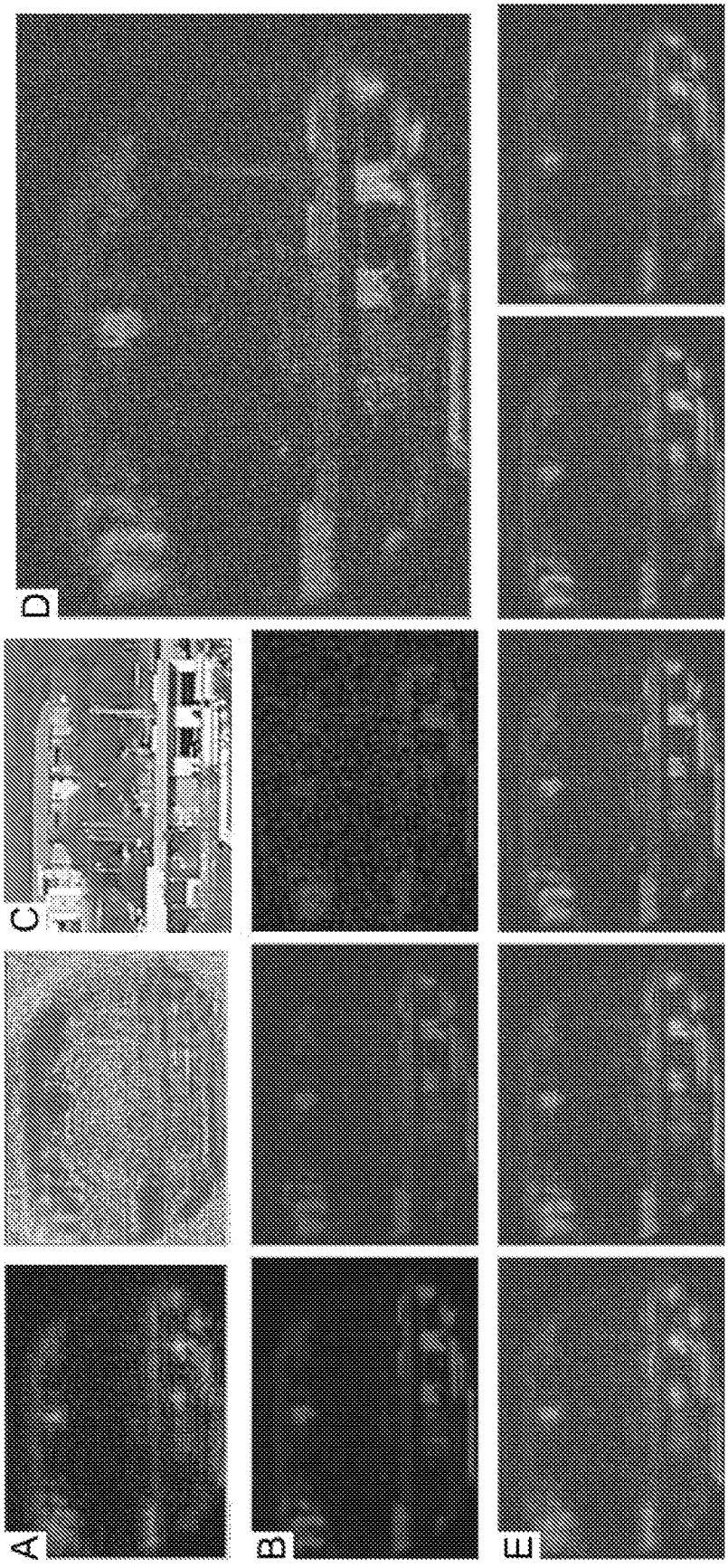


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/039737

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8).- G03H 1/02 (2014.01)
CPC - G03H 1/0866 (2014.09)
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - G03H 1/00, 1/02, 1/04, 1/08 (2014.01)
USPC - 356/457; 359/3, 22, 32

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
CPC - G03H 1/0443, 1/0866, 2001/0447, 2222/13 (2014.09) (keyword delimited)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatBase, Google Patents, Google Scholar
Search terms used: incoherent, digital holography, color holographic image, phase-shifted interferograms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X -- Y	WO 2012/150472 A1 (TOKES et al) 08 November 2012 (08.11.2012) entire document	1-3,7-8,11 --- 4-6,9-10
Y	US 2008/0137933 A1 (KIM) 12 June 2008 (12.06.2008) entire document	12-20
Y	US 5,822,066 A (JEONG et al) 13 October 1998 (13.10.1998) entire document	4-5,12-20
Y	US 2006/0132799 A1 (DUBOIS et al) 22 June 2006 (22.06.2006) entire document	6,9-10,19-20
Y	US 2005/0129082 A1 (POPPE et al) 16 June 2005 (16.06.2005) entire document	13-14

☐ Further documents are listed in the continuation of Box C. ☐

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

Date of the actual completion of the international search	Date of mailing of the international search report
05 November 2014	19 NOV 2014
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/039737

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
See extra sheet.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☒ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/039737

(Continued from Box III)

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-11, drawn to method for generating color holographic image comprising generating reconstructured color holographic image.
Group II, claims 12-20, drawn to system for generating color holographic image comprising an optical system and interferometer including a first and second mirror and beam splitter.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: generating a separate complex hologram, combining the separate complex holograms to obtain a color complex hologram and generating a reconstructed color holographic image as claimed therein is not present in the invention of Group II. The special technical feature of the Group II invention: an optical system, an interferometer that receives the light collected by the optical system, the interferometer including a first mirror, a second mirror, a beam splitter configured to send copies of the received light to each of the mirrors, color light sensor that receives light waves reflected by each of the mirrors of the interferometer as claimed therein is not present in the invention of Group I.

Groups I and II lack unity of invention because even though the inventions of these groups require the technical feature of method for generating a color holographic image, the method comprising: generating a separate complex hologram for each of multiple different colors of an object field illuminated with incoherent light; combining the separate complex holograms to obtain a color complex hologram; and generating a reconstructed color holographic image of the object field, this technical feature is not a special technical feature as it does not make a contribution over the prior art.

Specifically, WO 2012/150472 A1 (TOKES et al) 08 November 2012 (08.11.2012) teaches a method for generating a color holographic image (method for producing three-dimensional colour images based on holography, page 4, lines 4-8), the method comprising: generating a separate complex hologram for each of multiple different colors of an object field illuminated with incoherent light (light source 10, comprising mutually incoherent light beams, illuminates an object 18 located in an object space 22 such that each incoherent hologram generated is superimposed and the holograms obtained by the different colours can simply be separated, page 7, lines 23-27 and page 10, line 32-page 11, line 10 and Fig. 1); combining the separate complex holograms to obtain a color complex hologram (each hologram is brought into alignment with the application of correction propagation algorithms such that the components resulting from each colour can be matched in a way that the obtained colour image corresponds to the colour distribution of the object serving as a basis of the combined hologram, page 11, lines 1-11); and generating a reconstructed color holographic image of the object field (producing the three-dimensional colour image by reconstructing the holograms obtained for the different colours using a complex Fourier transformation, page 11, lines 1-11 and page 20, lines 14-28).

Since none of the special technical features of the Group I or II inventions are found in more than one of the inventions, unity of invention is lacking.