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(54) **DYNAMIC APERTURE HOLOGRAPHIC MULTIPLEXING**

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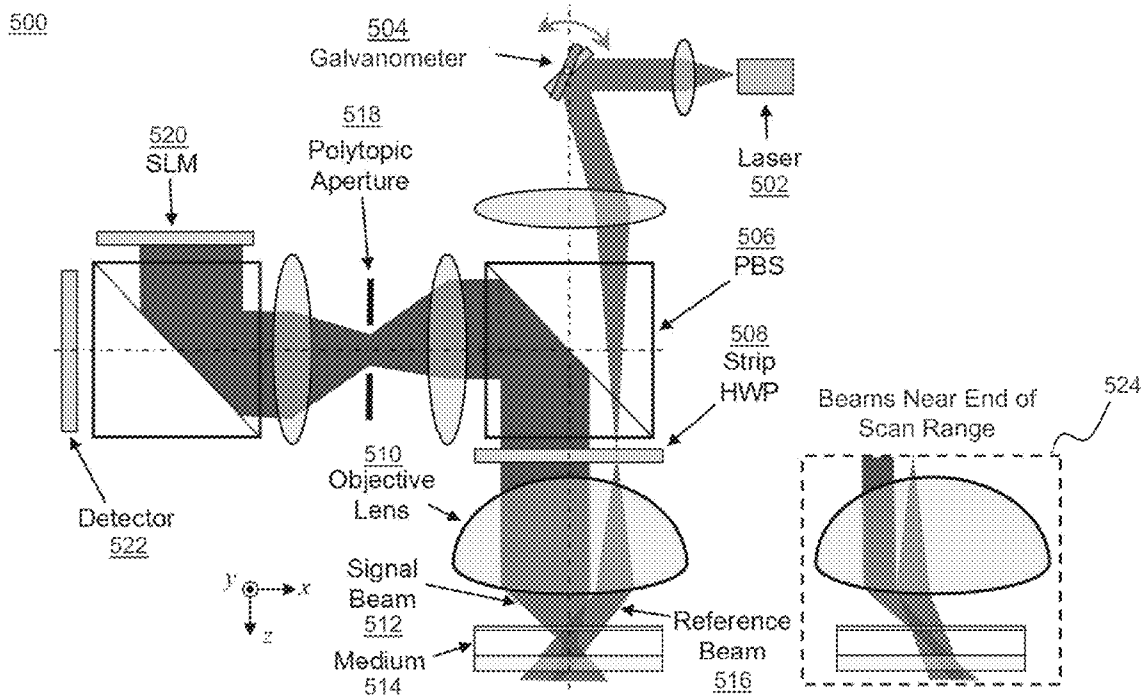
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- (60) Provisional application No. 61/755,893, filed on Jan. 23, 2013.

(57) **ABSTRACT**

Systems and methods for dynamic aperture holographic multiplexing are disclosed. One example process may include recording a set of holograms in a recording medium by varying both the reference beam angular aperture and the signal beam angular aperture. The angular aperture of the signal beam may be dynamically changed such that the closest edge of each signal beam angular aperture is selected to be a threshold angle different than the angular aperture of the reference beam used to record it. In some examples, the dynamic aperture holographic multiplexing process may include dynamic aperture equalization to reduce cross-talk, to improve error correction parity distribution for improved recovery transfer rate, to provide multiple locus aperture sharing for increased recording density, and to provide polarization multiplexed shared aperture multiplexing for increased transfer rate in both recording and recovery.



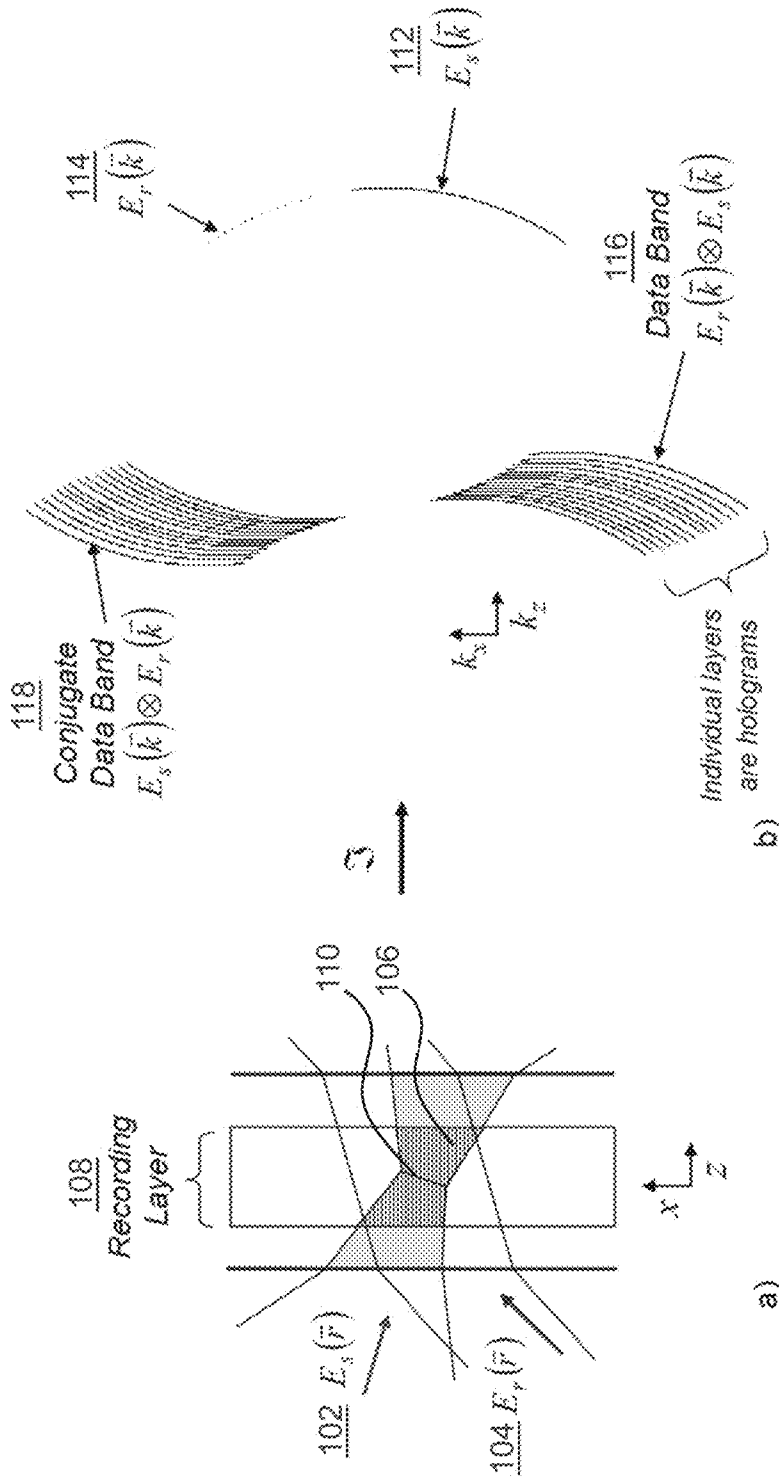


FIG. 1

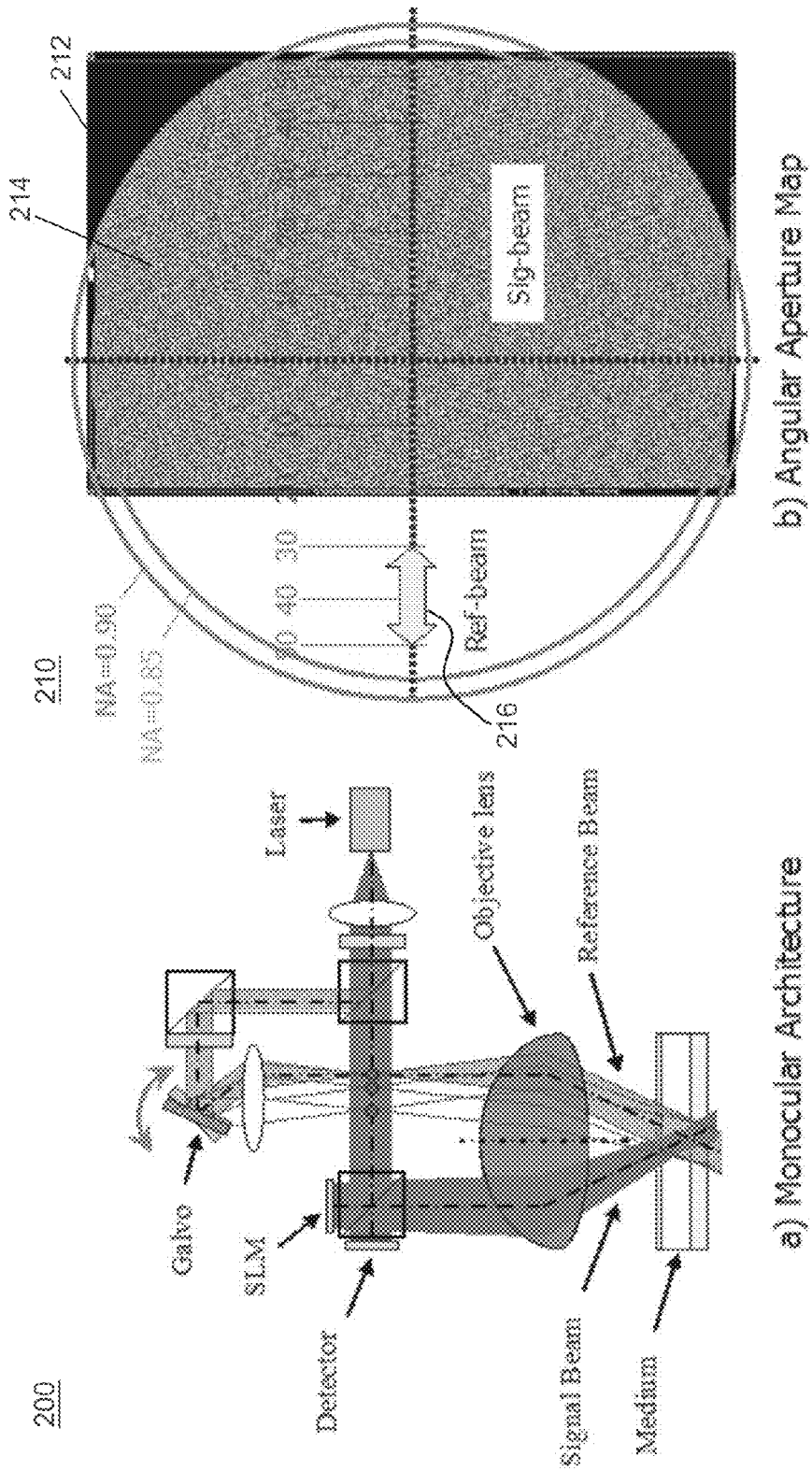


FIG. 2

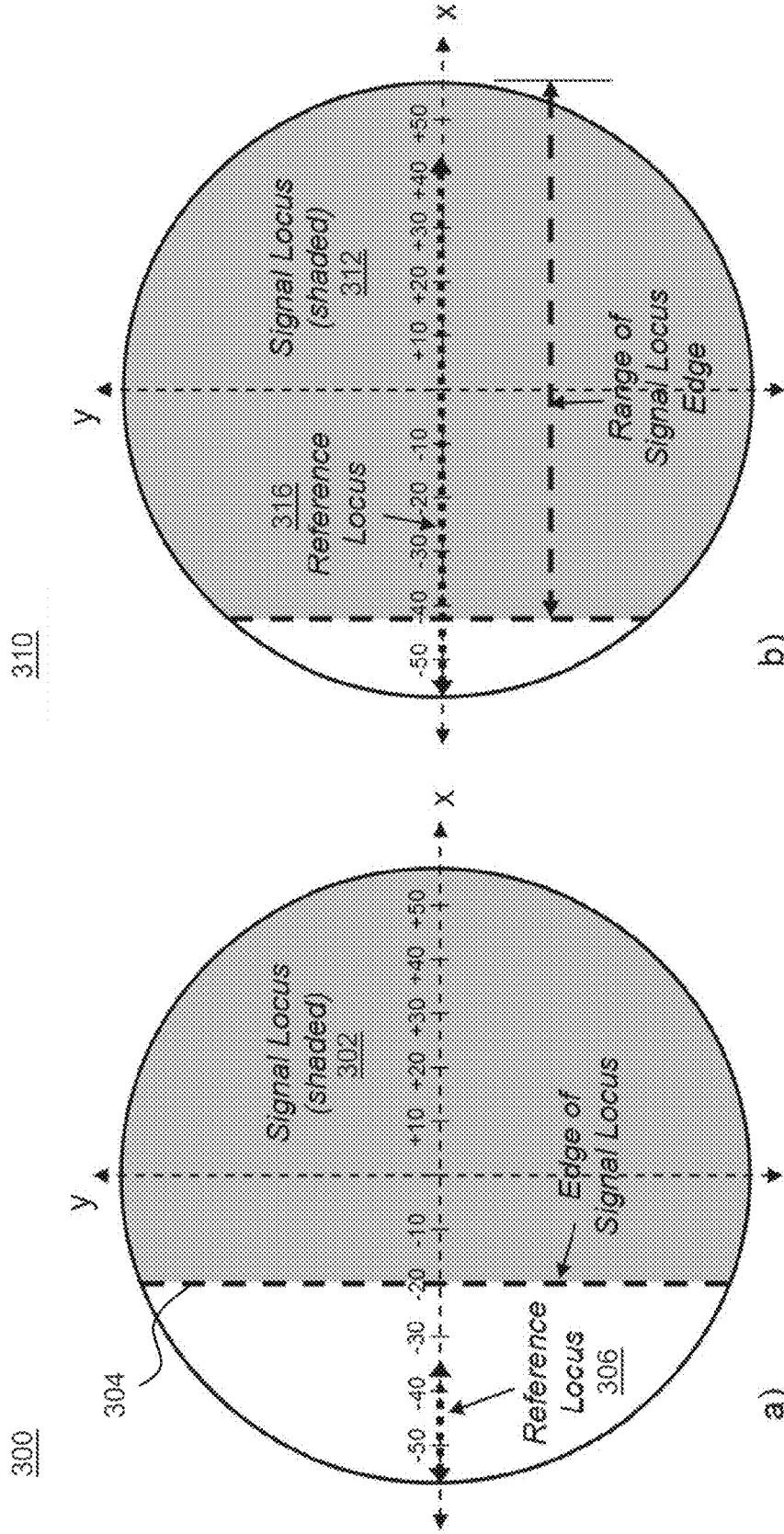


FIG. 3

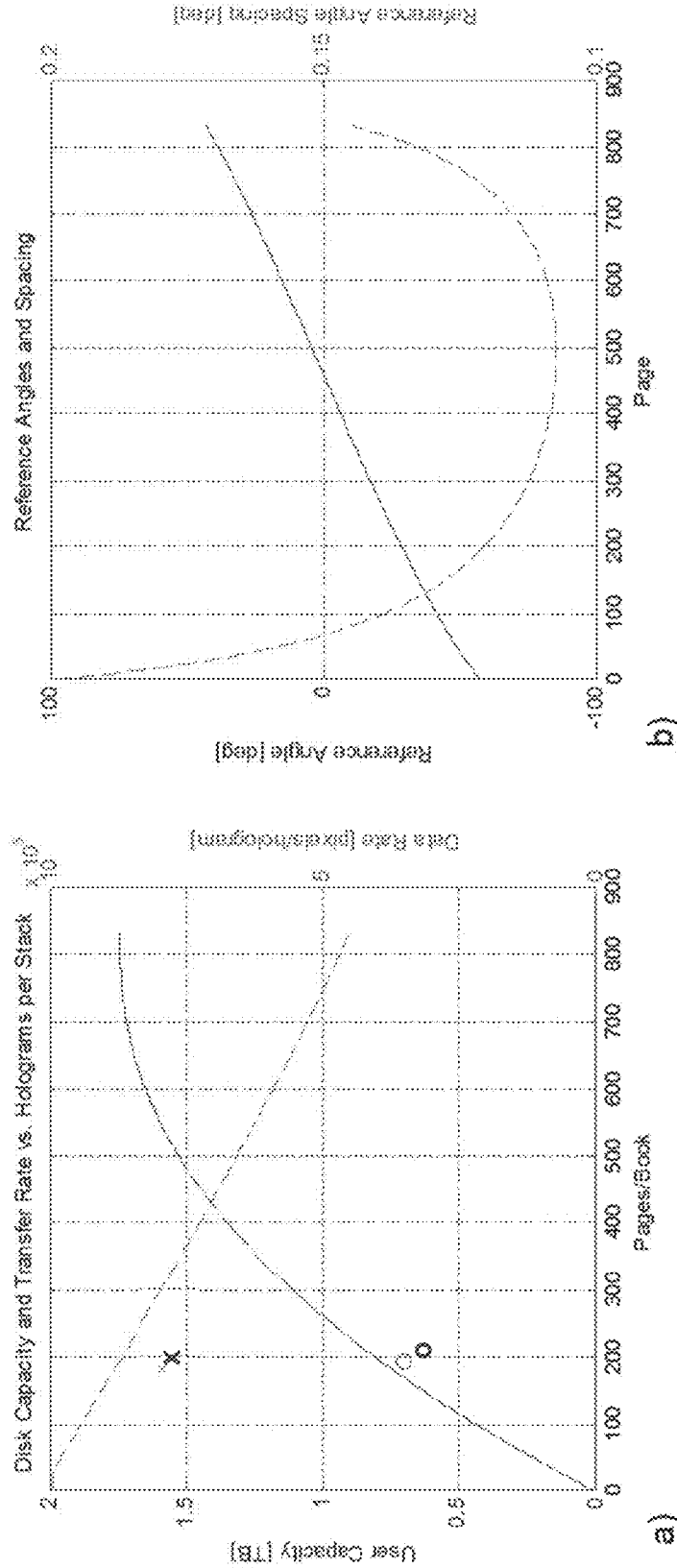


FIG. 4

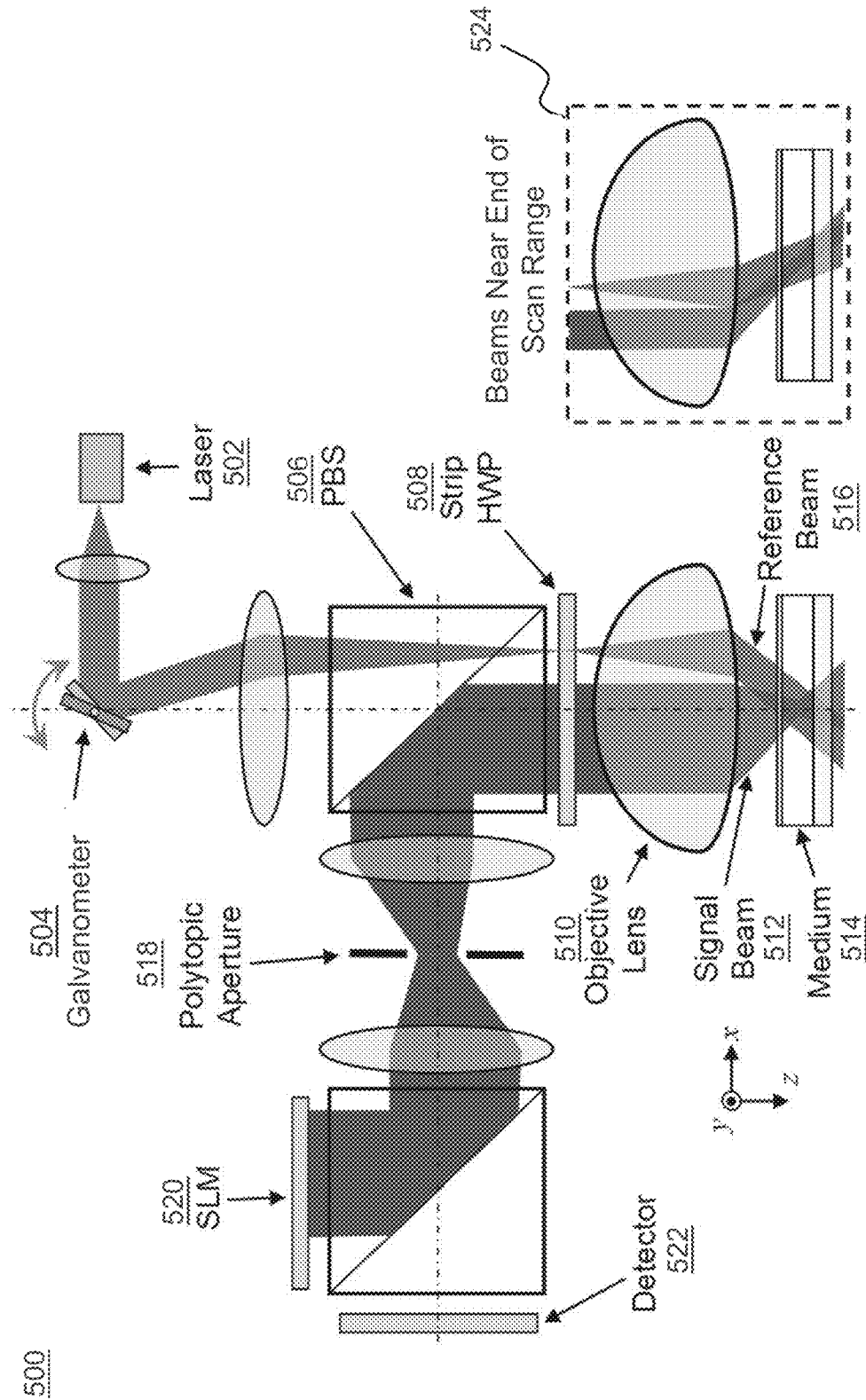


FIG. 5

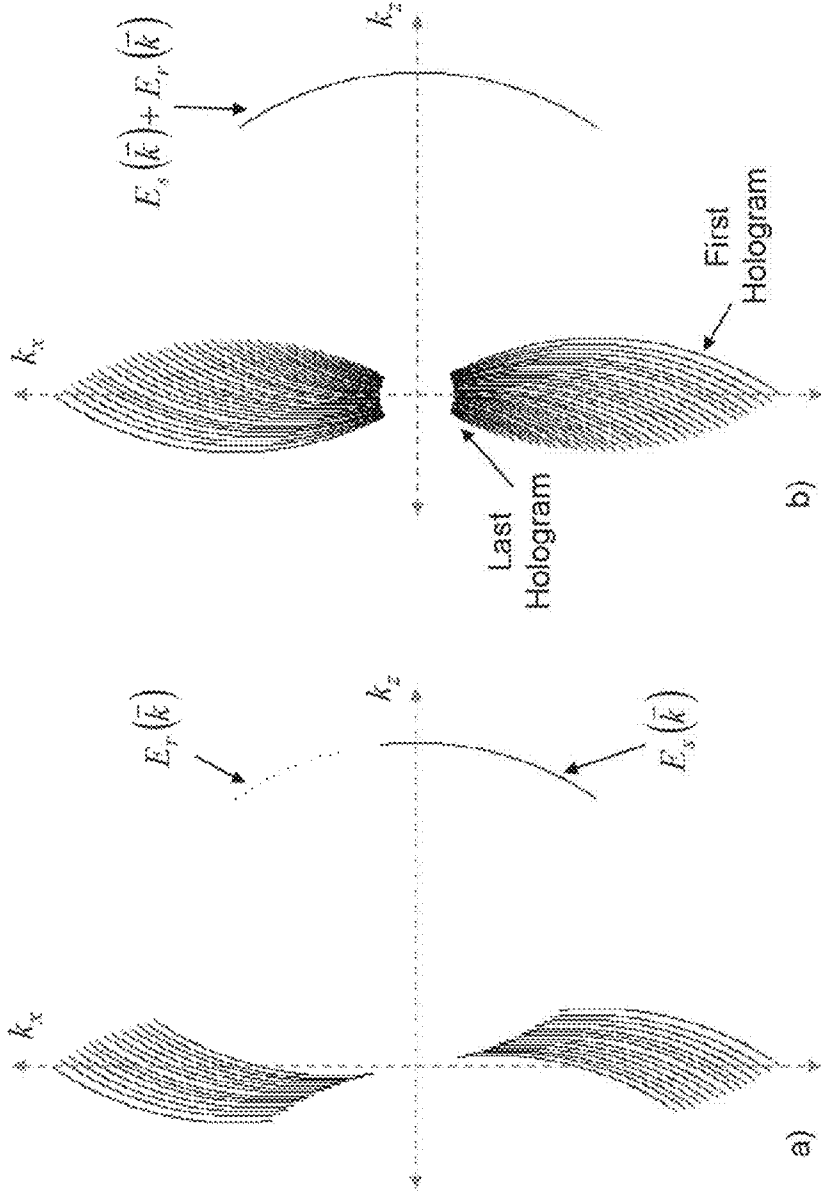


FIG. 6

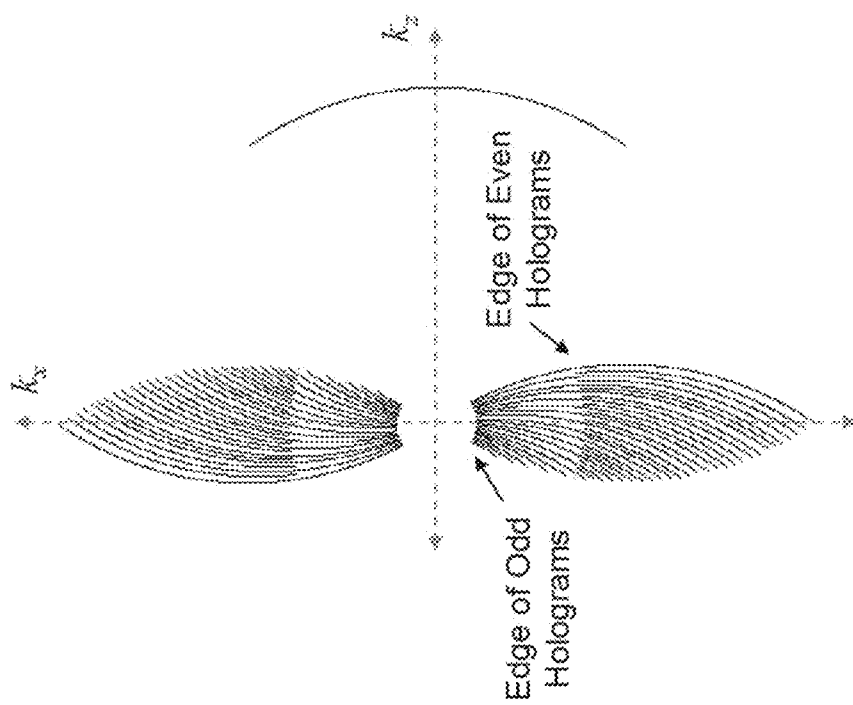


FIG. 7

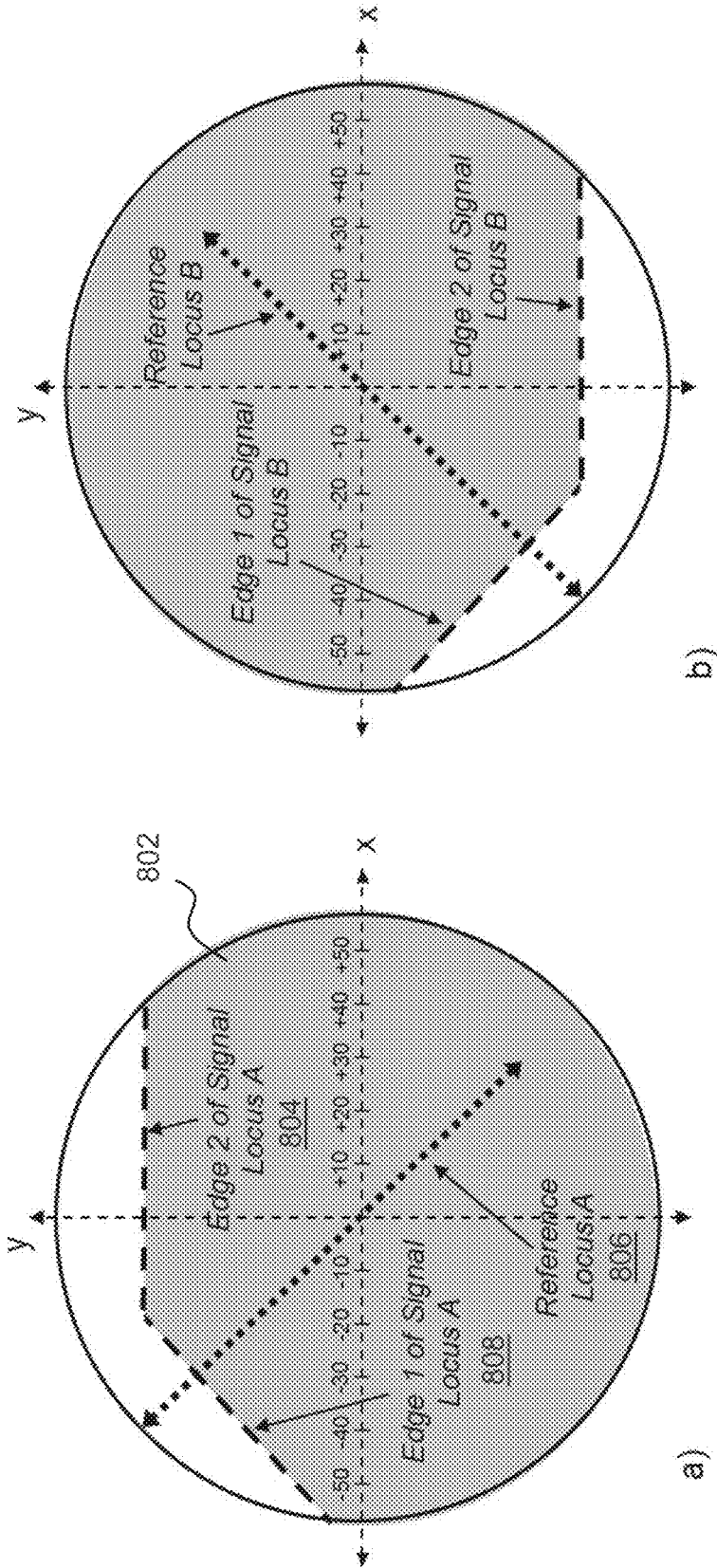


FIG. 8

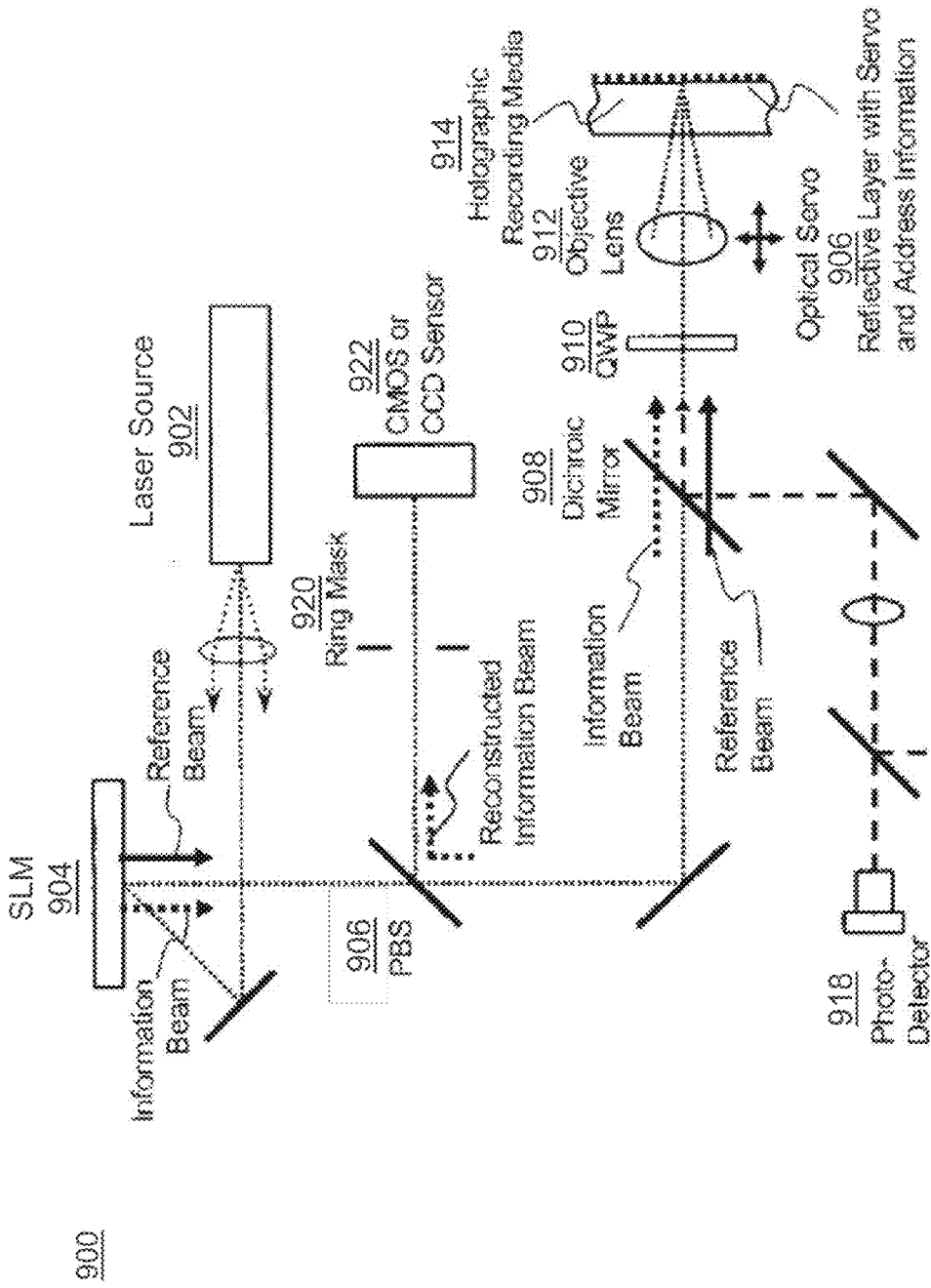


FIG. 9

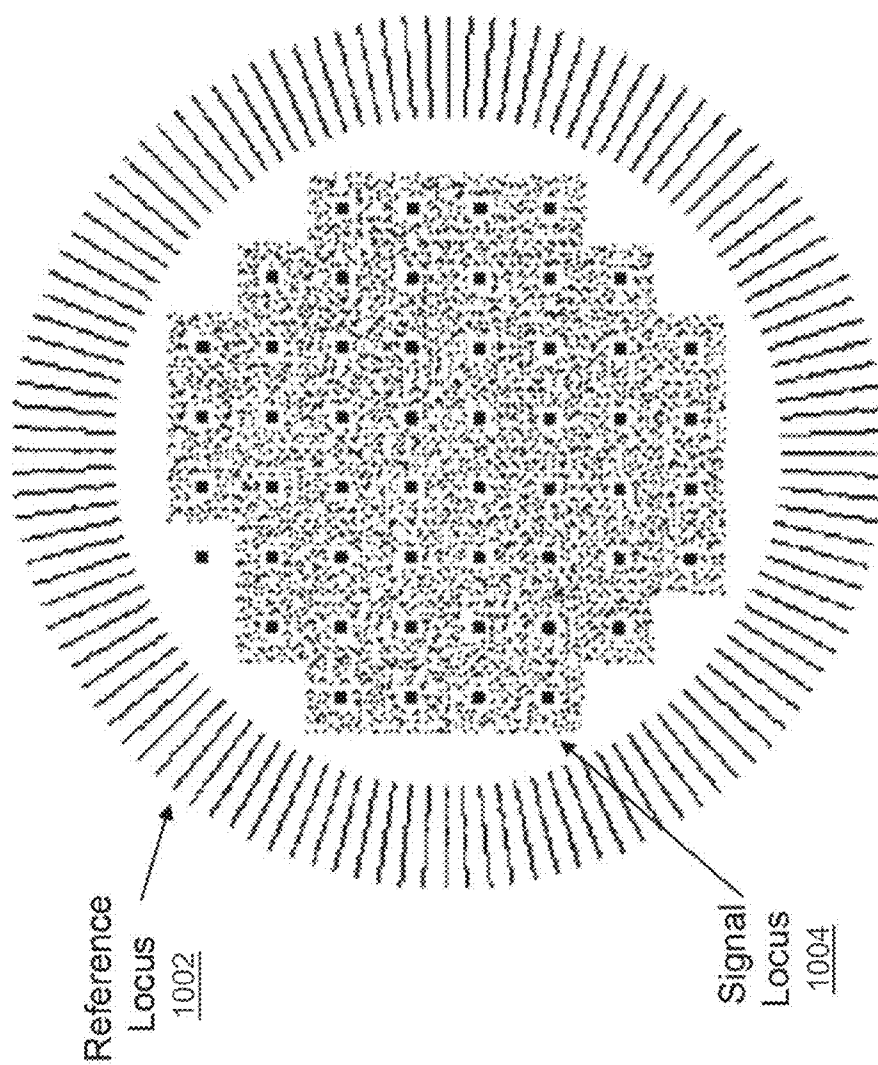


FIG. 10

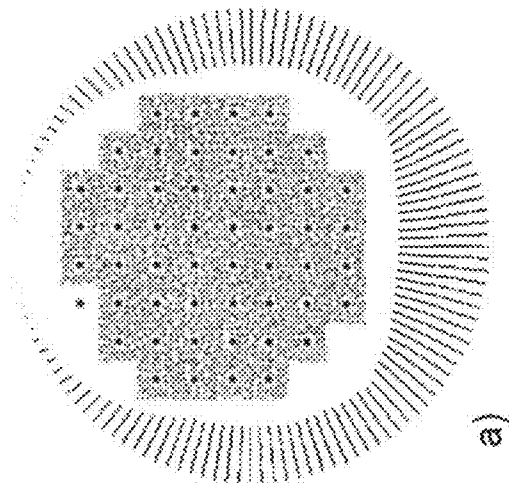
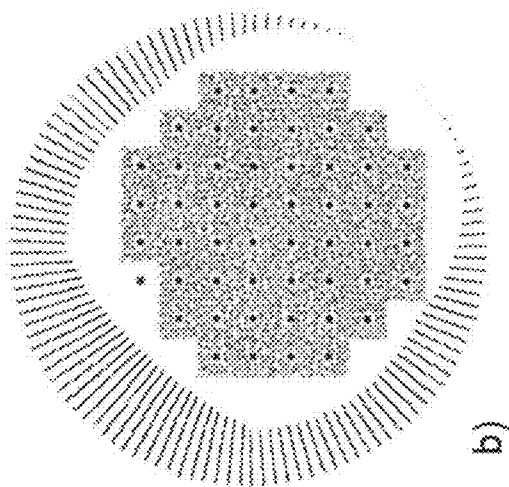
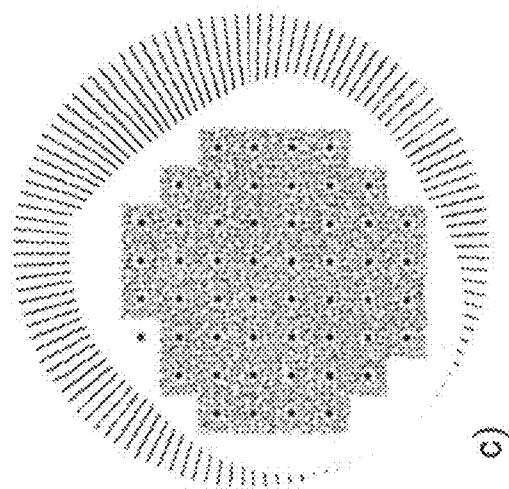


FIG. 11

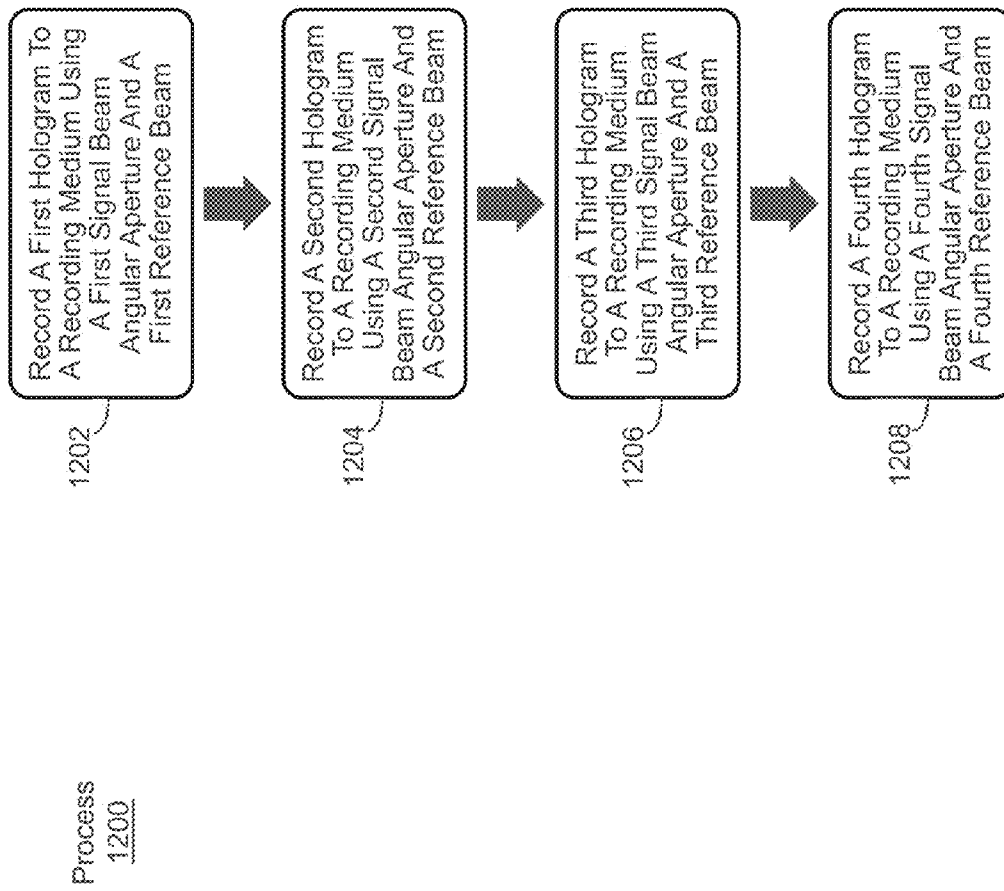


FIG. 12

System  
1300

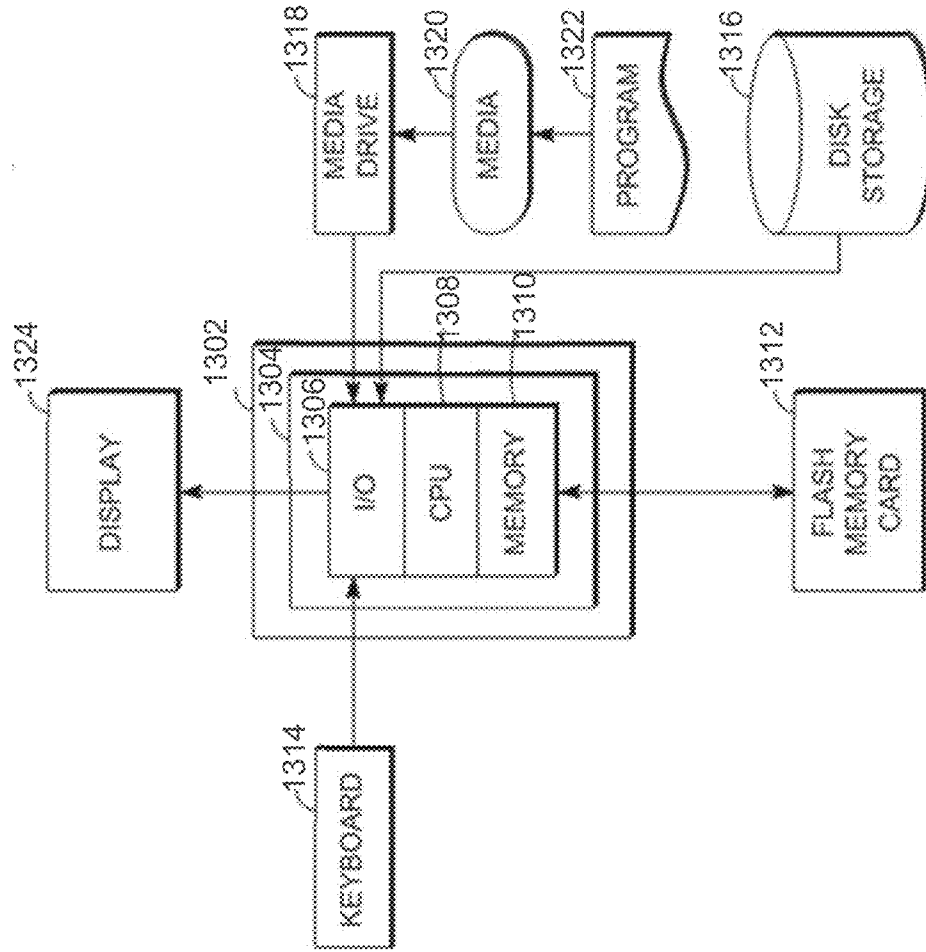


FIG. 13

## DYNAMIC APERTURE HOLOGRAPHIC MULTIPLEXING

### CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This application claims priority to U.S. Provisional Patent Application Ser. No. 61/755,893, filed Jan. 23, 2013, the entire disclosure of which is hereby incorporated by reference in its entirety for all purposes as if put forth in full below.

### BACKGROUND

**[0002]** 1. Field

**[0003]** The present disclosure relates generally to holography and, more specifically, to holographic multiplexing.

**[0004]** 2. Related Art

**[0005]** Holography is a technique for storing both phase and amplitude information of light by recording the interference pattern generated between a coherent object beam and a reference beam as a hologram in a photosensitive medium. During recovery, a probe beam (which is a replica of the reference beam) illuminates the hologram, and a diffracted beam (which is a replica of the object beam) may be generated. In the original “in line” configuration described by Dennis Gabor in “A new microscopic principle,” *Nature* 161, 777 (1948), the object and reference beams shared an optical axis, creating a diffracted “ambiguity” beam from the conjugate interference term, as well as resulting in a superposition of the diffracted beam with the probe beam. However, as described in E. N. Leith and J. Upatnieks, “Reconstructed wavefronts and communication theory,” *J. Opt. Soc. Amer.* 52, 1123-30 (1962), an “off-axis” configuration—one in which the object and reference beams have axes with different angles of incidence—would naturally allow for the separation of the diffracted beam from the other components. Such beams might be said to issue from separate, rather than shared, apertures in angle space. Off-axis holography subsequently became the dominant configuration, and is used for virtually all holographic systems, including holographic data storage systems.

**[0006]** Holography is attractive for digital data storage because many holograms may be written into the same volume (or overlapping volumes) of a thick recording medium using a process known as multiplexing, which is described by G. Barbastathis and D. Psaltis, “Volume holographic multiplexing methods,” in *Holographic Data Storage*, H. J. Coufal, D. Psaltis, and G. Sincerbox, eds. Springer (2000), pp. 21-62. Many different holographic multiplexing techniques have been developed. For example, using angle multiplexing, described by F. H. Mok, “Angle-multiplexed storage of 5000 holograms in lithium niobate,” *Opt. Lett.* 18, 915-917 (1993), one may record hundreds or thousands of different holograms in the same volume of media by using collimated (plane wave) reference beams that differ slightly from each other by their angle of incidence. Each hologram may record a different object beam (or signal beam) that has been modulated with a different digital data pattern. During recovery, the hologram may be illuminated by a probe beam. Due to the Bragg effect, only a hologram recorded with a reference beam angle at the same angle of incidence as the probe beam will produce substantial diffraction. Each signal beam may thus

be reconstructed independently, allowing the digital data to be recovered without cross-talk from the rest of the multiplexed holograms.

**[0007]** Other holographic multiplexing techniques, such as wavelength multiplexing described by D. Lande, J. F. Heanue, M. C. Bashaw, and L. Hesselink, “Digital wavelength-multiplexed holographic data storage system,” *Opt. Lett.* 21, 1780-1782 (1996), shift multiplexing described by D. Psaltis, A. Pu, M. Levene, K. Curtis, and G. Barbastathis, “Holographic storage using shift multiplexing,” *Opt. Lett.* 20, 782-784 (1995), and polytopic multiplexing described by K. Anderson and K. Curtis, “Polytopic multiplexing,” *Opt. Lett.* 29, 1402-1404 (2004), have been developed. These multiplexing techniques may be used alone or in combination with other multiplexing techniques to increase the amount of data stored in a recording medium.

**[0008]** Other features of the recording geometry may be varied to record data in the recording medium. For example, a page-oriented system is one in which the signal beam is modulated as a two-dimensional array of pixels, the modulation typically being imparted by a spatial light modulator (SLM). A Fourier architecture is one in which the recording medium is placed at or near an optical Fourier plane of the page image. A monocular system is one in which both the reference and signal beams pass through a single, shared objective lens before illuminating the recording medium, as described in U.S. Pat. No. 7,742,209, “Monocular holographic data storage system architecture,” Jun. 22, 2010.

### SUMMARY

**[0009]** Methods for recording a set of multiplexed holograms are provided. One example method may include: recording a first hologram of the set of multiplexed holograms to a recording medium using a first signal beam angular aperture and a first reference beam; and recording a second hologram of the set of multiplexed holograms to the recording medium using a second signal beam angular aperture and a second reference beam, wherein the second signal beam angular aperture is varied in at least one characteristic from the first signal beam angular aperture.

**[0010]** In one example, the first hologram and the second hologram may each comprise a data page of pixel information. In another example, the first signal beam angular aperture and the second signal beam angular aperture may vary in one or more of shape, size, and position.

**[0011]** In one example, the method may further include: recording a third hologram of the set of multiplexed holograms to the recording medium using a third signal beam angular aperture and a third reference beam, wherein the third signal beam angular aperture may be varied in at least one characteristic from the first signal beam angular aperture and the second signal beam angular aperture; and recording a fourth hologram of the set of multiplexed holograms to the recording medium using a fourth signal beam angular aperture and a fourth reference beam, wherein the fourth signal beam angular aperture may be varied in at least one characteristic from the first signal beam angular aperture, second signal beam angular aperture, and the third signal beam angular aperture.

**[0012]** In one example, an edge of the first signal beam angular aperture may be separated from an angular aperture of the first reference beam by a first angle; an edge of the second signal beam angular aperture may be separated from an angular aperture of the second reference beam by a second

angle; an edge of the third signal beam angular aperture may be separated from an angular aperture of the third reference beam by a third angle; and an edge of the fourth signal beam angular aperture may be separated from an angular aperture of the fourth reference beam by a fourth angle. In another example, the first angle, the second angle, the third angle, and the fourth angle may be substantially equal. In yet another example, the first angle and the third angle may be substantially equal; the second angle and the fourth angle may be substantially equal; and the first angle and the third angle may be different than the second angle and the fourth angle.

[0013] In one example, using the first signal beam angular aperture may include using a signal beam with an angular range. In another example, at least a portion of an angular locus of a set of reference beams used to record the set of multiplexed holograms may overlap at least a portion of an angular locus of a set of signal beams used to record the set of multiplexed holograms.

[0014] In one example, a first portion of the set of multiplexed holograms may be used to store error parity data and a second portion of the set of multiplexed holograms may be used to store input data, wherein the holograms of the first portion may be smaller than the holograms of the second portion.

[0015] Systems for recording a set of multiplexed holograms are also provided

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0016] The present application can be best understood by reference to the following description taken in conjunction with the accompanying drawing figures, in which like parts may be referred to by like numerals.

[0017] FIGS. 1(a) and 1(b) illustrate real and k-space distributions of holographic recording terms.

[0018] FIG. 2(a) illustrates an example holographic data storage system having a monocular architecture.

[0019] FIG. 2(b) illustrates an example angular aperture map of the monocular system of FIG. 2(a).

[0020] FIG. 3(a) illustrates an example angular aperture map of a monocular system.

[0021] FIG. 3(b) illustrates an example angular aperture map of a monocular system implementing dynamic aperture holographic multiplexing.

[0022] FIG. 4(a) illustrates an example graph showing the relationship between user capacity and the number of multiplexed holograms, and the relationship between the average number of recorded pixels per hologram and the number of multiplexed holograms.

[0023] FIG. 4(b) illustrates an example graph showing the relationship between the reference angle and the multiplexed hologram number, and the relationship between the angular spacing and the multiplexed hologram number.

[0024] FIG. 5 illustrates a system diagram for an example holographic data storage system for performing dynamic aperture holographic multiplexing.

[0025] FIG. 6(a) illustrates an example k-space distribution of holographic recording terms obtained using angle multiplexing.

[0026] FIG. 6(b) illustrates an example k-space distribution of holographic recording terms obtained using angle multiplexing and dynamic aperture holographic multiplexing.

[0027] FIG. 7 illustrates an example k-space distribution of holographic recording terms obtained using dynamic aperture equalization.

[0028] FIGS. 8(a) and 8(b) illustrate example angular aperture maps using multiple locus aperture sharing.

[0029] FIG. 9 illustrates a system diagram for an example collinear holographic data storage system for performing dynamic aperture holographic multiplexing.

[0030] FIG. 10 illustrates an example SLM pattern and angular aperture map for collinear recording.

[0031] FIGS. 11(a)-(c) illustrate an example scheme for performing dynamic aperture holographic multiplexing using a collinear system.

[0032] FIG. 12 illustrates an example process for performing dynamic aperture holographic multiplexing.

[0033] FIG. 13 illustrates an example computing system.

#### DETAILED DESCRIPTION

[0034] The following description is presented to enable a person of ordinary skill in the art to make and use the various embodiments. Descriptions of specific devices, techniques, and applications are provided only as examples. Various modifications to the examples described herein will be readily apparent to those of ordinary skill in the art, and the general principles defined herein may be applied to other examples and applications without departing from the spirit and scope of the various embodiments. Thus, the various embodiments are not intended to be limited to the examples described herein and shown, but are to be accorded the scope consistent with the claims.

[0035] Various embodiments are described below relating to dynamic aperture holographic multiplexing. One example dynamic aperture holographic multiplexing process may include recording a set of holograms in a recording medium by varying both the angular aperture of a reference beam and the angular aperture of a signal beam. The angular aperture of the signal beam may be dynamically changed such that the closest edge of each signal beam angular aperture is selected to be a threshold angle different than the reference beam angular aperture used to record it. Thus, at least a portion of the reference beam locus (e.g., the aggregate coverage of the individual reference beam angular apertures) may be shared with the signal beam locus (e.g., the aggregate coverage of the individual signal beam angular apertures), resulting in a greater number of holograms being recorded in the same volume of recording medium than obtainable without the use of dynamic aperture holographic multiplexing. In some examples, the dynamic aperture holographic multiplexing process may include dynamic aperture equalization to reduce cross-talk, to improve error correction parity distribution for improved recovery transfer rate, to provide multiple locus aperture sharing for increased recording density, and to provide polarization multiplexed shared aperture multiplexing for increased transfer rate in both recording and recovery.

[0036] In some examples, the processes for dynamic aperture holographic multiplexing may be combined with other multiplexing techniques, such as angle multiplexing, polytopic multiplexing, and the like. In one example, a page-oriented, monocular, Fourier geometry may be used to perform dynamic aperture holographic multiplexing. However, dynamic aperture holographic multiplexing may similarly be used with other architectures, such as collinear holography systems, common aperture holography systems, and the like. k-Space Formalism for Holography

[0037] Holographic recording and diffraction can be analyzed using k-space formalism, as described in M. R. Ayres, "k-Space Formalism," in K. Curtis, L. Dhar, W. L. Wilson, A.

Hill, M. R. Ayres, *Holographic Data Storage: From Theory to Practical Systems*, John Wiley & Sons, Ltd. (2010), pp. 26-31. In k-space, propagating optical waves and holographic gratings may be represented by three-dimensional Fourier transforms of their distributions in real space. For example, a collimated monochromatic reference beam can be represented in real space and k-space by

$$E_r(\vec{r}) = A_r \exp(i\vec{k}_r \cdot \vec{r}) \xrightarrow{\mathfrak{F}} E_r(\vec{k}) = A_r \delta(\vec{k} - \vec{k}_r), \quad (1)$$

**[0038]** where  $E_r(\vec{r})$  is the optical scalar field distribution at all  $\vec{r} = \{x, y, z\}$  3D spatial vector locations, and its transform  $E_r(\vec{k})$  is the optical scalar field distribution at all  $\vec{k} = \{k_x, k_y, k_z\}$  3D spatial frequency vectors.  $A_r$  is the complex amplitude of the field, and  $\vec{k}_r$  is a vector whose length indicates the spatial frequency of the light waves, and whose direction indicates the direction of propagation. In some examples, all beams may be composed of light of the same wavelength, so all optical k-vectors may have the same length (e.g.,  $|\vec{k}_r| = k_r$ ). Thus, all optical propagation vectors may lie on a sphere of radius  $k_r$ . This construct is known as the k-sphere.

**[0039]** The other important k-space distribution is that of the holograms themselves. Holograms for data storage usually include spatial variations of the index of refraction within the recording medium, typically denoted  $\Delta n(\vec{r})$ . Ideally, this index modulation pattern is proportional to the spatial intensity of the recording interference pattern, i.e.,

$$\Delta n(\vec{r}) \propto |E_s(\vec{r}) + E_r(\vec{r})|^2 = |E_s(\vec{r})|^2 + |E_r(\vec{r})|^2 + E_s^*(\vec{r})E_r(\vec{r}) + E_s(\vec{r})E_r^*(\vec{r}), \quad (2)$$

**[0040]** where  $E_s(\vec{r})$  is the spatial distribution of the signal beam field. The final term in this expansion,  $E_s^*(\vec{r})E_r^*(\vec{r})$ , is the signal-bearing (data band) term. Thus we can write

$$E_s(\vec{r})E_r^*(\vec{r}) \xrightarrow{\mathfrak{F}} E_r(\vec{k}) \otimes E_s(\vec{k}), \quad (3)$$

**[0041]** where  $\otimes$  is the 3D cross-correlation operator. This is to say, the product of one field and the complex conjugate of another in the spatial domain become a cross-correlation of their respective Fourier transforms in the frequency domain.

**[0042]** FIGS. 1(a) and 1(b) illustrate example distributions for a Fourier angular-multiplexing geometry. In particular, FIG. 1(a) shows a cross-section of the recording beams  $E_s(\vec{k})$

**102** and  $E_r(\vec{r})$  **104** in real space. The cross-hatched region **106** indicates where the beams intersect within the recording layer **108**, and thus where the data-bearing holographic fringes are located. The narrow waist **110** of this region **106** corresponds to the Fourier plane.

**[0043]** FIG. 1(b) illustrates these same distributions in k-space. Since  $E_s(\vec{k})$  **112** and  $E_r(\vec{k})$  **114** represent monochromatic optical fields, they may be confined to arcs along the k-sphere. Note that while  $E_r(\vec{r})$  **104** shows only a single collimated reference beam, the dots in the arc of  $E_r(\vec{k})$  **114**

represent multiple reference beams used to write an angle-multiplexed stack of holograms. Note also that while  $E_r(\vec{k})$  **114** may be confined largely to the plane of the figure,  $E_s(\vec{k})$  **112** may extend out of the figure plane to subtend a page-shaped region (or “patch”) on the surface of the sphere. In FIG. 1(b), it can be seen that the data band **116** distribution can be constructed graphically from the cross-correlation of the signal patch  $E_s(\vec{k})$  **112** with the reference arc  $E_r(\vec{k})$  **114**. The conjugate data band **118** may be similarly constructed by reversing the order of the operands.

**[0044]** The internal structure of the data bands is also indicated. The entire data band (along with the conjugate data band) represents the k-space locus of the holographic fringes for all of the holograms in an angle-multiplexed hologram stack, and each hologram occupies an  $E_s(\vec{k})$  **112** patch-shaped layer within each of the bands. Each layer has a slight thickness (determined by the Bragg selectivity imparted by the medium thickness) and may be packed in a nested fashion similar to the layers of an onion within the data band to maximize density. It should be noted that while FIG. 1(b) depicts only 14 layers, hundreds or more may be present in an actual implementation. Each hologram/layer may thus occupy a different (substantially disjoint) region of k-space, such that there is little to no cross-talk from other holograms during reconstruction.

#### Monocular System Architecture

**[0045]** FIG. 2(a) illustrates an example holographic data storage system **200** having a monocular architecture. A monocular architecture is a configuration that may employ a very high numerical aperture (NA) objective lens in order to maximize storage density. In this configuration, both the reference and signal beams may pass through the objective lens. The example system **200** shown in FIG. 2(a) is similar to a conventional, off-axis architecture in that it is a page-oriented, angle-multiplexed, Fourier geometry.

**[0046]** FIG. 2(b) illustrates the angular aperture map **210** of system **200**. The x and y locations of angular aperture map **210** indicate the external angle of incidence of beam components into the recording medium. The SLM region **212** is represented by a black rectangle, and the gray pixelated region **214** within the SLM region **212** and the acceptable NA (e.g., NA=0.90) indicates the size and shape of the data page, and thus the size and shape of the signal beam angular aperture. It should be noted that in a Fourier architecture, an image of the SLM may coincide with the angular aperture plane. The arrow **216** spanning 50° to 30° and labeled “Ref-beam” shows the locus of the reference beam angular apertures. In some examples, this locus may be further subdivided into multiple (e.g., 192) finely-spaced points corresponding to the multiple (e.g., 192) reference beam angular apertures (e.g., angle of incidences) used for angle multiplexing. For this example system **200**, the signal beam angular aperture may remain constant during the recording of the multiple (e.g., 192) holograms, and the locus of the signal beam angular aperture may be disjoint (non-overlapping) with the locus of the reference beam angular aperture.

#### Dynamic Aperture Holographic Multiplexing

**[0047]** Using a holographic data storage system having a monocular architecture like that shown in FIG. 2(a), overlapping holographic recordings can be made within a recording

medium. However, due to the static relationship between the signal beam angular aperture and the reference beam angular aperture, the recording medium is being used inefficiently. Thus, in some examples, a data storage system implementing dynamic aperture holographic multiplexing may be used to increase the amount of data that can be stored in a recording medium. Generally, dynamic aperture holographic multiplexing involves the changing of the signal beam angle aperture for different holograms in a multiplexed set.

**[0048]** To illustrate, FIG. 3(a) shows an angular aperture map of a data storage system having a monocular architecture that does not implement dynamic aperture holographic multiplexing. As shown in this example, the reference beam is confined (e.g., to a scan range of  $23^\circ$  ( $-58^\circ$  to  $-35^\circ$ )), and the edge **304** of the signal beam locus **302** is separated from the reference beam locus **306** (e.g., by a minimum of  $15^\circ$  (worst selectivity case)) according to a representative design criterion. The reference beam locus **306** may be subdivided into multiple (e.g., 192) reference angles, again according to a design rule based on constant minimum Bragg selectivity. According to a software model, this configuration (along with other assumptions) may result in a user capacity of 700 GB on a 120 mm disk.

**[0049]** In contrast, FIG. 3(b) shows an angular aperture map of a data storage system having a monocular architecture that implements dynamic aperture holographic multiplexing. As shown in this example, the reference beam scan range has been expanded to  $101^\circ$  ( $-58^\circ$  to  $+43^\circ$ ). The minimum separation of  $15^\circ$  between reference beam angular apertures of locus **316** and angular apertures of signal beam locus **312** may be achieved by dynamically changing the signal beam angular aperture such that the closest edge of each signal beam angular aperture is selected to be  $15^\circ$  higher than the angular aperture of the reference beam used to record it. The locus **316** of the reference beam angular apertures is thus shared with the locus **312** of the signal beam angular apertures. In some examples using dynamic aperture holographic multiplexing, holograms may be recorded in order of ascending reference beam angular aperture, and thus with a shrinking signal beam angular aperture as the reference beam scans from left to right in the figure. In other examples, the holograms may be recorded in other orders. While specific values (e.g., of minimum separation, reference beam scan range, and signal beam angular aperture) were provided for the example above, it should be appreciated that other values may be used.

**[0050]** In some examples, the signal beam angular aperture may be dynamically changed by changing the subset of the SLM pixels that are included in the holographic data page. In some examples, regions of the signal angular aperture that are not included in the holographic data page may be darkened to prevent their illuminating the recording medium. In some examples, this darkening may be accomplished by setting SLM pixels corresponding to the excluded regions to a dark, or “off” state. In other examples, this darkening may be accomplished using a knife edge shutter or similar device to selectively block illumination from excluded aperture regions while passing illumination from included regions. Such a method might be used if, for example, the SLM employed does not produce an appropriate dark pixel state. In still other examples, this darkening may be accomplished by a beam shaping device that dynamically redirects light from dark regions to illuminated regions.

**[0051]** Employing the same reference beam angular spacing design rule that was used in the preceding discussion of

FIG. 3(a), the number of holograms multiplexed may be increased from 192 to 834 using dynamic aperture holographic multiplexing. Because the size of the signal beam angular aperture may decrease as the reference angular aperture moves, the amount of data per hologram may also decrease. Nevertheless, the total amount of data that may be recorded in the recording medium may increase substantially. Applying the same model used for the example shown in FIG. 3(a), the maximum user capacity may increase from 700 GB to 1.7 TB, which is an improvement of over 240%.

**[0052]** FIGS. 4(a) and 4(b) illustrate example graphs showing relationships between various storage attributes with respect to the multiplexed hologram number when using dynamic aperture holographic multiplexing. In particular, the solid line of FIG. 4(a) indicates the user capacity in TB as a function of the number of multiplexed hologram (pages) according to the model. The dashed line of FIG. 4(a) shows the average number of recorded pixels per hologram, which is a useful proxy for the transfer rate that may be achieved by a real device. The points indicated by the circle and the x indicate the capacity and transfer rate of a conventional system, respectively. Because of the diminishing increases in capacity and decreasing transfer rate, a designer may elect to record only a subset of these holograms in a real system. For example, if **500** holograms were used instead of 834, the device would achieve over 1.5 TB of capacity with a transfer rate penalty of only 17% compared to the conventional system.

**[0053]** FIG. 4(b) shows the angle (solid line) and angular spacing (dashed line) of the reference beams produced by the model. The figure illustrates the increased angular density that may be available in the middle of the scan range to a design employing a constant minimum Bragg selectivity spacing rule. However, any spacing rule may be employed without departing from the scope of the present disclosure.

**[0054]** FIG. 5 illustrates an example holographic data storage system **500** for performing dynamic aperture holographic multiplexing. System **500** generally includes a laser source **502**, a beam directing device (e.g., a galvanometer) **504** for directing the output of the laser source **502**, a polarizing beam splitter (“PBS”) **506** in conjunction with a thin strip half-wave plate (“Strip HWP”) **508** that may collectively act as an aperture sharing element, a detector **522** for performing the recovery operation, an SLM **520** for modulating the signal beam **512**, a polytopic aperture **518**, a high NA objective lens **510** through which both the reference beam **516** and signal beam **512** may pass, and a recording medium **514**. While not shown, SLM **520** may receive an output from laser source **502** and modulate that output to generate the signal beam. System **500** may further include a processor (not shown) for controlling laser source **502**, beam directing device **504**, and SLM **520**.

**[0055]** System **500** may include an aperture sharing element to combine the reference **516** and signal beam **512** paths in the regions that are shared between the two. In the illustrated example of FIG. 5, the aperture sharing function may be performed using a passive method utilizing PBS **506** in conjunction with Strip HWP **508**. In particular, PBS **506** may serve to combine the beams **512** and **516** in orthogonal polarization states, for example, with the signal beam **512** in the linearly-polarized “s” state (with respect to the PBS **506** hypotenuse), and the reference beam **516** in the “p” state. Strip HWP **508** may be placed in the back focal plane of the objective lens **510** where the reference beam **516** comes to a focus. This plane may also be an image plane of the SLM **520**.

Strip HWP **508** may be aligned with the transit path of the reference beam **516**, but may be sufficiently narrow that it occludes only a few rows of SLM pixels. In some examples, the occlusion may be confined to a single row. To account for this occlusion, the occluded SLM pixel(s) may be easily omitted from the SLM page data format with negligible loss of capacity. The birefringent axes of the Strip HWP **508** may be oriented so as to rotate the reference beam polarization to the “s” state, thus allowing the reference beam to interfere with the signal beam and enabling the recording of holographic fringes. The fringes so written are disjoint in k-space. In other examples, passive aperture sharing may be accomplished using a thin strip mirror that reflects only the reference beam, thus allowing the beams to be combined in the same polarization state. The larger schematic in FIG. **5** shows the assembly with the reference beam **516** near the start of its scan range where the SLM page is large, whereas the inset **524** to the right shows the beam positions near the end of the scan range where the SLM page is small. In some examples, beam directing device **504** and SLM **520** may be used to adjust the angle of incidence of reference beam **516** and the signal beam angular aperture of signal beam **512**, respectively.

**[0056]** While passive aperture sharing methods are described above, in other examples, an active aperture sharing element employing a switchable element, such as a MEMS-actuated micro-mirror array, to dynamically select the desired beam source for each region of the shared aperture, may be used. In yet other examples, a single SLM may be used to generate both signal and reference beams, and may thus itself be considered to be an active aperture sharing element. Moreover, other architectures, potentially employing other methods of either passive or active aperture sharing, may additionally or alternatively be used.

#### K-Space Separability

**[0057]** FIGS. **6(a)** and **6(b)** illustrate the results of a k-space analysis for system **500** using a method similar to that described above with respect to FIGS. **1(a)** and **1(b)**. FIG. **6(a)** illustrates a cross-section of k-space distributions for a monocular system. In contrast, FIG. **6(b)** shows the analogous k-space distributions that may result using dynamic aperture holographic multiplexing as described above with respect to FIGS. **3-5**. As is evident in FIG. **6(b)**, the layers representing individual holograms within the data band continue to nest in disjoint regions of k-space despite the fact that the loci of  $E_s(\vec{k})$  and  $E_r(\vec{k})$  are no longer disjoint over the multiplexed set. The overall volume occupied by the data band and conjugate data band is larger than in that shown in FIG. **6(a)**, reflecting the increased multiplexing density of the present disclosure.

#### Dynamic Aperture Equalization

**[0058]** As shown in FIG. **6(b)** Error! Reference source not found., the distributions of the holograms are packed more densely near the origin (e.g., low spatial frequency) than they are further away from it. This is a manifestation of the lower Bragg selectivity exhibited by gratings of lower frequency compared to those of higher frequency, which is well-known among those skilled in the art. For this reason, cross-talk between holograms may be higher in page regions corresponding to lower grating frequencies, and these worst-case regions tend to limit the achievable density of angle multi-

plexing. Thus, in some examples, dynamic aperture equalization may be performed to mitigate this effect.

**[0059]** In some examples, dynamic aperture equalization may be performed by interleaving data page sizes. For example, the edge of the signal beam angular aperture may be changed every other hologram so that only the odd (or alternatively even) numbered holograms have the lowest allowable frequency components. In the example described with respect to FIG. **3(b)**, the angular apertures of the signal beams for odd holograms may be separated from the angular apertures of the reference beams by  $15^\circ$  as described, while the angular apertures of the signal beams for even (or alternatively odd) holograms may instead be separated from the angular apertures of the reference beams by  $40^\circ$ . The resulting k-space distributions are illustrated in FIG. **7**, which shows a considerable decrease in hologram packing density in comparison to FIG. **6(b)**. Interleaving data page sizes in this way may allow for the angular separation between reference beams to be decreased, leading to a considerable recording density increase. This increase may come at the cost of reduced transfer rate, as the average page size is smaller. Page size interleaving may present diminishing returns at higher reference angles, and might be stopped at these high angles rather than pursuing these diminishing returns.

**[0060]** In other examples, dynamic aperture equalization may be performed with or without shared aperture multiplexing. Additionally, interleaving patterns of different lengths (not just odd/even), and patterns that are not cyclical may also be performed. In general, any technique that equalizes the k-space modulation distribution may be performed and may be referred to as dynamic aperture equalization.

#### Error Correction Parity Distribution

**[0061]** Holographic storage devices typically employ error correcting codes in order to achieve robust data recovery in the presence of recovery errors. For example, systematic codes may be used to append parity data to the input data to allow for reconstruction when some part of the whole cannot be recovered. Examples of systematic codes include low density parity check (LDPC) codes and Reed-Solomon codes.

**[0062]** In some examples using dynamic aperture holographic multiplexing, the parity portion of the data recorded may be preferentially distributed to some subset of the data pages, while input data may be preferentially distributed to some other subset. In one example, parity data may be preferentially distributed to smaller data pages, while input data may be preferentially distributed to larger ones. Distributing the parity data in this way advantageously improves the recovery transfer rate because in the event of error-free recovery of the input data, the parity data residing on the smaller data pages need not be recovered. When used in a dynamic aperture system, the parity pages may be selectively distributed to lower data rate (smaller) pages.

#### Multiple Locus Aperture Sharing

**[0063]** In some examples, regions of the aperture may be shared multiple times. Multiple sharing of the signal and/or reference angular apertures can be used to access grating space that is inaccessible to the “singly shared” methods discussed above. Multiple sharing in this context is distinct from the “sharing” of an underlying multiplexing scheme, such as the angle multiplexing described above.

**[0064]** In one example, multiple locus aperture sharing may include double sharing and may be performed with the dynamic aperture holographic multiplexing described above. FIGS. 8(a) and 8(b) illustrate one example arrangement for double aperture sharing. In particular, FIG. 8(a) shows an aperture map comparable to the aperture sharing of FIG. 3(b) with two modifications: 1) the aperture map has been rotated by  $-45^\circ$ ; and 2) a second edge ("Edge 2") **804** has been added to the signal beam angular aperture locus **802**. This arrangement may then be used to affect aperture sharing in the manner described above, with Edge 1 **808** leading the reference beam angular aperture locus **806** by some amount (e.g.,  $15^\circ$ ). Furthermore, the new signal edge, Edge 2 **804**, may be dynamically changed so that its y-component is always slightly less than the y-component of the reference beam. Then, by applying the k-space formalism described above, it is apparent that the  $k_y$  component of the data band grating distribution so generated will always be less than zero (e.g., the data band lies in the negative  $k_y$  half of k-space). The conjugate data band, conversely, has a  $k_y$  component greater than zero.

**[0065]** FIG. 8(b) is similar to FIG. 8(a), except that the distributions have been flipped about the x-axis. By similar k-space formalism analysis, it is apparent that the data band grating distribution for this example will lie entirely in the positive  $k_y$  half of k-space (and the conjugate band will lie in the negative half). One may verify that the distributions of both data bands and both conjugate data bands are mutually disjoint by construction, and therefore both sets of holograms may be multiplexed into the same volume of recording medium. Such a system may achieve a recording density of somewhat less than double that of the example described with respect to FIGS. 3-5, with a somewhat decreased average number of pixels per hologram (and, hence, transfer rate).

**[0066]** While a specific locus shared aperture example is provided above, it should be appreciated that other multiple locus shared aperture schemes may be used. The multiple locus hologram distributions may or may not be symmetric in k-space, and three, four, or even more distributions may be employed. The method may be practiced in combination with multiplexing methods other than angular multiplexing and/or polytopic multiplexing.

#### Polarization Multiplexed Shared Aperture Multiplexing

**[0067]** In some examples in which multiple locus shared aperture techniques are used, multiple locus multiplexing may be performed simultaneously, rather than sequentially, by employing substantially orthogonal polarization states for the recording or recovery of two shared apertures simultaneously. In some examples, the shared apertures of FIGS. 8(a) and 8(b) may each be recorded or recovered with reference and signal light in the linearly-polarized "s" state with respect to their own reference beams. Since these polarizations are substantially orthogonal to each other, a recording operation may not produce significant interference fringes between reference A and signal B, or between reference B and signal A. Thus the two distributions may be recorded simultaneously. To perform the simultaneous recording, the holographic data storage system (e.g., system **500**) may include two separate SLMs and reference scanners, as well as another aperture sharing element based on polarization (such as a PBS) used to combine the beams. The system may further include two detectors to perform the recovery operation, and the new aperture sharing element may direct light of each

polarization toward the appropriate detector. Polarization multiplexing would thus achieve a factor of two increase in transfer rate for both recording and recovery compared to the equivalent non-polarization multiplexed system.

#### Collinear Dynamic Aperture Multiplexing

**[0068]** The examples described above relate to systems employing angle and polytopic multiplexing. However, it should be appreciated that the present disclosure may also be applied to other system architectures. For example, dynamic aperture holographic multiplexing may similarly be applied to a collinear holography system, such as that described in H. Horimai, X. Tan, and J. Li, "Collinear holography," *Appl. Opt.* 44, 2575-2579 (2005). According to Horimai et al., "[t]he unique feature of this technology is that 2-D page data are recorded as volume holograms generated by a coaxially aligned information beam and a reference beam, which are displayed simultaneously by one SLM and interfere with each other in the recording medium through a single objective lens." FIG. 9 illustrates an example collinear holographic data storage system **900**. System **900** generally includes a laser source **902** (e.g., green or blue), an SLM **904** for producing a reference beam and a signal (information) beam, a polarizing beam splitter (PBS) **906**, a dichroic mirror **908**, quarter-wave plate (QWP) **910**, objective lens **912**, recording media **914**, laser source **916** (e.g., red), photo-detector **918**, ring mask **920**, and CMOS or CCD sensor **922**. System **900** may further include a processor (not shown) for controlling laser sources **902** and **916**, SLM **904**, and other components of the system. Additional lenses and/or reflectors may also be included in system **900**, as shown in FIG. 9.

**[0069]** During the write process, a combined image of the signal beam and the reference beam, as shown in the angular aperture map of FIG. 10, may be produced by SLM **904**. The loci of the reference and signal components are labeled, showing the annular reference pattern **1002** surrounding a central data page **1004**. The p-polarized output of SLM **904** may pass through PBS **906** and may then be incident on QWP **910**. The p-polarized beams may be converted to a circularly polarized state by QWP **910** and may be focused in the holographic recording media **914** by objective lens **912**.

**[0070]** During the read process, only the outer reference beam may be generated by SLM **904** and passed through PBS **906**, QWP **910**, and objective lens **912** onto holographic recording media **914**. A reconstructed signal beam may be produced and may be reflected back through objective lens **912** and passed through QWP **908**, where it may be converted from a circularly polarized state to an s-polarized state. The reconstructed signal beam may be then reflected by PBS **906** and detected using CMOS or CCD sensor **922**. Laser source **916** may be used for optical servo control to adjust the focal point of the objective lens **912**.

**[0071]** A collinear system similar or identical to that shown in FIG. 9 may be modified to benefit from dynamic aperture holographic multiplexing. For example, the modified SLM patterns of FIG. 11 may be generated by shifting the position of the signal beam angular aperture to the edge of the SLM (e.g., in the directions of  $0^\circ$ ,  $120^\circ$ , and  $240^\circ$  for FIGS. 11(a), 11(b), and 11(c), respectively) and modifying the position of the reference beam angular aperture to accommodate these shifts. In some examples, a threshold angle difference may be maintained between edges of the signal beam angular aper-

ture and the reference beam angular aperture. The threshold angle may be the same or different for each of the modified patterns.

[0072] Modifying the collinear system in this way may advantageously provide at least two benefits:

[0073] 1) Though the k-space hologram distributions generated by the three patterns are substantially overlapping, the overall volume of the data bands and conjugate data bands of the holograms so multiplexed may be larger than in the conventional case. This may result in a higher theoretical recording density.

[0074] 2) According to a theoretical analysis as described in T. Shimura, M. Terada, Y. Sumi, R. Fujimura, and K. Kuroda, "Inter-page cross-talk noise in collinear holographic memory," Joint Int. Symp. on Opt. Memories and Opt. Data Storage, Waikoloa, Hi., July (2008), paper TuPO4, inter-page cross-talk noise in collinear holography goes as an incoherent sum of contributions from the multiplexed pages. The k-space hologram distributions for conventional collinear holograms are completely overlapping, but the distributions of, e.g., FIGS. 11(a) and 11(b) are only partially overlapping. Thus the cross-talk contributions between the differing SLM patterns of FIGS. 11(a) and 11(b) should be lower than in the conventional case, leading to increased signal-to-noise ratio and hence increased recording density.

[0075] Collinear holography relies on a correlation effect for holographic multiplexing. In contrast to angle multiplexing where individual holograms occupy disjoint regions of k-space, individual holograms in collinear recording are broadly distributed and densely overlapped with other holograms, leading to cross-talk expressions such as that of Shima et al. Dynamic aperture holographic multiplexing described herein serves to slightly reduce the overlap of these distributions, and thus serves to slightly reduce cross-talk by driving the design toward a more disjoint k-space partitioning scheme. Other variations of this technique may be implemented under the scope of the present disclosure.

#### Dynamic Aperture Holographic Multiplexing Process

[0076] FIG. 12 illustrates an exemplary process 1200 that can be used to perform dynamic aperture holographic multiplexing. In some examples, process 1200 may be performed by a holographic data storage system similar or identical to system 500 or 900. In other examples, a system similar to system 500, but modified as described with respect to FIGS. 8(a) and 8(b), may be used.

[0077] At block 1202, a first hologram may be recorded to a recording medium using a first signal beam angular aperture and a first reference beam having a first reference beam angular aperture.

[0078] In one example, using a system similar or identical to that shown in FIG. 5, a reference beam may be generated by a laser source (e.g., laser source 502) and directed toward an aperture sharing element, such as a PBS in combination with a thin strip half-wave plate (e.g., PBS 506 and Strip HWP 508), by a beam directing device (e.g., galvanometer 504). A signal beam may also be generated and modulated to contain data using an SLM (e.g., SLM 520). The signal beam may be directed toward the aperture sharing element, where the reference and signal beam paths may be combined in the regions that are shared between the two. For example, the PBS may combine the reference and signal beams in orthogonal polarization states (e.g., signal beam in the linearly-polarized "s" state with respect to the PBS hypotenuse and the reference

beam in the "p" state). The thin strip half-wave plate may be positioned in the back focal plane of an objective lens (e.g., objective lens 510) where the reference beam comes to a focus. This plane may also be an image plane of the SLM. The output of the thin strip half-wave plate may pass through the objective lens before entering a recording medium (e.g., medium 514) to record the first hologram.

[0079] In another example, using a collinear system similar or identical to that shown in FIG. 9, reference beam may be generated by a laser source (e.g., laser source 902) and directed toward an SLM (e.g., SLM 904). The SLM may generate both a reference beam and a signal beam, which may then pass through a PBS (e.g., PBS 906) and be incident on a QWP (e.g., QWP 910). The QWP may convert the p-polarized reference and signal beams to a circularly polarized state and may be focused in a recording medium (e.g., recording medium 914) by an objective lens (e.g., objective lens 912) to record the first hologram.

[0080] In some examples, the reference beam angular aperture and the edge of the signal beam angular aperture nearest the reference beam angular aperture may be separated by a threshold angle.

[0081] In one example, using a system similar or identical to that shown in FIG. 5, the separation between the reference beam angular aperture and the signal beam angular aperture may be set by adjusting the orientation of the beam deflecting device (e.g., galvanometer 504) reflecting the output of the laser source and/or by causing the SLM to change the size and position at which the signal beam enters the aperture sharing element (e.g., the PBS). For example, the signal beam angular aperture may be dynamically changed by changing the subset of the SLM pixels that are included in the holographic data page. In some examples, regions of the signal angular aperture that are not included in the holographic data page may be darkened to prevent their illuminating the recording medium. In some examples, this darkening may be accomplished by setting SLM pixels corresponding to the excluded regions to a dark, or "off" state. In other examples, this darkening may be accomplished using a knife edge shutter or similar device to selectively block illumination from excluded aperture regions while passing illumination from included regions. Such a method might be used if, for example, the SLM employed does not produce an appropriate dark pixel state. In still other examples, this darkening may be accomplished by a beam shaping device that dynamically redirects light from dark regions to illuminated regions. In some examples, the threshold angle separating the angular apertures of the reference and signal beams may be selected such that the edge of the signal beam angular aperture may be 15° higher than the angular aperture of the reference beam used to record it. However, other differences in angles may be used.

[0082] In another example, using a collinear system similar or identical to that shown in FIG. 9, the separation between the reference beam angular aperture and the signal beam angular aperture may be set by causing the SLM (e.g., SLM 904) to shift the signal beam angular aperture to the edge of the SLM (e.g., in the directions of 0°, 120°, or 240° as shown in FIGS. 11(a), 11(b), and 11(c), respectively) and to shift the reference beam angular aperture to accommodate the shifted signal beam angular aperture. This may be done in a manner that results in a threshold angle separation between the reference beam angular aperture and the edge of the signal beam angular nearest the reference beam angular aperture. In some examples, a separation of approximately 1, 2, 4, 8, or other

number of degrees may be created between the annular reference pattern (e.g., annular reference pattern **1002**) and the flat edges of the central data page (e.g., central data page **1004**) and a separation of less than 1, 2, 4, or other number of degrees may be created between the annular reference pattern and the corners of central data page.

**[0083]** At block **1204**, a second hologram may be recorded to the recording medium using a second signal beam angular aperture and a second reference beam having a second reference beam angular aperture. It should be appreciated that the second reference beam may be similar to the first reference beam used to record the first hologram at block **1202**, except that a characteristic of the first reference beam may be modified to generate the second reference beam at block **1204**. Similarly, the second signal beam angular aperture may be similar to the first signal beam angular aperture used to record the first hologram at block **1202**, except that a characteristic of the first signal beam angular aperture may be modified to generate the second signal beam angular aperture at block **1204**.

**[0084]** In one example, using a system similar or identical to that shown in FIG. 5, the reference beam may be modified so as to change its angular aperture (e.g., angle of incidence with respect to the recording medium). This may be performed by, for example, adjusting the orientation of the beam directing device reflecting the output of the laser source. Additionally, the signal beam angular aperture may be modified such that the reference beam angular aperture and the edge of the signal beam angular aperture nearest the reference beam angular aperture may be separated by a threshold angle. This may be accomplished by causing the SLM to change the size and position at which the signal beam enters the aperture sharing element, as described above. In some examples, the threshold angle may be the same or substantially the same (e.g., within a tolerance threshold) as the threshold angle used at block **1202** (e.g., the edge of the signal beam angular aperture may be 15° higher than the angular aperture of the reference beam used to record it). Thus, the signal beam angular aperture may be modified by the same or substantially the same (e.g., within a tolerance threshold) amount as the angular aperture of the reference beam used to record it. In other examples, the threshold angle may be different than the threshold angle used at block **1202**. For example, the threshold angle may be selected such that the edge of the signal beam angular aperture may be 40° higher than the angular aperture of the reference beam used to record it. However, other differences in angles may be used.

**[0085]** In another example, using a system similar or identical to that shown in FIG. 9, the SLM (e.g., SLM **904**) may shift the signal beam angular aperture to a different edge of the SLM (e.g., in the directions of 0°, 120°, or 240° as shown in FIGS. **11(a)**, **11(b)**, and **11(c)**, respectively, or other direction) and may shift the reference beam angular aperture to accommodate the shifted signal beam angular aperture. This may be done in a manner that results in a threshold angle separation between the reference beam angular aperture and the edge of the signal beam angular aperture nearest the reference beam angular aperture. The threshold angle may be the same as or different than the threshold angle used at block **1202**.

**[0086]** At block **1206**, a third hologram may be recorded to the recording medium using a third signal beam angular aperture and a third reference beam having a third angular aperture. It should be appreciated that the third reference beam

may be similar to the first reference beam used to record the first hologram at block **1202**, except that a characteristic of the first reference beam may be modified to generate the third reference beam at block **1206**. Similarly, the third signal beam angular aperture may be similar to the first signal beam angular aperture used to record the first hologram at block **1202**, except that a characteristic of the first signal beam angular aperture may be modified to generate the third signal beam angular aperture at block **1206**.

**[0087]** In one example, using a system similar or identical to that shown in FIG. 5, block **1206** may be performed in a manner similar to that of block **1204**, except that the reference beam angular aperture may be different than that used in any of the previous recordings (e.g., first and second recordings made at blocks **1202** and **1204**) and that the signal beam angular aperture may be modified such that the reference beam angular aperture and the edge of the signal beam angular aperture nearest the reference beam angular aperture may be separated by a threshold angle. In some examples where the threshold angles used at blocks **1202** and **1204** were the same (or at least substantially the same), the threshold angle used at block **1206** may also be the same (e.g., 15 degrees) or substantially the same. In other examples where the threshold angles used at blocks **1202** and **1204** were different, the threshold angle used at block **1206** may be the same (or at least substantially the same) as that used at block **1202** (e.g., 15 degrees). In this way, dynamic aperture equalization may be achieved by interleaving data page sizes to reduce cross-talk between holograms.

**[0088]** In another example, using a system similar or identical to that shown in FIG. 9, block **1206** may be performed in a manner similar to that of block **1204**, except that the reference beam angular aperture may be different than that used in any of the previous recordings (e.g., first and second recordings made at blocks **1202** and **1204**) and that the signal beam angular aperture may be modified such that the reference beam angular aperture and the edge of the signal beam angular aperture nearest the reference beam angular aperture may be separated by a threshold angle. In some examples where the threshold angles used at blocks **1202** and **1204** were the same (or at least substantially the same), the threshold angle used at block **1206** may also be the same or substantially the same. In other examples where the threshold angles used at blocks **1202** and **1204** were different, the threshold angle used at block **1206** may be the same (or at least substantially the same) as that used at block **1202**. In this way, dynamic aperture equalization may be achieved by interleaving data page sizes to reduce cross-talk between holograms.

**[0089]** At block **1208**, a fourth hologram may be recorded to the recording medium using a fourth signal beam angular aperture and a fourth reference beam having a fourth angular aperture. It should be appreciated that the fourth reference beam may be similar to the first reference beam used to record the first hologram at block **1202**, except that a characteristic of the first reference beam may be modified to generate the fourth reference beam at block **1208**. Similarly, the fourth signal beam angular aperture may be similar to the first signal beam angular aperture used to record the first hologram at block **1202**, except that a characteristic of the first signal beam angular aperture may be modified to generate the fourth signal beam angular aperture at block **1208**.

**[0090]** In one example, using a system similar or identical to that shown in FIG. 5, block **1208** may be performed in a manner similar to that of block **1204**, except that the reference

beam angular aperture may be different than that used in any of the previous recordings (e.g., first, second, and third recordings made at blocks **1202**, **1204**, and **1206**) and that the signal beam angular aperture may be modified such that the reference beam angular aperture and the edge of the signal beam angular aperture nearest the reference beam angular aperture may be separated by a threshold angle. In some examples where the threshold angles used at blocks **1202**, **1204**, and **1206** were the same (or at least substantially the same), the threshold angle used at block **1208** may also be the same (e.g., 15 degrees) or substantially the same. In other examples where at least some of the threshold angles used at blocks **1202**, **1204**, and **1206** were different, the threshold angle used at block **1208** may be the same or substantially the same as that used at block **1204** (e.g., 40 degrees). In these examples, the threshold angles for the first and third holograms may be the same or substantially the same, while the threshold angles for the second and fourth holograms may be the same or substantially the same. However, the threshold angle for the first and third holograms may be different than the threshold angle for the second and fourth holograms. In this way, dynamic aperture equalization may be achieved by interleaving data page sizes to reduce cross-talk between holograms.

[0091] In another example, using a system similar or identical to that shown in FIG. 9, block **1208** may be performed in a manner similar to that of block **1204**, except that the reference beam angular aperture may be different than that used in any of the previous recordings (e.g., first, second, and third recordings made at blocks **1202**, **1204**, and **1206**) and that the signal beam angular aperture may be modified such that the reference beam angular aperture and the edge of the signal beam angular aperture nearest the reference beam angular aperture may be separated by a threshold angle. In some examples where the threshold angles used at blocks **1202**, **1204**, and **1206** were the same (or at least substantially the same), the threshold angle used at block **1208** may also be the same or substantially the same. In other examples where at least some of the threshold angles used at blocks **1202**, **1204**, and **1206** were different, the threshold angle used at block **1208** may be the same or substantially the same as that used at block **1204**. In these examples, the threshold angles for the first and third holograms may be the same or substantially the same, while the threshold angles for the second and fourth holograms may be the same or substantially the same. However, the threshold angle for the first and third holograms may be different than the threshold angle for the second and fourth holograms. In this way, dynamic aperture equalization may be achieved by interleaving data page sizes to reduce cross-talk between holograms.

[0092] In some examples, additional holograms may be recorded in a manner similar to that described with respect to blocks **1204**, **1206**, and **1208**. Each additional hologram may be recorded using a reference beam that is different than any of those previously used to record holograms and a signal beam that has been dynamically adjusted accordingly, as described above. In some examples, the threshold angle offset between the reference beam angular aperture and the edge of the signal beam angular aperture nearest the reference beam may be the same or substantially the same as the threshold angles used in each of the previous recordings. In other examples, the threshold angle offset may be interleaved such that even numbered holograms may use the same or substantially the same threshold angle and odd numbered holograms

may use the same or substantially the same threshold angle (different from the angle used for the even numbered holograms) in order to perform dynamic aperture equalization to reduce cross-talk between holograms. In yet other examples, other non-uniform distributions of threshold angles may be used to generate the holograms.

[0093] In some examples, process **1200** may include the use of error correcting codes. In these examples, some of the data pages or holograms may be used to store parity information, while the other data pages are used to store input data. For example, the smaller data pages may be used to store the parity information, while the remaining data pages may be used to store input data. This may advantageously improve the recovery transfer rate because in the event of error-free recovery of the input data, the parity data residing on the smaller data pages need not be recovered.

[0094] In some examples, process **1200** may include multiple locus aperture sharing, as discussed above. In these examples, regions of the aperture may be shared multiple times. For example, process **1200** may include double sharing, as described above with respect to FIGS. **8(a)** and **8(b)**.

[0095] In some examples in which multiple locus shared aperture techniques are used in process **1200**, multiple locus multiplexing may be performed simultaneously, rather than sequentially, by employing substantially orthogonal polarization states for the recording or recovery of two shared apertures simultaneously. In some examples, the shared apertures of FIGS. **8(a)** and **8(b)** may each be recorded or recovered with reference and signal light in the linearly-polarized “s” state with respect to their own reference beams. Since these polarizations are substantially orthogonal to each other, a recording operation may not produce significant interference fringes between reference A and signal B, or between reference B and signal A. Thus the two distributions may be recorded simultaneously. To perform the simultaneous recording, the holographic data storage system (e.g., system **500**) may instead include two separate SLMs and reference scanners, as well as another aperture sharing element based on polarization (such as a PBS) used to combine the beams. The system may further include two detectors to perform the recovery operation, and the new aperture sharing element may direct light of each polarization toward the appropriate detector.

[0096] FIG. **13** depicts computing system **1300** with a number of components that may be used to perform the above-described processes. The main system **1302** includes a motherboard **1304** having an input/output (“I/O”) section **1306**, one or more central processing units (“CPU”) **1308**, and a memory section **1310**, which may have a flash memory card **1312** related to it. The I/O section **1306** is connected to a display **1324**, a keyboard **1314**, a disk storage unit **1316**, and a media drive unit **1318**. The media drive unit **1318** can read/write a non-transitory computer-readable storage medium **1320**, which can contain programs **1322** and/or data.

[0097] At least some values based on the results of the above-described processes can be saved for subsequent use. Additionally, a non-transitory computer-readable medium can be used to store (e.g., tangibly embody) one or more computer programs for performing any one of the above-described processes by means of a computer. The computer program may be written, for example, in a general-purpose programming language (e.g., Pascal, C, C++, Java) or some specialized application-specific language.

[0098] Although only certain exemplary embodiments have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this disclosure. For example, aspects of embodiments disclosed above can be combined in other combinations to form additional embodiments. Accordingly, all such modifications are intended to be included within the scope of this disclosure.

What is claimed is:

1. A method for recording a set of multiplexed holograms, the method comprising:

recording a first hologram of the set of multiplexed holograms to a recording medium using a first signal beam angular aperture and a first reference beam; and recording a second hologram of the set of multiplexed holograms to the recording medium using a second signal beam angular aperture and a second reference beam, wherein the second signal beam angular aperture is varied in at least one characteristic from the first signal beam angular aperture.

2. The method of claim 1, wherein the first hologram and the second hologram each comprise a data page of pixel information.

3. The method of claim 1, wherein the first signal beam angular aperture and the second signal beam angular aperture vary in one or more of shape, size, and position.

4. The method of claim 1, further comprising: recording a third hologram of the set of multiplexed holograms to the recording medium using a third signal beam angular aperture and a third reference beam, wherein the third signal beam angular aperture is varied in at least one characteristic from the first signal beam angular aperture and the second signal beam angular aperture; and

recording a fourth hologram of the set of multiplexed holograms to the recording medium using a fourth signal beam angular aperture and a fourth reference beam, wherein the fourth signal beam angular aperture is varied in at least one characteristic from the first signal beam angular aperture, second signal beam angular aperture, and the third signal beam angular aperture.

5. The method of claim 4, wherein:

an edge of the first signal beam angular aperture is separated from an angular aperture of the first reference beam by a first angle;

an edge of the second signal beam angular aperture is separated from an angular aperture of the second reference beam by a second angle;

an edge of the third signal beam angular aperture is separated from an angular aperture of the third reference beam by a third angle; and

an edge of the fourth signal beam angular aperture is separated from an angular aperture of the fourth reference beam by a fourth angle.

6. The method of claim 5, wherein the first angle, the second angle, the third angle, and the fourth angle are substantially equal.

7. The method of claim 5, wherein:

the first angle and the third angle are substantially equal; the second angle and the fourth angle are substantially equal; and

the first angle and the third angle are different than the second angle and the fourth angle.

8. The method of claim 1, wherein using the first signal beam angular aperture comprises using a signal beam with an angular range.

9. The method of claim 1, wherein at least a portion of an angular locus of a set of reference beams used to record the set of multiplexed holograms overlaps at least a portion of an angular locus of a set of signal beams used to record the set of multiplexed holograms.

10. The method of claim 1, wherein a first portion of the set of multiplexed holograms are used to store error parity data and a second portion of the set of multiplexed holograms are used to store input data, wherein the holograms of the first portion are smaller than the holograms of the second portion.

11. A system for recording a set of multiplexed holograms, the system comprising:

an aperture sharing element configured to output a modulated signal beam and a reference beam;

a recording medium; and

a controller configured to:

cause the recording of a first hologram of the set of multiplexed holograms to the recording medium by causing the aperture sharing element to output a first signal beam having a first signal beam angular aperture and a first reference beam having a first reference beam angular aperture; and

cause the recording of a second hologram of the set of multiplexed holograms to the recording medium by causing the aperture sharing element to output a second signal beam having a second signal beam angular aperture and a second reference beam having a second reference beam angular aperture, wherein the second signal beam angular aperture is varied in at least one characteristic from the first signal beam angular aperture.

12. The system of claim 11, wherein the aperture sharing element comprises a spatial light modulator, and wherein causing the aperture sharing element to output the first signal beam having the first signal beam angular aperture and the first reference beam having the first reference beam angular aperture comprises controlling the spatial light modulator to output the first signal beam having the first signal beam angular aperture and the first reference beam having the first reference beam angular aperture.

13. The system of claim 11, further comprising:

a laser source for generating a beam;

a beam directing device coupled to receive the beam; and a spatial light modulator coupled to receive the beam, wherein:

causing the aperture sharing element to output the first signal beam having the first signal beam angular aperture comprises controlling the spatial light modulator to cause the aperture sharing element to output the first signal beam having the first signal beam angular aperture; and

causing the aperture sharing element to output the first reference beam having the first reference beam angular aperture comprises controlling the beam directing device to output the first reference beam having the first reference beam angular aperture

14. The system of claim 11, wherein the controller is further configured to:

cause the recording of a third hologram of the set of multiplexed holograms to the recording medium by causing the aperture sharing element to output a third signal

beam having a third signal beam angular aperture and a third reference beam having a third reference beam angular aperture, wherein the third signal beam angular aperture is varied in at least one characteristic from the first signal beam angular aperture and the second signal beam angular aperture; and

cause the recording of a fourth hologram of the set of multiplexed holograms to the recording medium by causing the aperture sharing element to output a fourth signal beam having a fourth signal beam angular aperture and a fourth reference beam having a fourth reference beam angular aperture, wherein the fourth signal beam angular aperture is varied in at least one characteristic from the first signal beam angular aperture, second signal beam angular aperture, and the third signal beam angular aperture.

15. The system of claim 14, wherein:

an edge of the first signal beam angular aperture is separated from an angular aperture of the first reference beam by a first angle;

an edge of the second signal beam angular aperture is separated from an angular aperture of the second reference beam by a second angle;

an edge of the third signal beam angular aperture is separated from an angular aperture of the third reference beam by a third angle; and

an edge of the fourth signal beam angular aperture is separated from an angular aperture of the fourth reference beam by a fourth angle.

16. The system of claim 15, wherein the first angle, the second angle, the third angle, and the fourth angle are substantially equal.

17. The system of claim 15, wherein:

the first angle and the third angle are substantially equal; the second angle and the fourth angle are substantially equal; and

the first angle and the third angle are different than the second angle and the fourth angle.

18. The system of claim 11, wherein the first signal beam angular aperture comprises an angular range of the signal beam.

19. The system of claim 11, wherein at least a portion of an angular locus of a set of reference beams used to record the set of multiplexed holograms overlaps at least a portion of an angular locus of a set of signal beams used to record the set of multiplexed holograms.

20. The system of claim 11, wherein a first portion of the set of multiplexed holograms is used to store error parity data and a second portion of the set of multiplexed holograms is used to store input data, wherein the holograms of the first portion are smaller than the holograms of the second portion.

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