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(54) **HOLOGRAPHIC STORAGE**

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CPC **G11B 7/0065** (2013.01); **G11B 7/135**
(2013.01)

(58) **Field of Classification Search**

None

See application file for complete search history.

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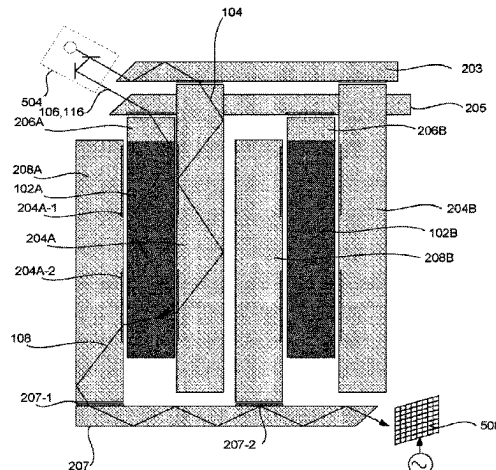
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(57) **ABSTRACT**

A holographic data storage system comprises an emitter
system, a holographic recording medium, and an input
waveguide network formed of one or more multimode
optical waveguides. The holographic recording medium has
multiple recording regions, each optically coupled to a
corresponding one of multiple out-coupling regions of the
input waveguide network, the holographic data storage
system arranged to persistently write data of an input beam,
received at any one of the out-coupling regions, to the
corresponding recording region. A controller is coupled to at
least one of the emitter system and at least one controllable
guiding element of the input waveguide network and controls
at least one optical characteristic of the input beam or
the at least one guiding element, so as to guide the input
beam from an in-coupling region to any selected one of the

(Continued)



multiple out-coupling regions. Similar waveguide networks are provided for carrying reference and output beams.

20 Claims, 12 Drawing Sheets

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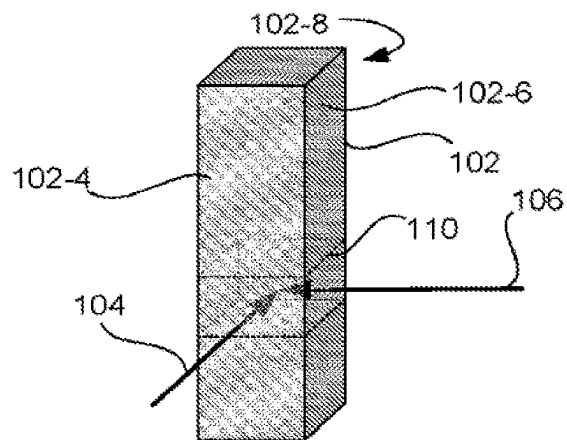


FIG. 1A

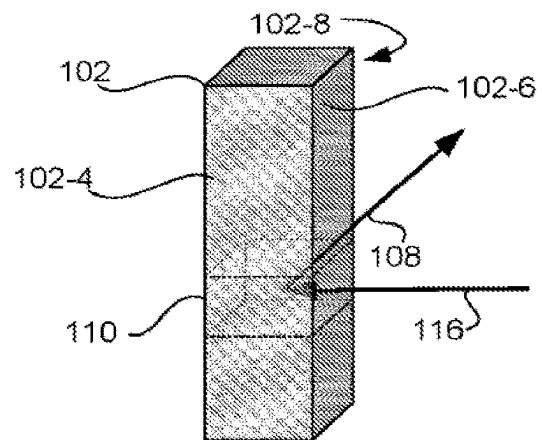


FIG. 1B

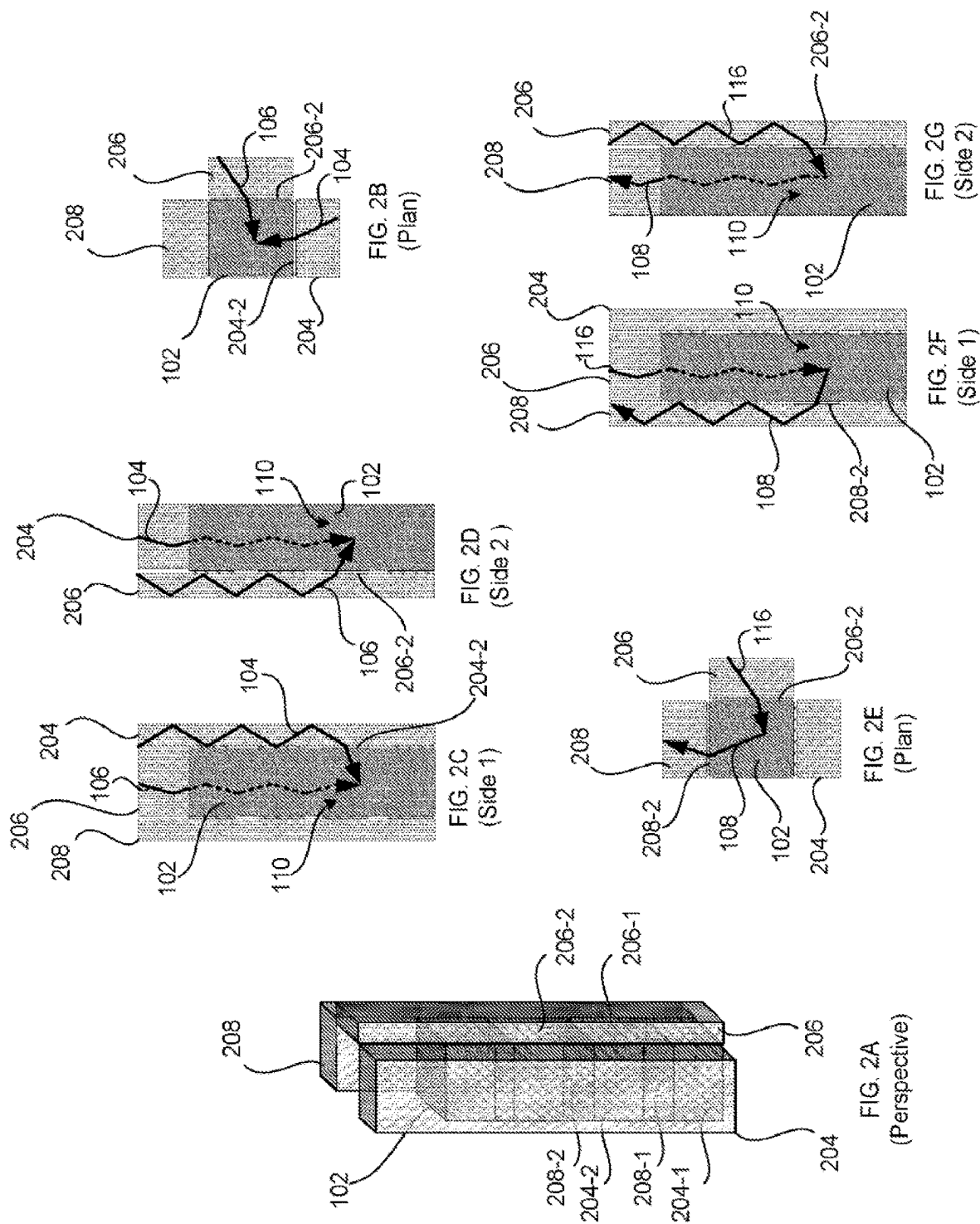


FIG 3A:

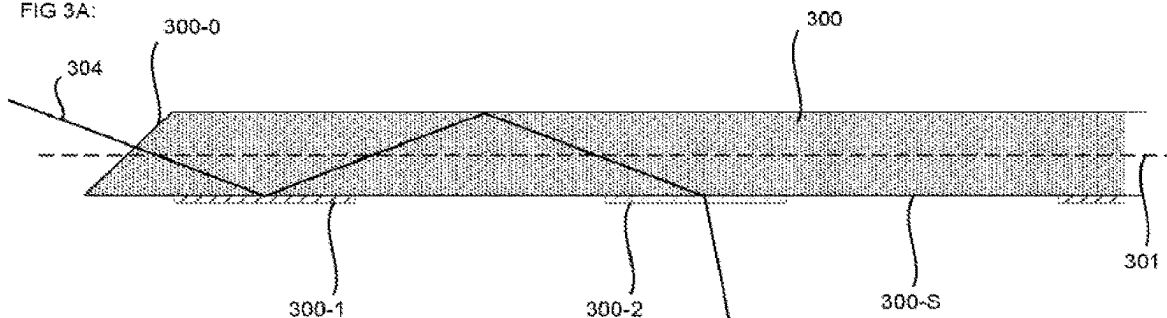


FIG 3B:

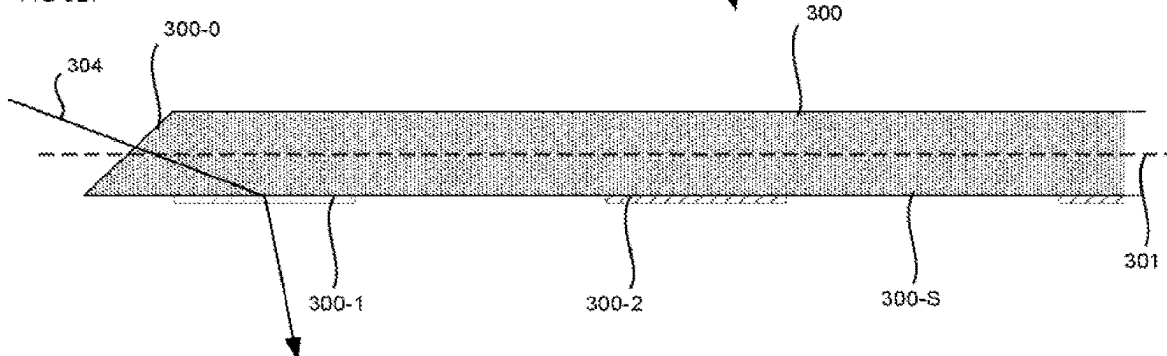


FIG 3C:

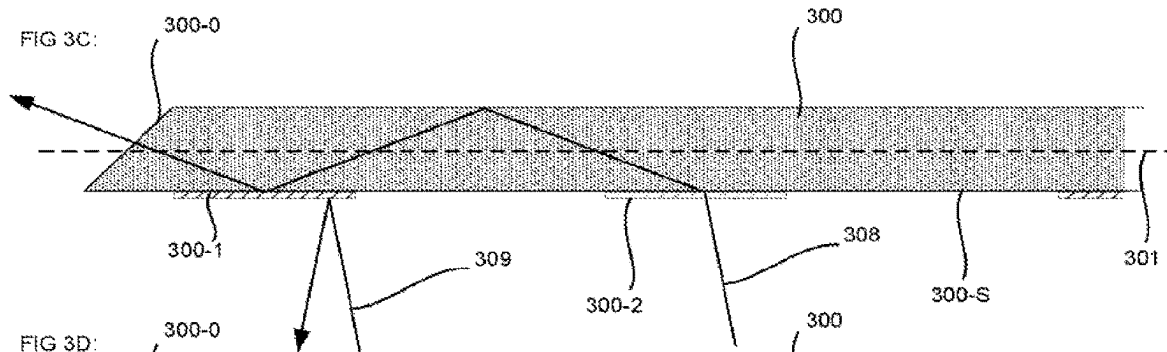


FIG 3D:

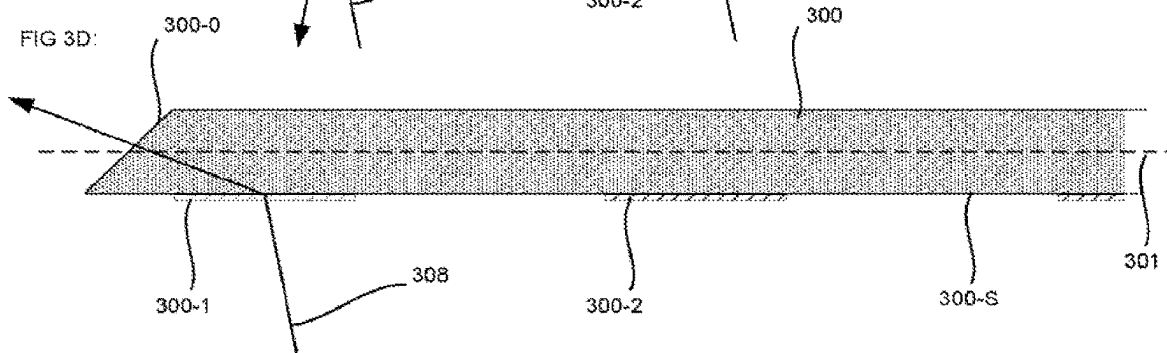


FIG 3E:

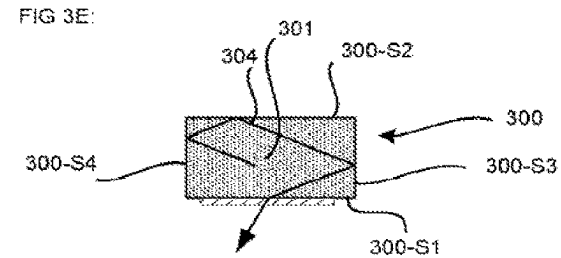
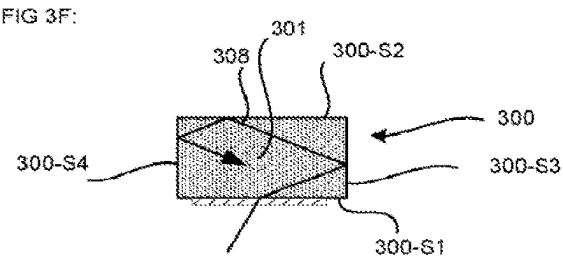


FIG 3F:



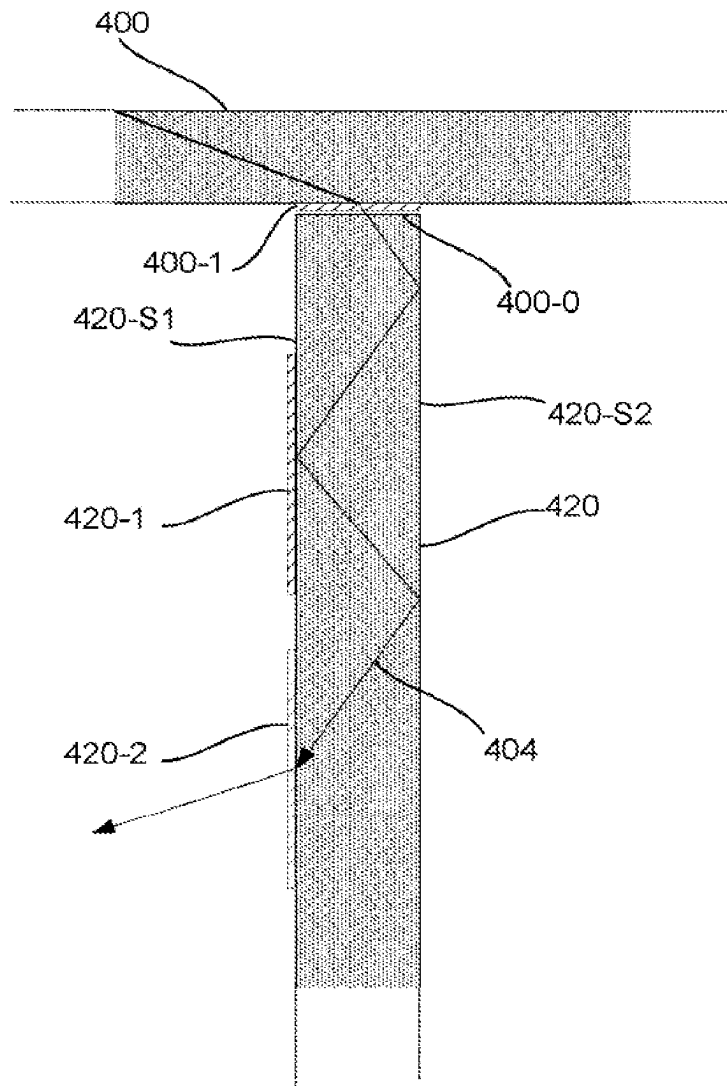


FIG. 4A

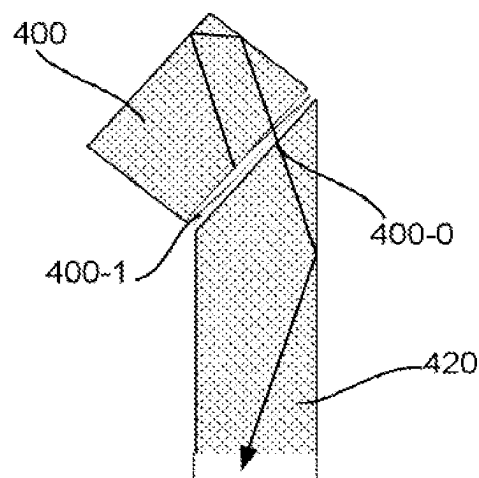


FIG. 4B

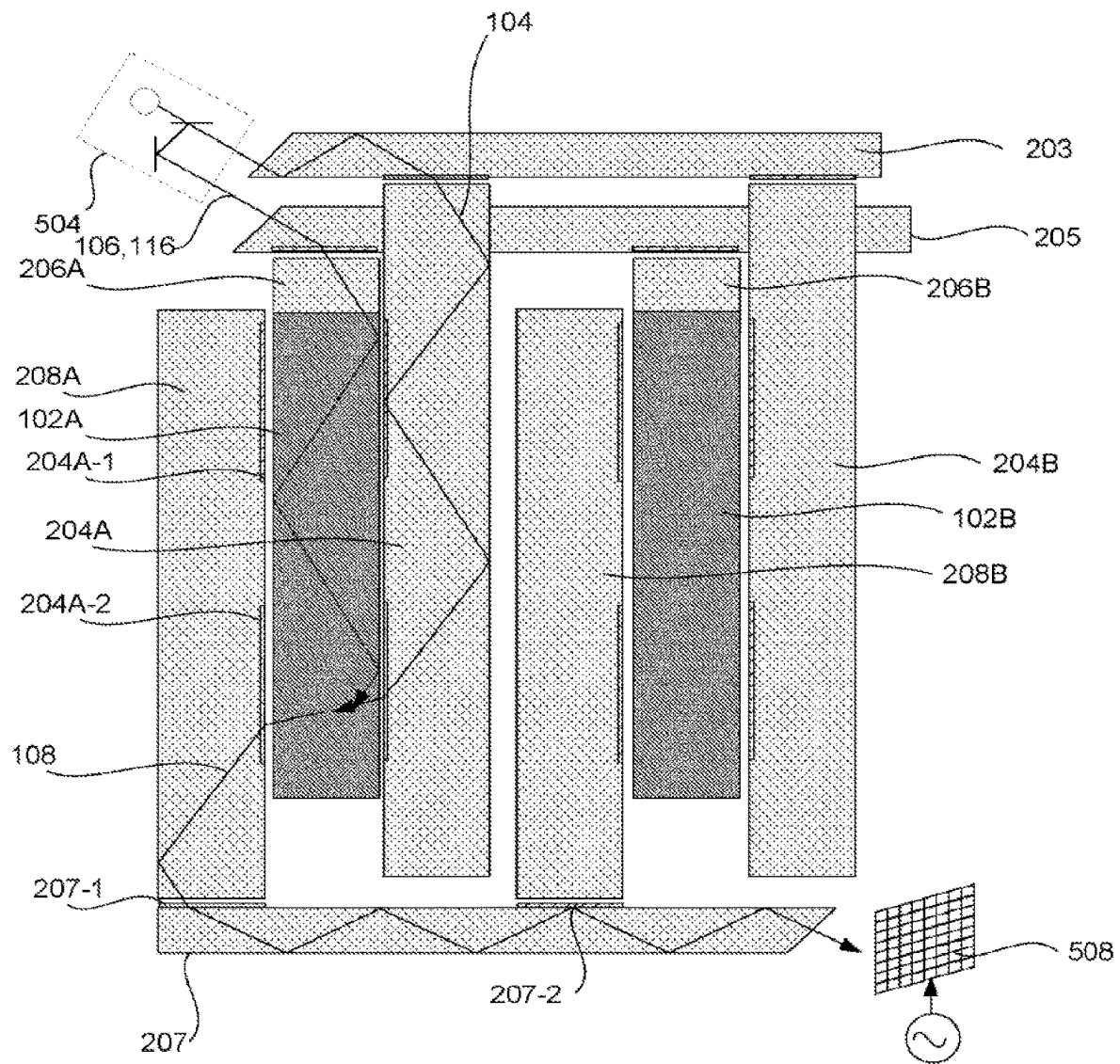


FIG. 5

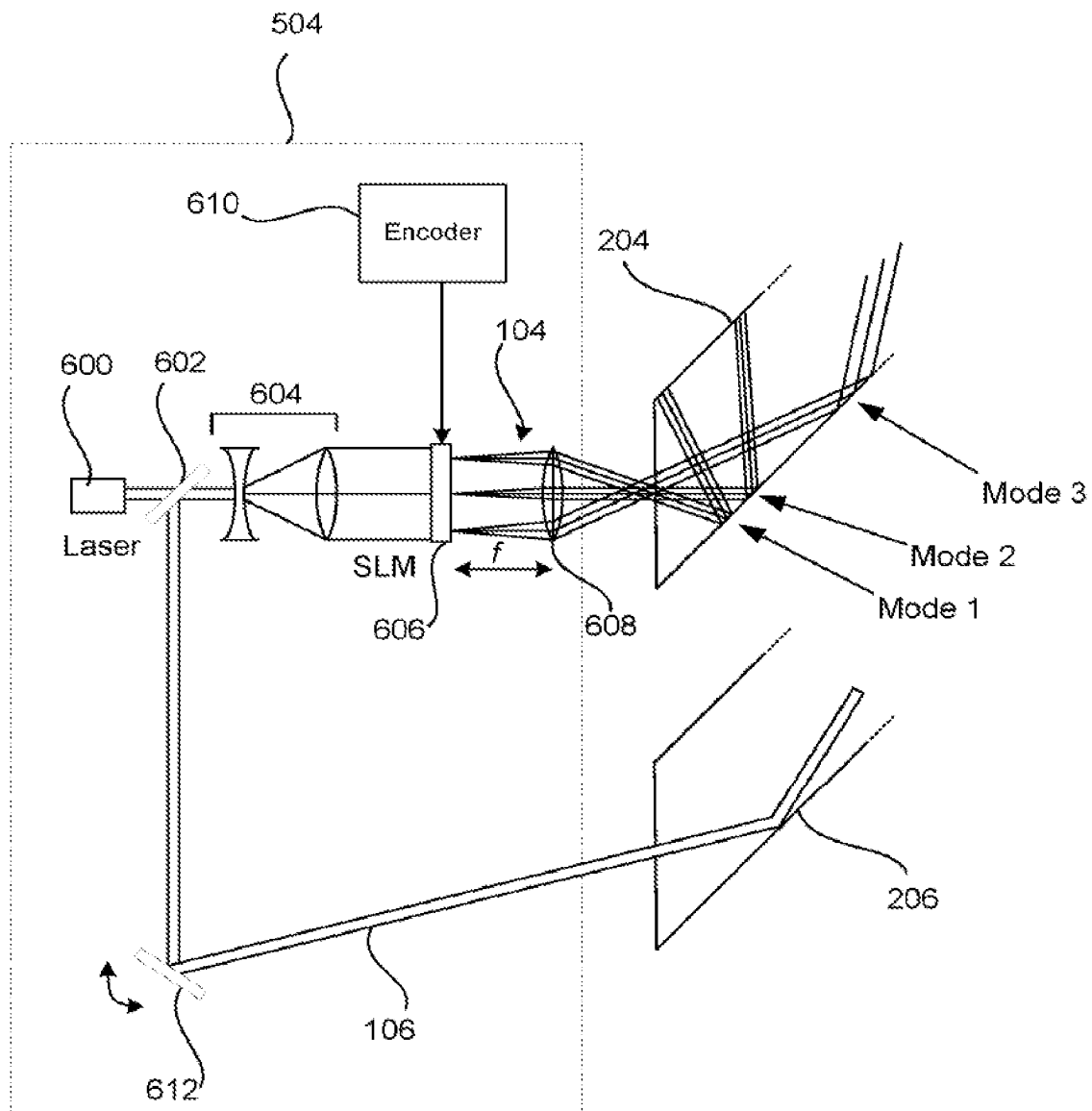


FIG. 6A

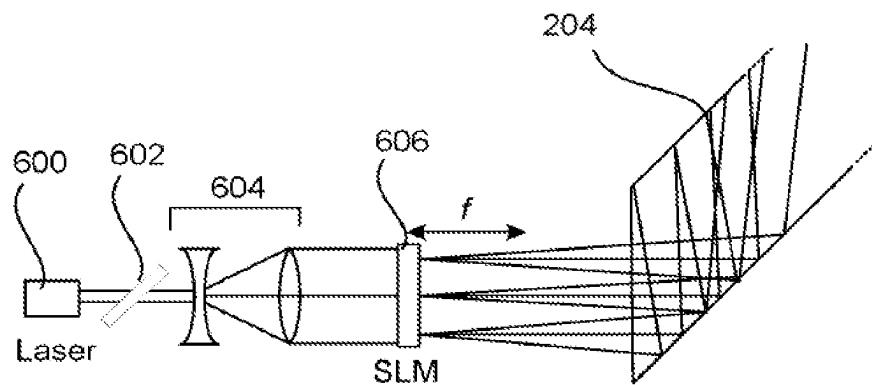
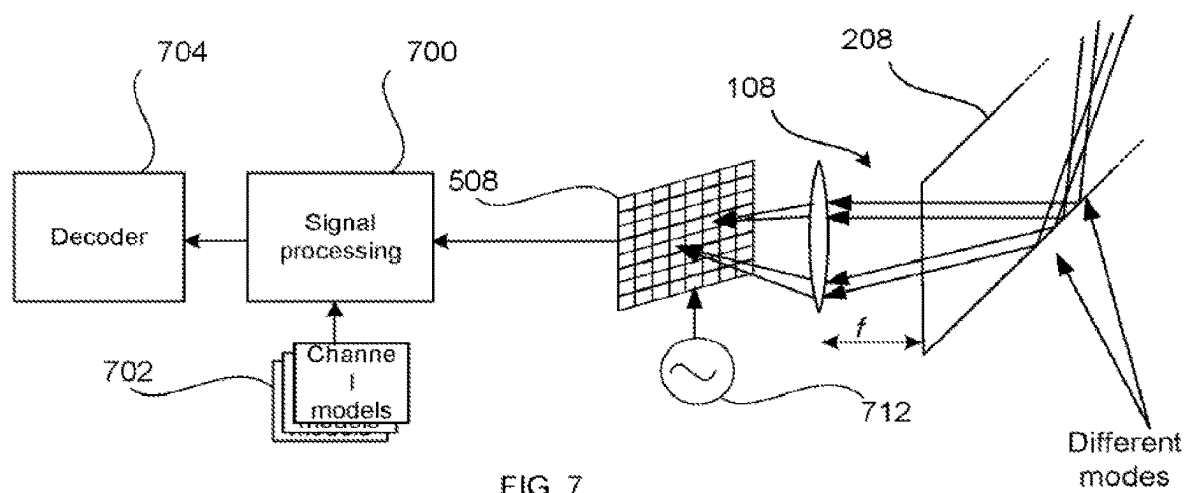


FIG. 6B



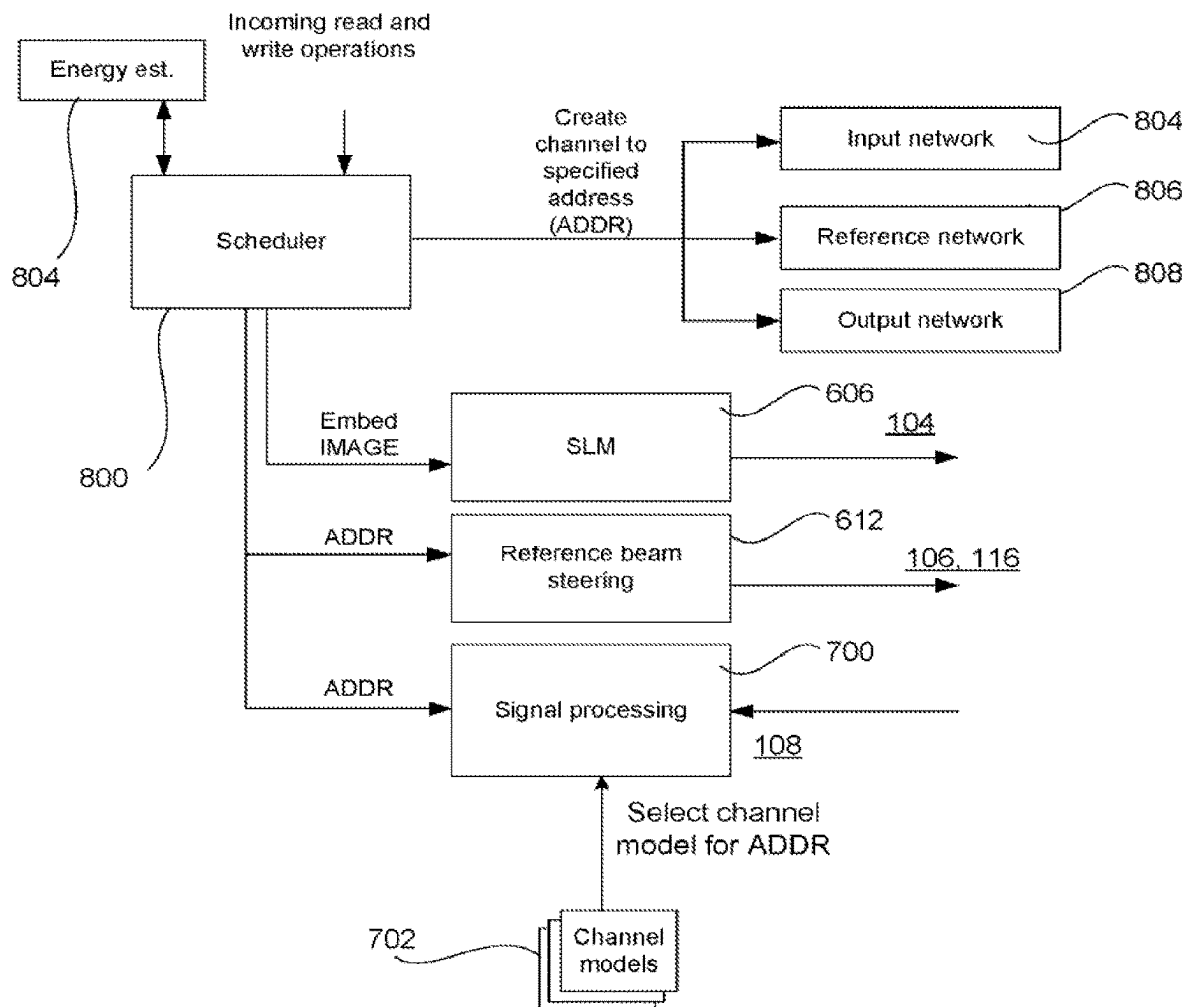


FIG. 8

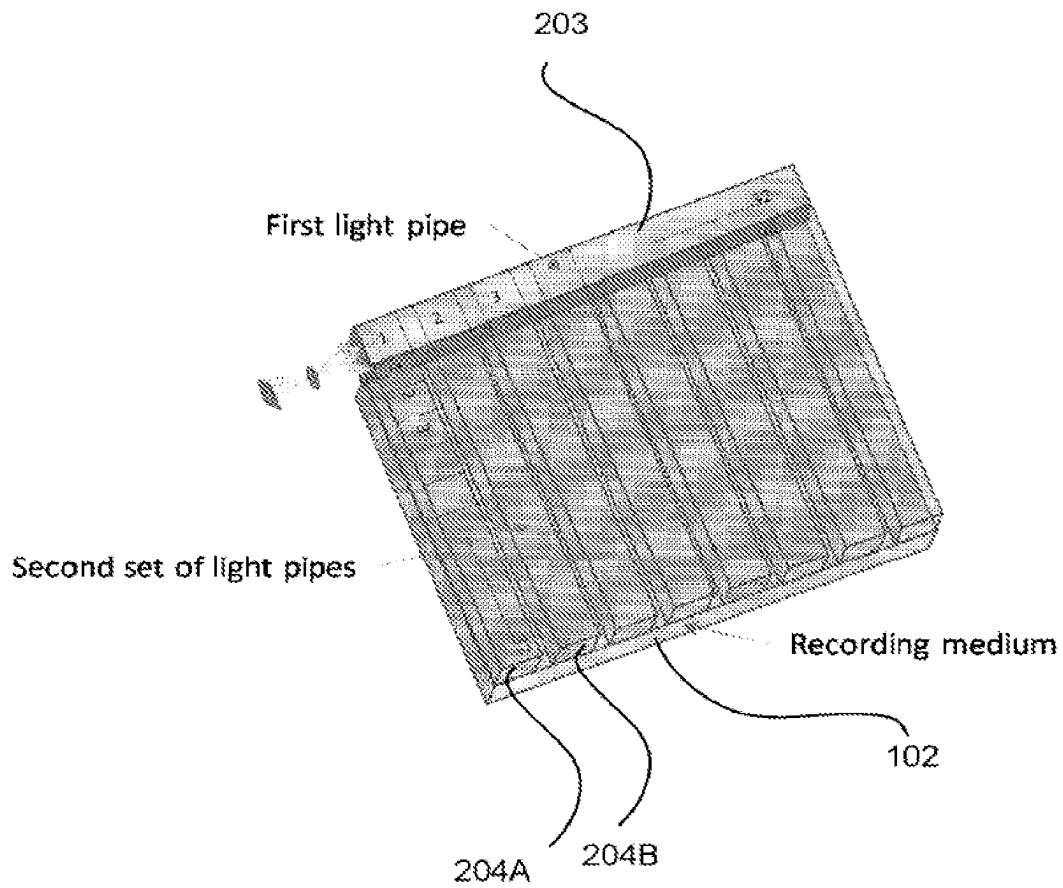


FIG. 9

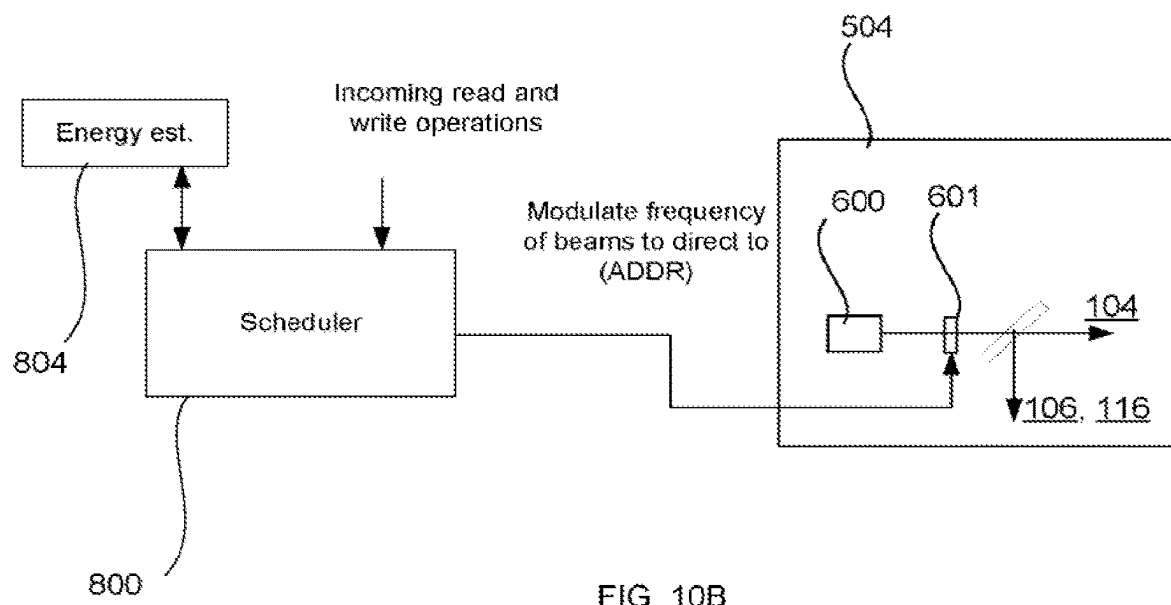
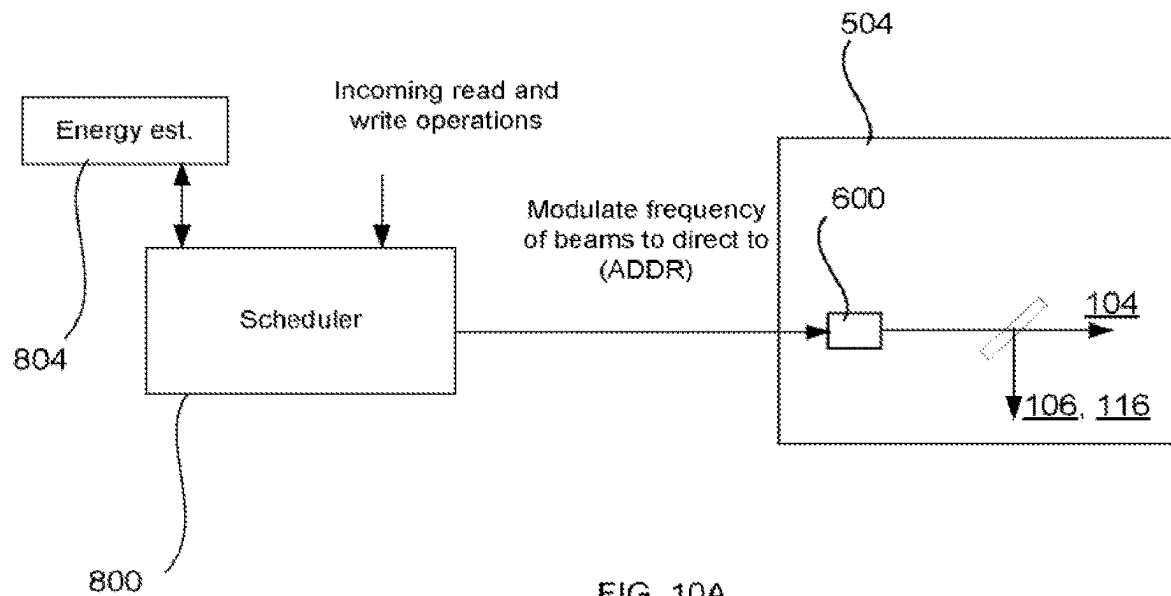


FIG 11A:

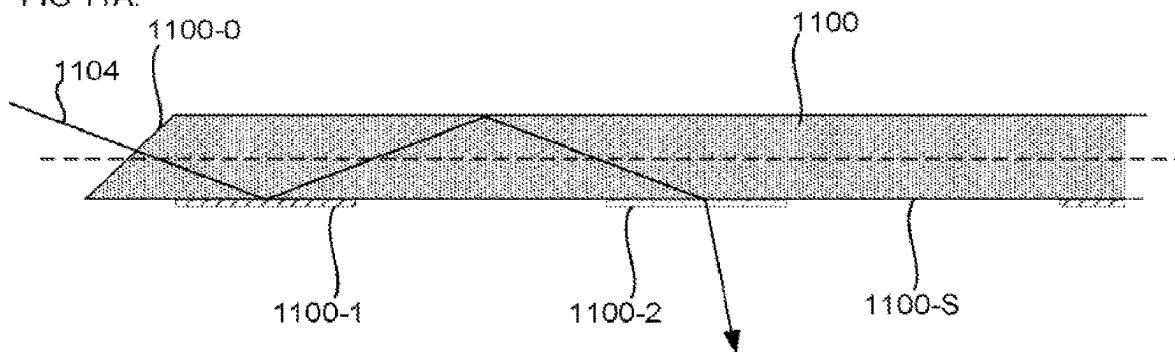
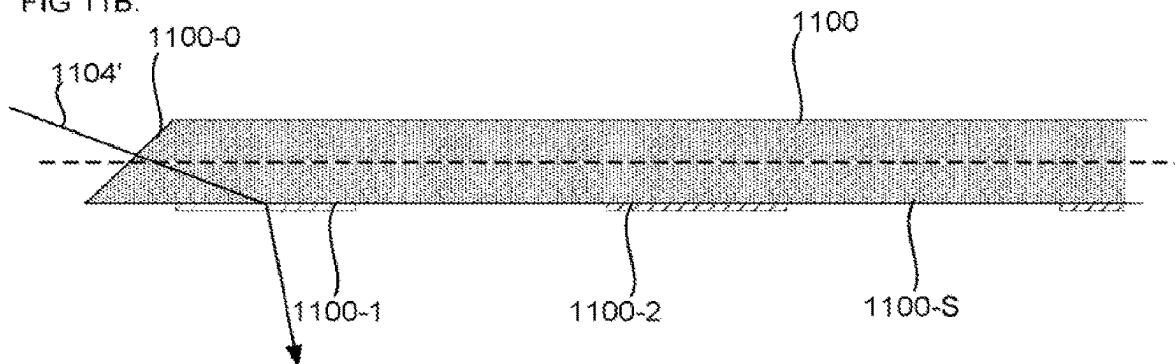


FIG 11B:



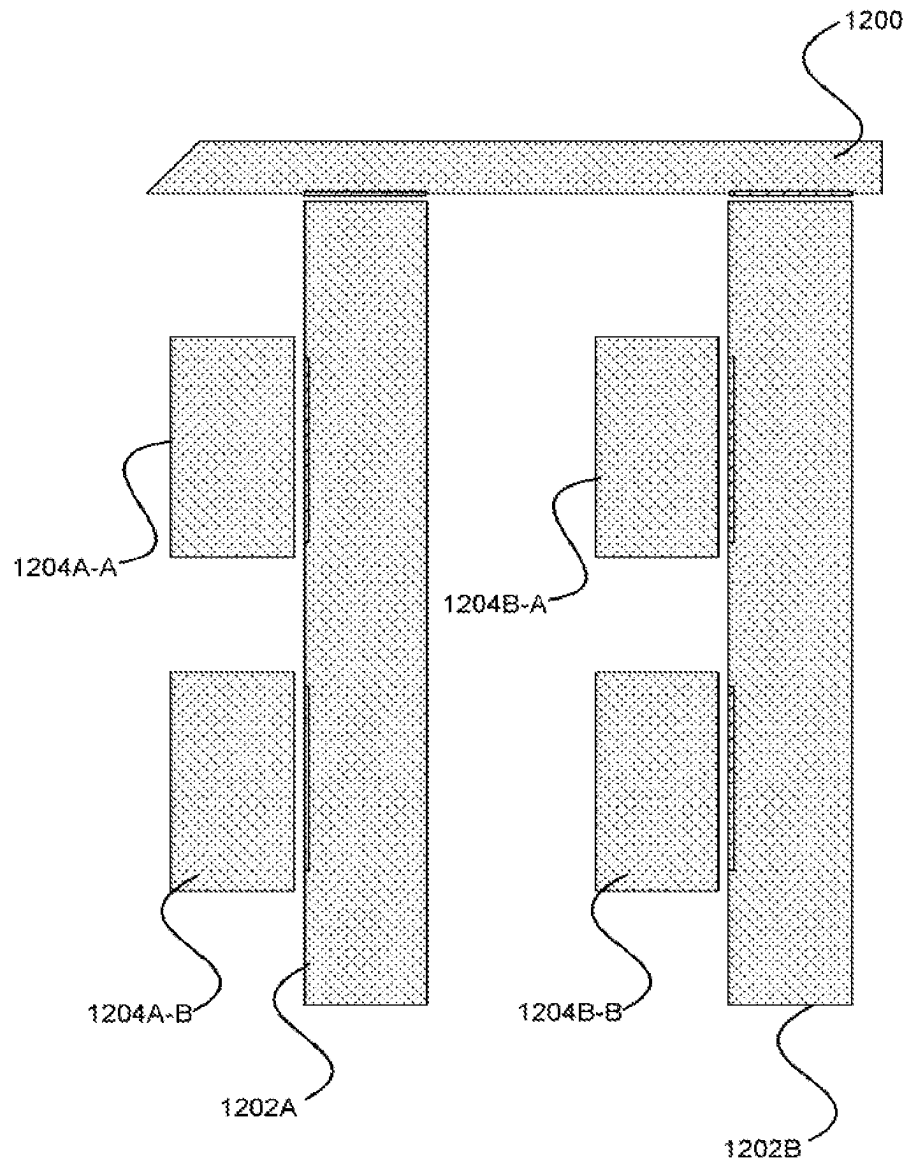


FIG 12

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HOLOGRAPHIC STORAGE**CROSS-REFERENCE TO RELATED APPLICATION**

This application is a continuation application of and claims priority to U.S. patent application Ser. No. 17/906,793, entitled "HOLOGRAPHIC STORAGE," filed on Sep. 20, 2022, which is a U.S. national phase application of PCT Application No. PCT/US21/18952, entitled "HOLOGRAPHIC STORAGE," filed on Feb. 22, 2021, which claims priority to EP Application No. 20165935.6, filed on Mar. 26, 2020, the disclosures of which are incorporated herein by reference in their entireties.

TECHNICAL FIELD

The present disclosure pertains generally to holographic storage.

BACKGROUND

Holographic storage is a form of computer storage, in which information is recorded in a light-sensitive holographic recording medium by exposing the medium to optical patterns. For example, a region (sub-volume) of the medium may be exposed to an optical interference pattern caused by interference between a reference beam and an input beam in which a set of data is embedded. The beams may, for example, be laser beams generated using a single laser and a beam splitter. Spatial light modulation (SLM) may be used to embed the set of data in the input beam, e.g. an image encoding the set of data may be spatially modulated into the input beam. For the avoidance of doubt, herein the terms "light", "optical" and the like are not restricted to visible light. Holographic storage can, for example, be implemented using infrared or ultraviolet beams within non-visible portions of the electromagnetic spectrum.

With sufficient beam power and exposure time, the optical interference pattern causes a persistent state change within the sub-volume (at this point, the interference pattern is said herein to be persistently recorded or written to the sub volume). The changed state of the sub-volume is such that, upon exposing the sub-volume to a substantially matching reference beam at a later time, the interaction between the matching reference beam and the sub-volume creates an output beam that essentially matches the original input beam, in the sense that the set of data originally embedded in the input beam can be recovered from the output beam (this may be referred to herein as reading the recorded pattern).

Rather than storing individual bits as discrete units, a single interference pattern can encode a large number (e.g. millions) of bits. For example, the set of data could be a megapixel image embedded in the input beam. Moreover, it is possible to record many such patterns (e.g. hundreds or thousands) to the same sub-volume, by exploiting the sensitivity of certain forms of holographic recording media to small changes in the angle of the reference beam. For such media, when an interference pattern is created with the reference beam at a given angle, the recorded pattern can only be read using a reference beam that closely matches the reference beam originally used to create it. This effect can be exploited to record multiple patterns (encoding different data sets) to the same sub-volume at different reference beam angles. Theoretically, the data storage capacity is limited only by the wavelength of the beams, with the potential to

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hundreds of megabytes per cubic millimetre for red light and tens of gigabytes for ultraviolet. In practice, there may be other limiting factors but there is nevertheless significant potential for high-density data storage.

SUMMARY

This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter. Nor is the claimed subject matter limited to implementations that solve any or all of the disadvantages noted herein.

Holographic data storage/retrieval systems which provide spatial multiplexing over a holographic recording medium, in the sense of being able to write to/read from different physical sub-volumes of the medium, typically require some form of mechanical actuator(s) to effect controllable mechanical movement of either the holographic medium, to move the medium relative to e.g. a read/write head of the system (from which the input and reference beams are emitted and at which the output beam is detected), or to move the read/write head relative to the medium. This, in turn, imposes limits on the speed at which data can be written/read, and also the scalability and reliability of such systems. Aspects of the technology disclosed herein reduce or eliminate the need for such mechanical movement.

A first aspect herein provides a holographic data storage system comprising an emitter system, at least one holographic recording medium, and an input waveguide network formed of one or more multimode optical waveguides for carrying multiple propagation modes simultaneously. The emitter system is configured to emit an input beam, in the form of a multimode optical signal that encodes multiple image pixels as multiple propagation modes of the input beam propagating in different directions. The input waveguide network has an in-coupling region for receiving an input beam from the emitter system and multiple out-coupling regions. The at least one holographic recording medium has multiple recording regions, each optically coupled to a corresponding one of the multiple out-coupling regions of the input waveguide network, the holographic data storage system arranged to persistently and simultaneously write multiple image pixels encoded in an input beam, received at any one of the out-coupling regions, to the corresponding recording region. A controller is coupled to at least one of the emitter system and at least one controllable guiding element of the input waveguide network, the controller configured to control at least one optical characteristic of the input beam or the at least one guiding element, so as to guide the input beam from the in-coupling region to any selected one of the multiple out-coupling regions. With this arrangement, different ones of the multiple recording regions may be written to from the same in-coupling region by changing said at least one optical characteristic or controlling said at least one guiding element to guide the input beam to different ones of the multiple out-coupling regions, whilst the multiple out-coupling regions of the multimode optical waveguide network remain at fixed locations relative to the corresponding recording regions of the holographic recording medium.

Accordingly, in the first aspect, spatial multiplexing over the holographic recording medium is achieved for write options, without requiring any mechanical movement of the emitter system, the holographic recording medium or the

input waveguide network. In the case that the guiding element(s) is controllable, it can be controlled to guide the input beams along different routes through the input waveguide network, to different regions of the medium; in the case that the optical characteristic(s) of the beam is varied, the input waveguide network may or may not be active (i.e. it could be passive or active) but, either way, the input waveguide network is responsive to changes in the optical characteristic(s) of the input beam(s) so that such changes similarly cause the input beam to be guided along different routes.

A second aspect herein provides a holographic data retrieval system comprising an emitter system, at least one detector array for detecting an image, at least one holographic recording medium and a reference waveguide network formed of one or more multimode optical waveguides. The reference waveguide network has an in-coupling region for receiving a reference beam from the emitter system and multiple out-coupling regions respectively optically coupled to corresponding recording regions of the at least one holographic recording medium. A controller is coupled to at least one of the emitter system and at least one controllable guiding element of the reference network, and is configured to control at least one optical characteristic of the reference beam or the at least one guiding element to guide the reference beam to any selected one of the recording regions to be read—thereby creating an output beam, via the reference beam interacting with a pattern stored thereat, for receiving at the detector array for recovering data of the stored pattern from the output beam. With this arrangement, different ones of the multiple recording regions may be read from using the same emitter system, by changing said at least one optical characteristic of the reference beam or controlling said at least one guiding element of the reference network, whilst the multiple out-coupling regions of the multimode optical waveguide network remain at fixed locations relative to the corresponding recording regions of the holographic recording medium. The controller is configured to vary an angle of the reference beam for reading different patterns stored at the same selected recording region, the multimode optical waveguides of the reference waveguide network for carrying a reference beam at any one of multiple possible angles.

A third aspect herein provides a holographic data retrieval system comprising at least one detector array, at least one holographic recording medium and an output waveguide network formed of one or more multimode optical waveguides. The output waveguide network has an out-coupling region for providing an output beam to the detector array, and multiple in-coupling regions respectively optically coupled to corresponding recording regions of the at least one holographic recording medium. A controller is configured to cause an output beam to be guided through the output waveguide network from any selected one of the recording regions, via the in-coupling region optically coupled thereto, to said out-coupling region for receiving at the detector array, by controlling at least one controllable guiding element of the output waveguide network or at least one optical characteristic of a reference beam used to create the output beam. With this arrangement, different ones of the multiple recording regions may be read from using the same detector array, without moving the detector array or the holographic recording medium, by changing said at least one optical characteristic or controlling said at least one guiding element, whilst the multiple out-coupling regions of the output waveguide network remain at fixed locations relative to the corresponding recording regions of the holographic record-

ing medium. The holographic data retrieval system is configured to create the output beam by causing a reference beam to interact with a pattern stored at the selected recording region, the stored pattern encoding multiple image pixels, which are encoded in the output beam as multiple propagation modes propagating simultaneously in different directions through the output waveguide network.

In the second and third aspects, spatial multiplexing over the holographic recording medium is achieved, without requiring any mechanical movement of the emitter system/detector array, the holographic recording medium, or the reference/output waveguide network. In the case that the guiding element(s) is controllable, it can be controlled to guide the reference/output beams along different routes through the reference/output waveguide network, to/from different regions of the medium; in the case that the optical characteristic(s) of the beam is varied, the reference/output waveguide network may or may not be active (i.e. it could be passive or active) but, either way, the reference/output waveguide network is responsive to changes in the optical characteristic(s) of the reference/output beam(s) so that such changes similarly cause the reference/output beam to be guided along different routes.

BRIEF DESCRIPTION OF FIGURES

For a better understanding of the present disclosure, and to show how embodiments of the same may be carried into effect, reference is made by way of example only to the following figures in which:

FIGS. 1A and 1B show schematic perspective views of a holographic recording medium;

FIG. 2A shows a schematic perspective view of a holographic storage system comprising a set of waveguides that may be used to guide beams to/from different sub-volumes of a holographic recording medium to provide spatial multiplexing over the medium;

FIGS. 2B, 2C and 2D show, respectively, plan and alternate side views of the system during a write interval;

FIGS. 2E-G shows plan and alternate side views during a read interval;

FIGS. 3A-3D show schematic side views of an active light pipe in various configurations; FIGS. 3E and 3F shows a plan (cross section) view of the active light pipe;

FIGS. 4A and 4B show alternate side views of (part of) an optical waveguide network;

FIG. 5 shows a schematic view of an example of multi-waveguide network used for multiplexing over multiple pieces of holographic storage media;

FIG. 6A shows an example of an emission system for providing input and reference beams in a holographic storage system; FIG. 6B shows a variation of the emission system with simplified optics;

FIG. 7 shows an example of a data retrieval system that uses spatial coherent detection to measure the optical field of an output beam and signal processing to mitigate waveguide distortion in the measured optical field;

FIG. 8 shows a function block diagram denoting functions performed within a holographic storage system;

FIG. 9 shows an alternative holographic storage system, in which at least one waveguide network is used to spatially multiplex over a slab of holographic recording media in two dimensions;

FIGS. 10A and 10B show how spatial multiplexing may be achieved with passive guiding elements, where spatial multiplexing is achieved by modulating beam characteristic(s);

FIGS. 11A and 11B show a light pipe with passive optical filters having different frequency responses; and

FIG. 12 shows an example of a waveguide network with three hierarchical levels.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

In order to achieve spatial multiplexing over one or more holographic storage media, in a way that reduces or eliminates the need for mechanical movement, “active” light pipes, “passive” light pipes or a combination of active and passive light pipes can be used. Note, the terms “waveguide” and “light pipe” are used interchangeably herein,

An “active light pipe” refers to a waveguide which has one or more active switching elements or other guiding elements attached to the surface of the waveguide or within the bulk of the waveguide, which in turn are configurable (i.e. have changeable optical properties) to effect “one-to-many” optical transfer, i.e. where light is guided from a first surface region to one of multiple possible second surface regions (in this case, the first surface region acts as an in-coupling region and the second regions act as out-coupling regions), or “many-to-one” optical transfer, i.e. where light can be guided from any one of the second surface regions (now acting as in-coupling regions) to the same first surface region (now acting as an out-coupling region). The term “passive light pipe” refers to a light pipe with guiding elements, having different optical sensitivity (e.g. different wavelength and/or polarization sensitivity), so that similar effect can be achieved by instead varying an optical characteristic(s) or the beam (e.g. varying its wavelength, polarization etc. to cause it to be guided along different routes by the guiding elements with different wavelength/polarization responses etc.; e.g. using a tuneable laser). The term “passive light guide” is merely a convenient label, consistent with the fact that, in this case, the guiding elements are not required to be active—however, active or passive guiding elements with different optical sensitivity (e.g. different wavelength and/or polarization sensitivity etc.) could be used in this context (that is, the guiding elements could be both active and have different optical sensitivities).

A digital image (or data encoded as a digital image) may be propagated as a beam along an active or passive light pipe. The guiding elements of the active light pipe can be individually controlled to either transmit or reflect an incident beam of light.

Many such light pipes (active, passive or a combination of both types) can be combined in various geometries to create a switching network that can be used to steer the beams and images to one of many addressable locations, in one or multiple spatial dimensions. The input to a light pipe can be created using a spatial light modulator (SLM) and the output read out on a CCD (charge-coupled device), for example. Phase interference and noise can be corrected using a combination of optical and computation techniques, including machine learning techniques, which would involve the learning of one or more signal processing parameters from training data. Certain embodiments use coherent detection in combination with such techniques to provide more effective waveguide distortion mitigation.

In contrast to optical switches and fibres of the kind traditionally used in optical data communication, the described embodiments use light pipes that are able to transfer an entire image at a time. This exploits the high resolution of optical devices available today such as SLMs and digital cameras. These devices have many millions of

pixels allowing megabytes of data to be encoded and decoded. This allows high bandwidth transmission even with modest switching rates for the SLMs, cameras, and active light pipe elements (in the case of active light pipes) or beam optical characteristics(s) (in the case of passive light pipes). In addition, applications such as holographic storage require interference between multiple beams, at least one of which is modulated with an image. In holographic storage, using active light pipes the beams and images can be efficiently steered, and made to interfere, at any desired location in a holographic storage medium. As noted, similar benefits can be achieved with passive light pipes, where the switching is applied at the emitter stage instead.

The light pipes described below are “multimode” waveguides in the sense of having physical dimensions sufficient to support a range of “modes” (i.e. spatial paths through the waveguide for a given channel, e.g. corresponding to different directions of propagation). This is in contrast to simple single-mode optical waveguides, such as thin optical fibres used in fibre optic system, where the aim is to restrict light entering a fibre to essentially a single propagation mode. Whereas a single-mode optical waveguide can only convey data using amplitude, phase or frequency modulation, a multimode optical waveguide allows more data (e.g. an entire image with potentially millions of pixels) to be conveyed by via angular variation within the waveguide. To put it another way, a multimode waveguide provides greater bandwidths through increased angular and/or spatial diversity, by providing multiple optical paths through the waveguide from emitter to detector for any given channel (the different paths corresponding to different propagation modes).

Another aspect disclosed herein is a holographic data storage system which uses one or more waveguide networks to spatially multiplex over a holographic recording medium (i.e. read and write from/to different sub-volumes of the media) without requiring any relative mechanical movement between the media and the waveguide network(s). An example of such a system is described below, which makes use of active and/or passive light pipes. In the described examples, a multimode waveguide can be used to carry an entire digital image to/from a holographic recording medium simultaneously, or to carry a reference beam at one of multiple possible angles.

Active Light Pipes:

FIGS. 3A-D show a schematic side-view of an example form of active light pipe **300** having a particular physical structure. As will be appreciated, this is merely one example of a suitable physical structure that can provide the desired optical configurability. Further examples are considered below.

The active light pipe **300** is shown to have at least first surface region **300-0** and multiple active switches in the form of switchable Bragg gratings (SBGs), which could be on the surface or volume-embedded. Two such SBGs **300-1**, **300-2** are shown on a first surface **300-S1** of the waveguide **300** in this example, but it will be appreciated that there may be a greater number of SBGs disposed at suitable locations on the surface **300-S1** of the waveguide **300** and/or embedded within the bulk of the waveguide **300**. Each SBG **300-1**, **300-2** can be individually controlled to change its reflective/transmissive properties so as to either transmit or reflect an incident beam. The SBGs **300-1**, **300-2** form respective surface regions of the active light pipe **300**, at which light can enter the waveguide **300** (in-coupling) or exit the waveguide **300** (out-coupling) depending on how the waveguide **300** is used.

The first surface region **300-0** is an end region of the waveguide **300**, from which the first side surface **300-S1** of the waveguide extends along an axis **301** of the waveguide **300**.

FIGS. 3E and 3F each show a cross section view of the waveguide **300**, which can be seen, in this example, to have a rectangular shape in cross section, with four side surfaces **300-S1**, **300-S2**, **300-S3**, **300-S4** extending along the axis **301** of the waveguide **300**. In this example, the SBGs **300-1**, **300-2** are all located along the first of the side surfaces **300-S1**, as depicted in the figures, though in general such SBGs could be attached to multiple surfaces of the waveguide **300** depending on the application.

The SBGs **300-1**, **300-2** are located along the first side surface of waveguide **300-S1** at increasing distances from the first region **300-0**, with a first SBG **300-1** located closest to the first region **300-0**.

FIGS. 3A, 3B and 3E depict a “one-to-many” use case, in which the first surface region **300-0** acts as an in-coupling region and the second surface regions of the SBGs **300-1**, **300-2** act as out-coupling regions. By way of example, FIG. 3 shows a first ray **304** that is coupled into the waveguide **300** via the in-coupling region **300-0**. In this example, the first surface region **300-0** is angled relative to the side surfaces **300-S1**, . . . , **300-S4** such that the first ray **304** can pass through the first surface region **300-0** into the bulk of the waveguide **300** at an angle sufficient to achieve total internal reflection at each of the side surfaces **300-1**, . . . , **300-4** within the waveguide **300**.

Each of the SBGs **300-1**, **300-2** is configurable to change it between a reflective state and a transmissive state. FIG. 3A shows a configuration in which the first SBG **300-1** is in a reflective state, causing the incident ray **300** to be reflected from it, back into the waveguide **300**, and guided along the waveguide **300** until reaching the second SBG **300-2**. The SBG **300-2** is shown in a transmissive state, causing the ray **304** to be diffracted out of the waveguide **300** via the second SBG **300-2**, and thereby coupled out of the waveguide **300** via the surface region of the second SBG **300-2**. This configuration of the SBGs **300-1**, **300-2** creates a “channel” through the waveguide **300** between the first surface region **300-0** and the surface region of the second SBG **300-2**.

In contrast, FIG. 3B shows the first SBG **300-1** in a transmissive state. Hence the first ray **304**, upon reaching the first SBG **300-1**, is instead diffracted out of the waveguide **300** via the first SBG **300-1**, and thereby coupled out of the waveguide **300** via the surface region of the first SBG **300-1** instead. This configuration creates a channel through the waveguide **300** between the first surface region **300-0** and the surface region of the first SBG **300-1**.

In this manner, it is possible to guide a first ray **304** through the waveguide **300** from the first region **300-0** and out of the waveguide **300** at the surface region of any of the SBGs **300-1**, **300-2**. Although described in relation to only two SBGs **300-1**, **300-2** for the sake of simplicity, it will be appreciated that the same principles can be applied with a greater number of SBGs.

FIG. 3E shows how the first ray **304** might propagate when viewed in cross section, via TIR from some or all of the side surfaces **300-S1**, . . . , **300-S4** depending on the angle of the first ray **304**.

It is equally viable to use the depicted active light pipe **300** for many-to-one optical transfer, as depicted in FIGS. 3C, 3D and 3F.

FIG. 3C shows the same configuration of the SBGs as FIG. 3A. The only difference is how the waveguide **300** is used: now a second ray **308** is shown incident on the second

SBG **300-2** from an external source (not shown). With the second SBG in a transmissive state, the second ray **308** is diffracted into the waveguide **300** via the second SBG (now providing in-coupling at its surface region), from which it is guided through the waveguide **300** to the first surface region **300-0** (now an out-coupling region); this includes reflection from the first SBG **300-1** currently in a reflective state. The reflective state of the first SBG **300-1** prevents the ray **308** from exiting the waveguide via the first SBG **300-1**. Moreover, any external ray **309** that might happen to be incident on the first SBG **300-1** will be essentially reflected away from it and thus not enter the waveguide **300**.

FIG. 3D shows the same configuration as FIG. 3B, but now with the second ray **308** incident on the first SBG **300-1** from an external source. With the first SBG **300-1** in a transmissive state, the third ray **310** enters the waveguide **300** thereat by diffraction, and is guided to the first surface region **300-0**.

FIG. 3F shows how the second ray **308** might propagate within the waveguide **300** in cross section, and the same description of FIG. 3E applies but with the ray direction reversed.

The above description assumes perfect reflectivity/transmittivity of the SBGs in the transmissive/reflective states. As will be appreciated, this is not an absolute requirement in practice, and the system will have some tolerance to imperfections in the SBGs **300-1**, **300-2** and the waveguide **300** more generally. Suitable signal processing techniques for compensating for distortion introduced within the waveguide **300** are describe later.

Although depicted as separate elements, the SBGs **300-1**, **300-2** could in fact be separate, independently controllable regions of a single large SBG extending over all or most of the first side surface **300-S1**.

SBGs are merely one possible form of active switching element. For example, with polarized beams, the same effects could be realized using controllable polarization filters, attached to the surface of the waveguide **300** or embedded within the bulk of the waveguide. SBGs and controllable polarization filters are examples of non-mechanical active switches which can change the optical properties of the waveguide **300** via non-mechanical effects. Other examples of guiding elements include controllable mirrors such as micro mirror devices or other microelectromechanical systems (MEMs), the latter being examples of mechanical guiding elements.

When using polarization filters as guiding elements, the SBGs **300-1**, **300-2** could be replaced with passive diffractive elements, with the polarization filters acting to guide beams to or away from the passive diffractive elements as needed in a controllable fashion, without needing to reconfigure the diffractive elements.

Note that even when the guiding elements themselves are mechanical, this still avoids the need for mechanical movement of the waveguide **300** as a whole.

Active Light Pipe Network

Herein, a “waveguide network” can take the form of a single waveguide or multiple intercoupled waveguide networks. Waveguide networks with multiple active light pipes have particular benefits in terms of flexible optical data transfer.

FIGS. 4A and 4B shows alternate side views of (part of) a waveguide network comprising first and second active light pipes **400**, **420**. The second light pipe **420** has a first surface region **420-0** located adjacent and aligned with a corresponding surface region of the first light pipe **400** for receiving a beam from or guiding a beam to the second

waveguide **420** via the first surface region **400-0**. Purely by way of example, a ray **404** is shown propagating through the first waveguide **400** to the corresponding surface region of the first waveguide **400** that lies adjacent the first surface region **420-0** of the second waveguide **420**. The ray **404** is coupled out of the first waveguide **400** via an SBG **400-1** attached to the adjacent surface region of the first waveguide **400**, and into the second waveguide **420** via the first surface region **400-0**. From there, it can be guided to any one of multiple SBGs **420-1**, **420-2** of the second waveguide **420** in a one-to-many fashion. The same arrangement can be used to guide a beam in the other direction, from the second waveguide **420** into the first waveguide **400**, in a many-to-one fashion, with the ray direction reversed.

Whilst this example considers two intercoupled waveguides **400**, **402**, the principles can be applied to a greater number of inter-coupled waveguides to allow flexible data routing through the waveguide network.

More generally, a surface region of a medium may be otherwise optically coupled to a corresponding surface region of a waveguide, for example via an air interface or one or more other optical components (which could themselves be waveguides that may or may not provide active or passive switching functionality).

Holographic Storage

An application of active light pipes to holographic storage will now be described.

FIGS. 1A and 1B show schematic perspective views of a holographic recording medium **102**, which is a volume of relatively thick, photosensitive material capable of persistently storing optical patterns as “holograms” embodied within the holographic recording medium **102** (which may be referred to as simply a medium **102** for conciseness). A hologram is created by exposing a sub-volume **110** (region) of the medium **102** to an optical pattern in a way that causes a persistent state change within that sub-volume **110**. The hologram created with the sub-volume **110** by that state change records the optical pattern to the medium **102** such that the optical pattern can be reproduced therefrom at a later time. The hologram is persistent in that, once created, the medium **102** does not require power to maintain it. The composition and structure of the medium **102** may be such that a hologram cannot be erased once created and therefore provides a form of “write once read many” (WORM) storage, or it may be that holograms can be erased and replaced (but persist unless and until they are erased).

A single hologram can record an optical pattern that encodes a very large number (e.g. millions) of bits, allowing very large volumes of data to be written to/read from the holographic recording medium **102** in parallel (simultaneously). Another benefit of holographic storage is that many holograms can be written to the same sub-volume **110** of the holographic recording medium **102**, which greatly increases the data storage capacity of the holographic recording medium **102** per unit volume.

In more detail, FIG. 1A shows how, in order to write a set of data to the medium **102**, an input beam **104** and a reference beam **106** are directed into the sub-volume **110**, via first and second side surfaces **102-4**, **102-6** of the medium **102** respectively. This creates an optical pattern in the form of an interference pattern caused by interference between the input beam **104** and the reference beam **106**. Provided the beams **104**, **106** have sufficient power and the sub-volume **110** is exposed for a sufficient duration, the interference pattern created by the interfering beams **104**, **106** will be persistently recorded within the sub-volume **110** as a hologram. A set of data is embedded in the input beam

104 and can be recovered from the resulting hologram as described below. In this manner, the encoded set of data is written to the sub-volume **110**. In the examples below, the set of data is encoded as a digital image, which is then embedded in the input beam **104** via spatial modulation.

As shown in FIG. 1B, in order to read the data from the sub-volume **110**, a matching reference beam **116** is directed into the sub-volume **110**, via the second side surface **102-6** of the medium **102**, where it interacts with the hologram to create an output beam **108** that will essentially match the input beam **104** used to write the hologram, to the extent that the embedded data is recoverable from the output beam **110**. The output beam **108** propagates out of the sub-volume **110**, via a third side surface **102-8** of the medium **102**.

The reference beam **116** used to read the data substantially matches the reference beam **106** originally used to write the data, and in particular is directed at an angle (or, more generally, direction) that closely matches that of the original reference beam **106**. This is because the ability to read the hologram (i.e. produce an output beam **108** from which the data can be recovered) is highly sensitive to angular deviation between the reference beams **106**, **116** used to write and read the hologram respectively. It is this sensitivity that can be exploited to record multiple holograms within the same sub-volume **110**—each hologram is created using a different reference beam angle, and two distinct holograms may be created with only a slight difference in reference beam angle. In this manner, a large number (e.g. hundreds or thousands) of holograms can be written to the same sub-volume **110**, each encoding a large number (e.g. millions) of bits.

FIG. 2A shows a schematic perspective view of an example holographic storage system **200** which incorporates certain principles of the present disclosure. In this particular example, three separate waveguides **204**, **206** and **208** are used to carry the input beam **104**, the reference beams **116**, **126** and the output beam **118**, and may be individually referred to as the input waveguide **204**, the reference waveguide **206** and the output waveguide **208**. As noted, the terms “optical waveguide” and “light pipe” are used interchangeably herein. Each of the waveguides **204**, **206** and **208** provides spatial multiplexing in the sense that it can guide a signal to (in the case of the input and reference waveguides **204**, **206**) or from (in the case of output waveguide **208**) any one of multiple sub-volumes within the holographic recording medium **102**. This provides spatial multiplexing across the volume of the holographic recording medium **102** without requiring any mechanical movement of any of the waveguides **204**, **206**, **208** relative to the holographic recording medium **102**. In order to avoid the need for such mechanical movement, guiding elements are located on or within each of the waveguides **204**, **206**, **208** and are configurable to change the optical properties of the waveguides **204**, **206**, **208** so as to guide signals to or from different sub-volumes of the medium **102**. That is, to create different channels within the waveguides **204**, **206**, **208** as needed. In this particular example, the guiding elements take the form of active optical switching elements (switches). There are various forms the switches can take. In this example, the switches take the form of SBGs located in different surface regions of the waveguides **204**, **206**, **208**, in the same general arrangement as FIGS. 3A-E. That is, the waveguides **204**, **206** and **208** each take the form of active light pipes, and each of the waveguides **204**, **206**, **208** has the same general physical structure as the active light pipe **300** of FIGS. 3A-E.

Each waveguide **204**, **206**, **208** is arranged with its first surface (i.e. the surface on which its SBGs are located)

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adjacent a different side surface of the medium **102**, such that its SBGs extend along that side surface of the medium **102**. First and second SBGs of each waveguide **204**, **206**, **208** are denoted by reference numerals **204-1**, **204-2**; **206-1**, **206-2**; and **208-1**, **208-2** respectively, all of which are configurable in the manner described above. Further SBGs are depicted without reference numerals, and the number of SBGs can be chosen to accommodate any size of holographic recording medium **102**. The following description refers to the first and second SBGs of each waveguide **204**, **206**, **208** for conciseness but it will be appreciated that the description applies to a greater number of SBGs.

FIGS. **2B** to **2D** show how the input and reference waveguides **204**, **206** are used to write data to the medium **102** in a one-to-many fashion. FIG. **2B** shows a schematic plan view of the system **200** and FIGS. **2C** and **2D** show alternate side views, in which the input and reference waveguides **204**, **206** are visible respectively. The input waveguide **404** is used to guide the input beam **104** to any one of multiple sub-volumes of the medium **102** via any one of the SBGs **404-1**, **404-2** of the input waveguide **204** in the manner described above. The reference waveguide **406** is configured to guide the reference beam **106** to the same sub-volume simultaneously in order to create the desired interference pattern to be written to that sub-volume. In the depicted examples, both the input and reference waveguides **204**, **206** are currently configured to guide the input and reference beams **104**, **106** to the sub-volume denoted by reference numeral **110**, via the second SBGs **204-2**, **206-2** of each waveguide **204**, **206**.

FIGS. **2E** to **2G** show how the reference and output waveguides **206**, **208** may be used to read data from the medium **102**. FIG. **2E** is a plan view and FIGS. **2F** and **2G** show alternate side views in which the reference and output waveguides **204**, **206** are visible. The reference waveguide **206** is used in exactly the same way as depicted in FIGS. **2B** to **2D**, but now to guide the reference beam **116** to any sub-volume from which a hologram is to be read—the sub-volume **110** in this case. The output waveguide **208** is used in a one-to-many fashion to guide the resulting output beam **108** from the sub-volume **110** and through the through waveguide **208** for subsequent detection.

Each sub-volume **110** could for example have a height and width of a few millimetres as measured along any of the side surfaces, and this would generally be sufficient to store several million pixels per data “page” (e.g. multiplexing angle)—in which case, the sub-volume volume is sufficient to store (millions of pixels)*(#multiplexing angles).

The guiding elements of the input waveguide **204** and reference waveguide **206** (the SBGs in this example) are configured as needed to provide channels for the input beam **104** and reference beams **106**, **116** from a beam source (emission system) to the sub-volume **108** to be read to. With SBGs, this is a case of setting the SBGs to transmissive or reflective states as needed to create the channel. Similarly, the guiding elements of the output waveguide **208** (also SBGs in this example) are similarly set to provide a channel from the sub-volume **108** being read from to a detector. In order to provide additional context, this is described in more detail below with reference to a multi-waveguide network depicted in FIG. **5**. However, the principles described in relation to the specific example FIG. **5** apply more generally to other waveguide network topologies, both simpler networks (e.g. a single waveguide) or more complex waveguide networks.

As set out above, this allows spatial multiplexing over the medium **102**, without any mechanical movement of the

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medium **102** relative to the waveguides **204**, **206**, **208**. This is true whatever form the guiding elements take (the guiding elements themselves could be mechanical or non-mechanical, as noted above).

Holographic Storage Using Multi-Waveguide Networks

FIG. **5** shows an example of a holographic storage system incorporating multi-waveguide networks of the kind shown in FIG. **4**.

An input waveguide network is shown to comprise a first input light pipe **203** (a “parent” waveguide) to which multiple second input light pipes **204A**, **204B** (“child” waveguides) are coupled. An input beam **104** from an emitter system **504** is coupled into the first input waveguide **203** via an in-coupling region thereof, and can be guided from there into any of the second input waveguides **204A**, **204B**.

A reference waveguide network is shown to comprise a first reference waveguide **205** to which multiple second reference waveguides **206A**, **206B** are coupled. A reference beam **106**, **116** from the emitter system **504** is similarly coupled into the first reference waveguide **205**, and can be guided to any of the second reference waveguides **206A**, **206B**.

An output waveguide network is shown to comprise a first output waveguide **207** to which multiple second output waveguides **208A**, **208B** are coupled.

The depicted arrangement allows beams to be directed to/from different sub-volumes of multiple pieces of holographic storage media **102A**, **102B**.

Although FIG. **4** shows an input beam **104**, reference beams **106**, **116** and the output beam **108**, it will be appreciated that a sub-volume would typically be written to and read from at different times, in the manner described above with reference to FIGS. **2A-G**.

A first group of the second waveguides **204A**, **204B**, **204C** (one each of input, reference and output) are located around the first piece of holographic storage media **102A** (first medium), and a second group of the second waveguides **204B**, **206B**, **208B** are located around the second piece **102B** (second medium), each in the same general arrangement as FIGS. **2A-G**. Hence, input and reference beams **104**, **106**, **116** can be directed to any-sub volume of any piece of media **102A**, **102B** by first guiding those beams to the desired second waveguide of the input and reference networks respectively, and then to the desired sub-volume of the piece of media adjacent the desired waveguide.

The output waveguide network can be used to guide an output beam **108** from any sub-volume of any piece of media **102A**, **102B** from the applicable second output waveguide **208A**, **208B** into the first output waveguide **207**, and from there to a detector via an out-coupling region of the first output waveguide **207** a detector **508**. In order to read from a specific sub-volume, the SBGs are configured to provide a channel from that sub-volume to the detector; so, in this case, SBGs **204A-2** and **207A-1** are set to transmissive states and other SBG(s) of the output waveguide network are set to reflective states as needed to provide a channel for the output beam **108** to the detector **508** (e.g. in this case, SBG **207-2** of the first output waveguide **207** is set to reflective to prevent propagation of the output beam **104** into waveguide **207-2**). Other SBGs of the output waveguide network can be set to reflective to the extent needed to prevent transmission of any unwanted light, i.e. “leakage” from other regions of the same piece of media **102A** or from different piece(s) of media **102B** (e.g., in this example, SBG **204A-1** near to the sub-volume being read from is shown set to reflective to prevent unwanted leakage).

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Whilst in the above examples, three separate waveguide networks are used for the input, reference and output beams **104**, **106**, **116**, **108**, this is not necessarily required. For example, the same waveguide network could be used to carry both the input beam **104** and the reference beams **106**, **116** and/or the same waveguide network could be used to carry the input beam **104** and the output beam **108** and/or the same waveguide network could be used to carry the output beam **108** and the input beam **104**. It is generally expected that having three separate networks will provide optimal performance, but there are nevertheless perfectly viable implementations using one or two waveguide networks only.

Although not depicted in any of the figures, a fourth waveguide network could be used to carry beams to the remaining side surfaces of the pieces of media **108A**, **108B**. For example, a fourth network could be used to carry an erase beam to a desired sub-volume, suitable for erasing at least hologram therefrom (in the case of erasable holographic storage).

FIG. 9 shows an alternative physical structure, where a single “slab” of holographic media **102** is used in place of the individual pieces **102A**, **102B** of FIG. 5. An input waveguide network is depicted, and has the essentially the same physical configuration, but with the second input waveguides **204A**, **204B** now configured to guide an input beam **104** to different sub-volumes of the same slab **102**. Whereas in FIG. 5, each second input waveguide **204A**, **204B** provides multiplexing in a single dimension, along the length of a different single piece of media **102A**, **102B**, in FIG. 9, the second waveguides **204A**, **204B** provide spatial multiplexing in two dimensions over the slab of holographic medium **102** (each waveguide individually provides one-dimensional multiplexing, but there is 2D multiplexing over the slab **102** as a whole).

The system of FIG. 9 is limited to a maximum of two waveguide networks (one on each side of the slab **102**). As noted above, this is nonetheless a viable arrangement because it is possible to use the same network to carry multiple beams.

FIG. 9 illustrates another benefit of the use of waveguides. Certain existing holographic storage systems use beams that propagate in free space, with individually placed optical components (reflectors, beam splitters etc.) to guide the beams. Such systems are not readily scalable—in fact, they are only really suitable in a laboratory-type setting. This is because the individual components have to be individually placed and calibrated. By contrast, the use of waveguides allows “self-contained” systems to be manufactured and then deployed much more easily. The system of FIG. 9 is, in some ways, analogous to an “off-the-shelf” solid state storage device—the system not only has no moving parts, but can be built and provided as a complete unit, significantly reducing the time and effort required to deploy it (e.g. in a data center). This greatly improved the scalability of holographic storage, and does so without compromising on bandwidth or storage capacity because the use of multimode waveguides allows whole images to be read/written simultaneously, and allows angular multiplexing over multiple reference beam angles. FIG. 9 is merely one arrangement that illustrates these benefits, and those benefits apply more generally to other waveguide systems within the scope of the present disclosure.

Data Encoding

FIG. 6A shows an example of an emitter system **504** which provides both an input beam **104** and a reference beam **106**. The input beam is an expanded, spatially modu-

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lated laser beam. A laser **600** emits a coherent, narrow laser beam, which is split using a beam splitter **604**.

One part of the beam from the beam splitter **602** is used as the reference beam **106**. In this example, a controllable reference beam steering element **612** is used to steer the reference beam **106** into a reference waveguide **106** at a desired angle. By changing the angle of the reference beam **106** before it is coupled into the reference waveguide **206**, different holograms can be written to/read from the same sub-volume of media in the manner described above.

Alternatively or in addition to beam angle multiplexing, multiple patterns may be stored to and read from the same sub-volume with different phases of the reference beam **106**, **116** (phase multiplexing). Thus, a logical address may correspond to a particular reference beam angle and/or phase characteristic. All description pertaining to the modulation of reference beam angle applies equally to phase modulation.

The other part of the beam from the beam splitter **602** is expanded using a beam expander **604** and the expanded beam passes through a spatial light modulator (SLM) **606**. An encoder **610** receives a set of data to be encoded and encodes it as a digital image that is then modulated into the expanded beam via the SLM **606**. In-coupling optics—in this case, a Fourier lens **608** located such that the plane of the SLM **606** lies substantially in the focal plane of the Fourier lens **608**—is used to separate the expanded beam into distinct modes of propagation; a mode corresponding to a unique direction of propagation in this example, with each mode now corresponding to a particular point in the plane of the SLM **606**. The different propagation modes are coupled into an input waveguide **202**, through which they are guided in the manner described above. With the in-coupling optics **608**, data is “angularly encoded” within the input beam, in the sense that points within the digital image essentially correspond to unique directions of propagation, i.e. unique propagation modes of the input beam **104**. This is analogous to the rays from a distant object taken to be at infinity. The angularly encoded input beam **104** of FIG. 6A is one example of a “multimode” optical signal multiple propagation modes (i.e. components propagating in different directions) and this arrangement provides a form of angular diversity.

Note the term “multimode” does not necessarily imply the use of such in-coupling optics **608**, nor does it require that every image point uniquely corresponds to a given direction of propagation. That is, multimode does not necessarily imply a one-to-one correspondence between propagation modes and image points/data points. For example, FIG. 6B shows an alternative viable emitter system in which the spatially modulated beam is coupled directly into the input waveguide **204**. In this case, there are still multiple modes (i.e. multiple spatial paths through the waveguide for any given channel), but without the one-to-one correspondence between directions of propagation and image points, and possibly without any one-to-one correspondence between image/data points and modes. This provides a form of spatial diversity based on a form of MIMO (multiple input multiple output) transfer, via the multiple pixels of the SLM **606** and the detector array of the spatially coherent detector **508**.

Data Decoding

FIG. 7 shows a spatial coherent detector **508** used for measuring the optical field of the output beam **108**. In contrast to conventional “direct detection”, the spatial coherent detector **508** comprises an array of pixels (or, more generally, detector elements) each of which is configured to measure both an amplitude and a phase of an optical field at

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a location of that pixel (and not simply the intensity). These may be measured e.g. using a local oscillator **712** of the spatial coherent detector **508**. The array of pixels is thus able to measure variations in the phase and amplitude of the optical field in both time and space, and thus provide an analogue or digital representation of the measured optical field. In this case, the measured optical field is an optical field of an output beam **108** guided to the spatial coherent detector **208** via an output waveguide **208**.

Although only a single array is depicted, there could in fact be multiple physical arrays that cooperate as a single “logical array”. For example, this logical array may be split over two physical cameras.

A physical detector array could take the form of a single camera (with each detector element being a pixel or a set of pixels of the camera), or multiple cameras. In the extreme case, each detector element could be a separate camera, and in that case the logical detector array may potentially be split over very many physical detectors.

As noted, a route from a specific in-coupling region at which a beam enters a waveguide network to a specific outcoupling region at which it exits the waveguide network (where those regions could be in the same or different waveguides) may be referred to herein as a “channel”. As noted, in a multimode waveguide network, a single channel will encompass multiple spatial paths. The output beam **108** will have been guided via a specific channel of an output waveguide network, i.e. from a specific in-coupling region thereof to the out-coupling region of the output waveguide **208**. Moreover, it will have been generated from a hologram that was created using an input beam guided from the in-coupling region of an input waveguide network to a specific out-coupling region thereof. The hologram will have been created and read using reference beams similarly guided via specific channels through a reference waveguide network. The input beam **104**, reference beams **106**, **116** and output beam **108** are all susceptible to distortion within the relevant waveguide network that is specific to the channels via which they have been guided. A signal processing component **700** applies analogue and/or digital signal processing to the representation of the measured field in order to compensate for such distortion; it does so using a channel model associated with the sub-volume currently being read from (i.e. from which the output beam **108** was produced). The channel model associated with a particular sub-volume will model not only the channel via which the output beam **108** has been guided to the detector **508**, but also the channels via which the input beam **104** used to write the hologram was guided to that sub-volume, and the channel via which the reference beams **106**, **116** used to write to/read the hologram were guided to that sub-volume.

Each channel model could for example take the form of a transfer function (directly modelling the channel) or an inverse transfer function (modelling the channel in terms of its approximate inverse). Note that the transfer function is applied to the representation of the measured optical field, i.e. both its measured phase and amplitude at different spatial points, and not simply the intensity of the light. Spatial coherent detection provides greater scope for removing or reducing such channel distortion, the aim being to recover the original digital image sufficiently accurately to facilitate decoding of the encoded data from the recovered image by a decoder **704**.

The signal processing **700** could, for example, correct for phase interference and noise using a combination of optical and computation techniques, which may, for example, include machine learning techniques.

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Although described in the context of holographic storage, the use of such signal processing **700** in combination with spatial coherent detection is not limited in this respect, and can be applied in other contexts such as optical communication or optical computation, or any other context in which a received output beam is susceptible to distortion introduced in one or more waveguide networks.

FIG. 7 shows out-coupling optics **715** arranged to essentially reverse the effect of the in-coupling optics **608** of FIG. 6B, i.e. to resolve each propagation mode to essentially a single point within the plane of the spatial coherent detector **508**. Again, this is not essential, and with the alternative emission system of FIG. 6B, the out-coupling optics **715** could be omitted.

Although not depicted in FIG. 6A or 6B, some level of pre-processing may be applied to the digital image before it is modulated into the input beam **104**. This may reduce the level of compensation needed at the detector side. Even with such pre-processing, some amount of detector side processing may be applied, to account different distortion effects between different channels.

Dynamic Scheduling

FIG. 8 shows a controller, in the form of scheduler **800** which can schedule read and write operations within a holographic storage system of the kind described above. To facilitate effective scheduling, sub-volumes within the media **108**, or within each piece of media **108A**, **108B**, are assigned unique addresses. This provides a form of addressable holographic storage, analogous to more conventional forms of addressable electronic storage. However, there are a number of distinctions over conventional addressing.

Firstly, as described above, a single sub-volume can store multiple holograms at different reference beam angles. To accommodate this, each address uniquely corresponds to a specific sub-volume in combination with a specific reference beam direction, i.e. each available tuple is assigned a unique address, where denoted a specific sub-volume within the medium **102** or one of the pieces of media **102A**, **102B** and denotes a particular reference beam direction (e.g. an angle or set of multiple angles defining the beam direction; the term “angle” may be used as shorthand to refer to the direction of the reference beam, though it will be appreciated that the direction may in fact be defined by multiple angles depending on the configuration of the system). Hence, a sub-volume may be associated with a potentially large number of addresses, corresponding to different reference beam angles. The tuple defines a logical storage location where multiple logical storage locations are provided, at the physical level, by the same sub-volume at different reference beam angles. Each logical storage location has a unique address (ADDR). The notation is used as shorthand to mean address corresponding to sub-volume and reference beam angle, though it will be appreciated that this does not imply any particular representation of the address. Any address space and addressing mechanism that uniquely identifies logical storage locations of this nature can be used.

Secondly, in contrast to conventional storage, each logical storage location can store an entire image, and hence a single logical storage location can potentially store a very large number (e.g. thousands or millions) of bits.

The scheduler **800** operates at the logical storage level and schedules income read and write operations pertaining to different addresses within appropriate time intervals.

Reference numerals **804**, **806** and **808** are used to denote input, reference and output optical waveguide networks respectively. As noted above, each be a single-waveguide network or multi-waveguide network (e.g. as in FIG. 5),

with one or more configurable guiding elements (e.g. SBGs or other active switching elements) which can be used to create channels to different sub-volumes of a piece (or pieces) of holographic storage media.

During an interval in which a write operation pertaining to a particular address is scheduled (write interval), the guiding elements within the input and reference waveguide networks **804**, **806** are set to create a channel for the input beam **104** and reference beam **106** from the emitter system **504** through the input and reference networks **804**, **806** respectively to the corresponding sub-volume; additionally, the reference beam steering element **612** is set to direct the reference beam **106** into the reference network **806** in the corresponding direction. This causes the desired interference pattern to be created within sub-volume at reference beam angle, which in turn causes that interference pattern to be persistently stored as a hologram provided the sub-volume is exposed to the interference pattern for a sufficiently long duration.

During an interval in which a read operation pertaining to a particular address is scheduled (read interval), the guiding elements within the reference and output networks **806**, **808** are similarly set to create a channel for the reference beam **116** through the reference network **806** to the sub-volume and to create channel for the output beam **108** through the output network **808** from the sub-volume to the detector **508**; the reference beam steering element **612** is similarly set to direct the reference beam **116** into the reference network **806** in the corresponding direction, in order to read the intended hologram at sub-volume and reference beam angle. Alternative Waveguide Network:

FIGS. **10A** and **10B** shows alternative systems, in which spatial multiplexing is instead achieved by modulating one or more optical characteristics of the input and reference beams **104**, **106**, **116**. In such a system, passive (non-switchable) guiding elements may be used in place of the active (switchable) guiding elements of the earlier figures.

The example of FIG. **10A** considers frequency (or, equivalently, wavelength) modulation. In this case, the light pipe(s) itself (themselves) could be passive, with static wavelength-dependent outcoupling (such as successively longer-pass dichroic interference filters, or varying centre wavelength bandpass filters).

FIG. **11A** shows a light pipe **1100** having an outer surface **1100-S**, along which multiple passive filters **1100-1**, **1100-2** lie. The configuration of the light pipe **1100** is the same as that of FIGS. **3A-D**, aside from the fact that the filters **1100-1**, **1100-2** replace the SBGs **300-1**, **300-2**. The filters **1100-1**, **1100-2** have different frequency responses (i.e. they act as frequency filters). More specifically, each filter **1100-1**, **1100-2** is essentially transmissive to a relatively narrow range of optical frequencies, and essentially reflective to frequencies outside of that range. FIG. **11A** shows an in-coupled beam **1104** with a frequency within the range of the second filter **1100-2**, but outside the range of the first filter **1100-1**. Hence, the beam **1104** is reflected from the former, but transmitted through the latter (thus exiting the light pipe **1100** at that location). FIG. **11B** shows a beam **1104'** of different frequency, now within the range of the first filter **1100-1**, which is thus transmitted through the first filter **1100-1**.

Such a light pipe **1100** can be used in place of the active light pipes described above, and the above description applies equally with the following modification to the system.

FIG. **10A** shows the scheduler **800** communicatively coupled to the laser **600** of the emitter system for varying the

frequency (or, equivalently, wavelength) of the input and reference beams **104**, **106**, **116**. In this case, either beam can be directed to a desired holographic storage region by setting the frequency accordingly. Different beam frequencies now correspond to different routes through the waveguide networks (defined by the different frequency characteristics of the passive filters), and the frequency can be set to correspond to any desired route.

In this case, wavelength is used as the switching dimension. The laser **600** is a fast tuneable laser that functions as an active element.

In such a realisation, switching could be in one spatial dimension only (i.e. along a single pipe). However, with a laser with sufficient range and line narrowness, a first light pipe could filter coarsely (i.e. over relatively wider wavelength ranges) and subsequent light pipes sample more finely (i.e. over narrower wavelength ranges). Another factor that restricts line width is the desire for a relatively long coherence length, so the line may be sufficiently narrow in any event. To achieve replication of the input field to addressable locations across a 2D output space in a holographic storage context, this implementation could, for example, be combined with a second implementation using a different switchable parameter (e.g. polarisation).

In the context of a read operation, the frequency of the output beam **108** will match that of the reference beam **116** used to read a particular sub-volume, and can be guided back to the detector using suitable filters in the output waveguide network **808**, applying the same principles.

FIG. **10B** shows an example of such an implementation with a controllable polarization element **601**, which can be used to vary the polarization of the input and reference beams **104**, **106**, **116**. This could be combined with passive polarization filters on or within the light pipes. This could be implemented as an alternative or in addition to the passive frequency filters in the example of FIG. **10A**. Such polarization modulation would provide two independent routes, and can be usefully combined e.g. with passive wavelength filtering and/or active light pipe(s). Polarization modulation of the beam could also be combined with active polarization filter(s).

Note, all of the various “passive” and “active” implementations described above can be implemented separately or in combination, e.g. a combination of active and passive guiding elements could be used. That is, a waveguide could have both passive and active elements and/or active and passive waveguides could be combined in the same network.

Additional Hierarchical Levels:

The above examples consider waveguide networks with two hierarchical “levels” of parent and child waveguides. However, a multi-waveguide network could have three levels (parent, child, grandchild) or more. Note the terms “child”, “parent” and “grandparent” do not necessarily imply direct hierarchical relationships, i.e. the term child or grandchild could refer to any waveguide at any hierarchical level below a parent or child waveguide respectively; that is, a child/grandchild waveguide could be optically coupled to a parent/child waveguide not only via e.g. an air interface (direct descendant) but also via one or more other child/grandchild waveguides thereof (indirect descendant).

FIG. **12** shows an example of a waveguide network with three hierarchical levels. A parent waveguide **1200** has two direct child waveguide networks **1202A**, **1202B** optically coupled thereto in the above manner, and each of those child waveguides **1202A/1202B** has two grandchild networks **1204A-A**, **1204A-B/1204B-A**, **1204B-B** optically coupled thereto in same way.

An extreme example would be a “binary tree” architecture, where every waveguide has exactly two direct children, with a potentially more than three levels of waveguide. However, in practice, there may also be circumstances where it is preferable to increase the number of direct children to reduce the required number of hierarchical levels.

The scheduler **800** shown in FIGS. **8**, **10A** and **10B** is a functional component of the system. Similarly, the encoder **610**, decoder **704** and signal processing component **700** are functional components. Such components can be implemented in software (i.e. as program code executed on one or more programmable hardware processors, such as CPUs, accelerators, e.g. GPUs etc.), or using other forms of processor hardware such as Field Programmable Gate Array(s) and/or Application Specific Integrated Circuit(s). The signal processing performed by the signal processing component **700** can be analogue or digital signal processing, or any combination thereof. Such program code and other data (e.g. the channel models **702**) may be encoded in computer readable storage. Examples of computer readable storage include optical, magnetic and/or solid-state storage, in which code, data and the like may be stored in non-transitory form. This contrasts with a transitory media such as a transient signal carrier.

A first aspect herein provides a holographic data storage system comprising: an emitter system; an input waveguide network, formed of one or more multimode optical waveguides, the input waveguide network having an in-coupling region for receiving an input beam from the emitter system and multiple out-coupling regions; at least one holographic recording medium having multiple recording regions, each optically coupled a corresponding one of the multiple out-coupling regions of the input waveguide network, the holographic data storage system arranged to persistently write data of an input beam, received at any one of the out-coupling regions, to the corresponding recording region; and a controller coupled to at least one of the emitter system and at least one controllable guiding element of the input waveguide network, the controller configured to control at least one optical characteristic of the input beam or the at least one guiding element, so as to guide the input beam from the in-coupling region to any selected one of the multiple out-coupling regions, wherein different ones of the multiple recording regions may be written to from the same in-coupling region by changing said at least one optical characteristic or controlling said at least one guiding element to guide the input beam to different ones of the multiple out-coupling regions, whilst the multiple out-coupling regions of the multimode optical waveguide network remain at fixed locations relative to the corresponding recording regions of the holographic recording medium.

In embodiments, the emitter system may be configured to provide a reference beam and the holographic data storage system may be configurable to guide the reference beam to any one of the recording regions, and the controller may be configured, in a write interval, to cause the reference beam and the input beam to be guided to the same recording region for storing the data of the input beam as a pattern caused by interference between the input beam and the reference beam.

For example, the holographic data storage system may comprise a reference waveguide network, formed of one or more further multimode optical waveguides, the reference waveguide network having an in-coupling region for receiving the reference beam from the emitter system and multiple out-coupling regions, each of the multiple recording regions of the holographic recording medium also being optically

coupled to a corresponding one of the multiple out-coupling regions of the reference waveguide network, and the controller may be configured to control at least one optical characteristic of the reference beam or at least one controllable guiding element of the reference waveguide network, so as to cause the reference beam to be guided from the in-coupling region of the reference waveguide network to any selected one of the multiple out-coupling regions of the reference waveguide network, the controller configured, in said write interval, to cause the reference beam to be guided to the out-coupling region optically coupled to said same recording region.

Alternatively, the input waveguide network may be arranged to receive both the input beam and the reference beam, and the controller may be configured, in said write interval, to control: the at least one optical characteristic of the input beam and at least one optical characteristic of the reference beam, or the guiding element to guide both of those beams to the same recording region.

The controller may be coupled to the emitter system for controlling a phase characteristic of and/or an angle at which the reference beam is coupled into the input waveguide network or the reference waveguide network for causing multiple patterns to be stored in a single one of the recording regions, created with different phase characteristics and/or at different angles of the reference beam.

The holographic data storage system may comprise at least one detector array, and the controller may be configured, in a read interval, to cause the reference beam to be guided from the emitter system to one of the recording regions to be read, thereby causing an output beam, created by the reference beam interacting with a pattern stored thereat, to be received at the detector array for recovering data of the stored pattern from the output beam.

The input waveguide network or the reference waveguide network may be arranged to receive the output beam and the controller may be configured to control the optical characteristic of the reference beam or the at least one guiding element of the input waveguide network or the reference waveguide network in order to cause the output beam to be guided to the detector array, whereby the same detector array may be used to read from different ones of the recording regions.

Alternatively, the holographic data storage system may comprise an output waveguide network, formed of one or more further multimode waveguides, the output waveguide network having multiple in-coupling regions, each of the multiple recording regions of the holographic recording medium also being optically coupled to a corresponding one of the multiple in-coupling regions of the output waveguide network for receiving an output beam therefrom, and an out-coupling region for providing an output beam to the detector array. The controller may be coupled to at least one of: the emitter system for controlling the at least one optical characteristic of the reference beam, and thus at least one corresponding optical characteristic of the output beam, and at least one controllable guiding element of the output waveguide network, and the controller may be configured, in said read interval, to control the at least one optical characteristic of the reference beam or the at least one guiding element of the output waveguide network to cause the output beam to be guided to the detector array, wherein different ones of the recording regions may be read from using the same detector array, whilst the in-coupling regions of the output waveguide network remain at fixed locations relative to the recording regions of the holographic recording medium.

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A multimode waveguide of the input waveguide network may have a side surface extending along an axis of that waveguide, that side-surface being aligned with a first side surface of the holographic recording medium, with the out-coupling regions of the input waveguide network at different locations on that side surface of that waveguide.

Multiple second multimode optical waveguides of the input waveguide network may be optically coupled to a first multimode optical waveguide of the input waveguide network at different locations along a side surface of the first waveguide, said multimode optical waveguide of the input waveguide network being one of the second waveguides, wherein each of the other second waveguide(s) may also have a plurality of out-coupling regions optically coupled to: respective further recording regions of the holographic recording medium, or respective recording regions of at least one further holographic recording medium, and the controller may be configured to control the at least one optical characteristic of the input beam or the at least one guiding element of the input waveguide network to cause the input beam to be guided from the in-coupling region, via the first waveguide into to any one of the second waveguides, and to any one of the out-coupling regions of that second waveguide.

A multimode optical waveguide of the reference waveguide network may have a side surface extending along an axis of that waveguide, that side-surface being aligned with a second side surface of the holographic recording medium, with the out-coupling regions of the reference waveguide network at different locations on that side surface of that waveguide.

Multiple second multimode optical waveguides of the reference waveguide network may be optically coupled to a first multimode optical waveguide of the reference waveguide network at different locations along a side surface of that first waveguide, said multimode optical waveguide of the reference waveguide network being one of the second waveguides of the reference waveguide network, wherein each of the other second waveguide(s) of the reference waveguide network may also have a plurality of out-coupling regions optically coupled to: the respective further recording regions of the holographic recording medium, or the respective recording regions of at least one further holographic recording medium,

and the controller may be configured to control the at least one optical characteristic of the reference beam or the at least one guiding element of the reference waveguide network to cause the reference beam to be guided from the in-coupling region, via the first waveguide of the reference waveguide network into to any one of the second waveguides of the reference waveguide network, and to any one of the out-coupling regions of that second waveguide.

A second aspect herein provides a holographic data storage or retrieval system comprising: an emitter system; at least one detector array; at least one holographic recording medium; a reference waveguide network, formed of one or more multimode optical waveguides, the reference waveguide network having an in-coupling region for receiving a reference beam from the emitter system and multiple out-coupling regions respectively optically coupled to corresponding recording regions of the at least one holographic recording medium; a controller coupled to at least one of the emitter system and at least one controllable guiding element of the reference network, the controller configured to control at least one optical characteristic of the reference beam or the at least one guiding element to guide the reference beam

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to any selected one of the recording regions to be read, thereby creating an output beam, via the reference beam interacting with a pattern stored thereat, for receiving at the detector array for recovering data of the stored pattern from the output beam, wherein different ones of the multiple recording regions may be read from using the same emitter system, by changing said at least one optical characteristic of the reference beam or controlling said at least one guiding element of the reference network, whilst the multiple out-coupling regions of the multimode optical waveguide network remain at fixed locations relative to the corresponding recording regions of the holographic recording medium.

In embodiments, the holographic data retrieval system may comprise an output waveguide network, in the form of one or more further multimode optical waveguides, the output waveguide network having an out-coupling region, and multiple in-coupling regions respectively optically coupled with the recording regions of the at least one holographic recording medium, wherein the controller may be coupled to at least one of the emitter system and at least one controllable guiding element of the output waveguide network, and is configured to control: the at least one guiding element of the output waveguide network, and the at least one optical characteristic of the reference beam, and thus a corresponding optical characteristic of the output beam, in order to guide the output beam from the selected recording region, via the in-coupling region optically coupled to the out-coupling region of the output waveguide network for receiving at the detector array, wherein different ones of the recording regions may be read from using the same detector array, whilst the in-coupling regions of the output waveguide network remain at fixed locations relative to the recording regions of the holographic recording medium.

A multimode waveguide of the output waveguide network may have a side surface extending along an axis of that waveguide, that side-surface being aligned with a side surface (e.g. third side surface) of the holographic recording medium, with the in-coupling regions of the output waveguide network at different locations on that side surface of that waveguide.

Multiple second multimode optical waveguides of the output waveguide network may be optically coupled to a first multimode optical waveguide of the output waveguide network at different locations along a side surface of the first waveguide, said multimode optical waveguide of the output waveguide network being one of the second waveguides, wherein each of the other second waveguide(s) may also have a plurality of in-coupling regions optically coupled to: respective further recording regions of the holographic recording medium, or respective recording regions of at least one further holographic recording medium, and the controller may be configured to control the at least one optical characteristic of the reference beam or the at least one guiding element of the output waveguide network to cause the output beam to be guided from the in-coupling region optically coupled to the recording region being read, through that second waveguide into the first waveguide, and to the out-coupling region of the output waveguide network for receiving at the detector array.

A third aspect herein provides a holographic data retrieval system comprising: at least one detector array; at least one holographic recording medium; an output waveguide network, formed of one or more multimode optical waveguides, the output waveguide network having an out-coupling region for providing an output beam to the detector array, and multiple in-coupling regions respectively optically

coupled to corresponding recording regions of the at least one holographic recording medium; and a controller configured to cause an output beam to be guided through the output waveguide network from any selected one of the recording regions, via the in-coupling region optically coupled thereto, to said out-coupling region for receiving at the detector array, by controlling at least one controllable guiding element of the output waveguide network or at least one optical characteristic of a reference beam used to create the output beam, wherein different ones of the multiple recording regions may be read from using the same detector array, by changing said at least one optical characteristic or controlling said at least one guiding element, whilst the multiple out-coupling regions of the output waveguide network remain at fixed locations relative to the corresponding recording regions of the holographic recording medium.

In embodiments, a multimode waveguide of the output waveguide network may have a side surface extending along an axis of that waveguide, that side-surface being aligned with a side surface (e.g. third side surface) of the holographic recording medium, with the in-coupling regions of the output waveguide network at different locations on that side surface of that waveguide.

Multiple second multimode optical waveguides of the output waveguide network may be optically coupled to a first multimode optical waveguide of the output waveguide network at different locations along a side surface of the first waveguide, said multimode optical waveguide of the output waveguide network being one of the second waveguides, wherein each of the other second waveguide(s) may also have a plurality of in-coupling regions optically coupled to: respective further recording regions of the holographic recording medium, or respective recording regions of at least one further holographic recording medium the controller configured to control the at least one optical characteristic of the reference beam or the at least one guiding element of the output waveguide network to cause the output beam to be guided from the in-coupling region optically coupled to the recording region being read, through that second waveguide into the first waveguide, and to the out-coupling region of the output waveguide network for receiving at the detector array.

In certain embodiments of the above, waveguide network(s) as set out below may be used.

A multimode optical waveguide network may comprise: a parent waveguide; and a plurality of child waveguides; wherein each of the parent and child waveguides is a multimode optical waveguide having a first surface region, multiple second surface regions, and at least one guiding element attached to a surface of the waveguide or embedded within the waveguide, each of the second surface regions of the parent waveguide being optically coupled to the first surface region of a corresponding one of the child waveguides; and wherein the at least one guiding element of the parent waveguide is arranged to guide a beam, from or to its first surface region, to or from any selected second surface region of its multiple second surface regions, the beam being coupled into or received from the corresponding child waveguide whose first surface region is optically coupled to that second surface region of the parent waveguide, via that second surface region of the parent waveguide and that first surface region of the corresponding child waveguide, the at least one guiding element of each child waveguide arranged to guide a beam, from or to its first surface region, to or from any selected second surface region of its multiple second surface regions, wherein the at least one guiding element of each of the waveguides is configurable for selecting the

second surface region of that waveguide and/or responsive to at least one beam characteristic for selecting the second surface region of that waveguide via modulation of the at least one beam characteristic.

The multimode optical waveguide network may comprise a plurality of grandchild waveguides, each of which is a multimode optical waveguide having a first surface region, multiple second surface regions, and at least one guiding element attached to a surface of the grandchild waveguide or embedded within the grandchild waveguide, each of the second surface regions of each of the child waveguides being optically coupled to the first surface region of a corresponding one of the grandchild waveguides; wherein the at least one guiding element of each grandchild waveguide may be arranged to guide a beam, from or to its first surface region, to or from any selected second surface region of its multiple second surface regions, the beam being coupled into or out of that grandchild waveguide via its first surface region and the second surface region of the child waveguide optically coupled thereto, the at least one guiding element of each of the grandchild waveguides being configurable for selecting the second surface region of that grandchild waveguide and/or responsive to at least one beam characteristic for selecting the second surface region of that grandchild waveguide via modulation of the at least one beam characteristic.

Each of the waveguides may have at least one active guiding element configurable for selecting the second surface region of that waveguide.

Each of the waveguides may have at least one guiding element responsive to at least one beam characteristic for selecting the second surface region of that waveguide via modulation of the at least one beam characteristic.

At least one of the waveguides may have at least one active guiding element configurable for selecting the second surface region of that waveguide, and at least another of the waveguides may have at least one guiding element responsive to at least one beam characteristic for selecting the second surface region of that other waveguide via modulation of the at least one beam characteristic.

One of the parent waveguide and one of the child waveguides may have at least one wavelength-responsive guiding element, such that a beam within a first wavelength range is guided, from or to its first surface region, into or from a first of the child or grandchild waveguides, and a beam within a second wavelength range is guided, from or to its first surface region, to or from a second of the child or grandchild waveguides; wherein the first child or grandchild waveguide may have at least one wavelength-responsive guiding element, such that a beam within a first sub-range of the first wavelength range is guided, from or to its first surface region, to or from one of its second surface regions, and a beam within a second sub-range of the first wavelength range is guided, from or to its first surface region, to or from another of its second surface regions; and wherein the second child or grandchild waveguide may have at least one wavelength-responsive guiding element, such that a beam within a first sub-range of the second wavelength range is guided, from or to its first surface region, to or from one of its second surface regions, and a beam within a second sub-range of the second wavelength range is guided, from or to its first surface region, to or from another of its second surface regions.

The or each active guiding element may have at least one of: a configurable transmissivity or reflectivity, or a configurable refractive index.

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The or each active guiding element may be a switchable grating or grating region.

At least one of the guiding elements may be a wavelength and/or polarization filter having a fixed or configurable wavelength response and/or a fixed or configurable axis of polarization.

At least one of the waveguides may have two or more guiding elements and three or more second surface regions, any of which may be selected by configuring one or both of the two or more guiding elements and/or modulating at least one beam characteristic.

An optical system incorporating such a waveguide network(s) may comprise: a first optical system component; a plurality of second optical system components; at least one multimode optical waveguide network in accordance with any of the above aspects or embodiments, the multimode optical waveguide network arranged to guide a beam, from or to the first optical system component, to or from any selected second optical system component of the plurality of second optical system components; and a controller configured to select a second optical system component of the plurality of second optical system components, and cause a beam to be guided, from or to the first optical system component, to or from the selected second optical system component, by configuring at least one of the guiding elements of the multimode optical waveguide network and/or modulating at least one beam characteristic.

The first system component may comprise: an emitter system from which a beam is emitted and guided to the selected second system component, or a detector array to which a beam is guided from the selected second system component.

The optical system may comprise one or more holographic recording media, wherein at least some of the second system optical components may be respective sub-volumes of the one or more holographic recording media.

The optical system may comprise a second multimode optical waveguide network in accordance with any of the above aspect or embodiments, and the controller may be configured to cause a second beam to be guided, from or to the first optical system component, to or from the same selected second optical system component, by configuring at least one of the guiding elements of the second multimode optical waveguide network and/or modulating at least one beam characteristic.

The optical system may comprise a third multimode optical waveguide network in accordance with any of the above aspects or embodiments, and the controller may be configured to cause a third beam to be guided, from or to the first optical system component, to or from the same selected second optical system component, by configuring at least one of the guiding elements of the third multimode optical waveguide network and/or modulating at least one beam characteristic.

It will be appreciated that the above embodiments have been described by way of example only. Other variants or use cases of the disclosed techniques may become apparent to the person skilled in the art once given the disclosure herein. The scope of the disclosure is not limited by the described embodiments but only by the accompanying claims.

The invention claimed is:

1. An optical system comprising:
 - a first optical system component;
 - a plurality of second optical system components;
 - a multimode optical waveguide network; and

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a controller configured to:

select a second optical system component of the plurality of second optical system components, and cause a beam to be guided, from or to the first optical system component or to or from the selected second optical system component by controlling a phase characteristic or an angle at which the beam is coupled into the multimode optical waveguide network for causing multiple patterns to be stored in a single recording region.

2. The optical system of claim 1, wherein causing the beam to be guided, from or to the first optical system component or to or from the selected second optical system component comprises configuring a guiding element to cause the beam to be guided from an in-coupling region of the multimode optical waveguide network to any selected one of multiple out-coupling regions of the multimode optical waveguide network.

3. The optical system of claim 1, wherein causing the beam to be guided, from or to the first optical system component or to or from the selected second optical system component further comprises configuring a guiding element of the multimode optical waveguide network.

4. The optical system of claim 3, wherein configuring the guiding element comprises changing the guiding element from a transmissive state to a reflective state.

5. The optical system of claim 1, wherein the first optical system component comprises the guiding element and the selected second optical system component comprises a second guiding element.

6. The optical system of claim 3, wherein the guiding element changes an optical property of the first optical system component.

7. The optical system of claim 1, wherein the first optical system component comprises a first plurality of guiding elements and the selected second optical system component comprises a second plurality of guiding elements.

8. The optical system of claim 1, wherein the multimode optical waveguide network is arranged to guide a beam, from or to the first optical system component and to or from any selected second optical system component of the plurality of second optical system components.

9. An apparatus comprising:

a processor; and

a memory comprising computer-executable instructions that, when executed by the processor, cause the processor to perform the following operations:

select a first optical system component of a plurality of optical system components, and

cause a beam to be guided, from or to a second optical system component or to or from the selected first optical system component by controlling a phase characteristic or an angle at which the beam is coupled into the multimode optical waveguide network for causing multiple patterns to be stored in a single recording region.

10. The apparatus of claim 9, wherein the second optical system component comprises an emitter system configured to emit the beam, in a form of a multimode optical signal that encodes multiple image pixels as multiple propagation modes of the beam propagating in different directions.

11. The apparatus of claim 9, wherein wherein the multiple patterns to be stored in the single recording region are created with different phase characteristics, different angles, or both, of the beam.

12. The apparatus of claim 9, wherein causing the beam to be guided, from or to the second optical system component or to or from the selected first optical system compo-

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nent comprises configuring a guiding element of the multimode optical waveguide network.

13. The apparatus of claim 12, wherein configuring the guiding element comprises configuring the guiding element to cause the beam to be guided from an in-coupling region of the multimode optical waveguide network to any selected one of multiple out-coupling regions of the multimode optical waveguide network.

14. The apparatus of claim 12, wherein configuring the guiding element comprises changing the guiding element from a reflective state to a transmissive state or from the transmissive state to the reflective state.

15. The apparatus of claim 9, wherein the second optical system component comprises a guiding element, and wherein the guiding element changes an optical property of the first optical system component.

16. An optical system comprising:

a first optical system component comprising a guiding element;

a second optical system component;

a multimode optical waveguide network; and

a controller configured to cause a beam to be guided from the first optical system component to the second optical

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system component by controlling a phase characteristic or an angle at which the beam is coupled into the multimode optical waveguide network for causing multiple patterns to be stored in a single recording region.

17. The optical system of claim 16, further comprising an emitter system configured to emit the beam in a form of a multimode optical signal.

18. The optical system of claim 17, wherein the multimode optical signal encodes multiple image pixels as multiple propagation modes of the beam propagating in different directions.

19. The optical system of claim 16, wherein the multimode optical waveguide network is arranged to guide a beam to the second optical system component.

20. The optical system of claim 16, wherein causing the beam to be guided, from or to the first optical system component or to or from the selected second optical system component comprises configuring the guiding element to cause the beam to be guided from an in-coupling region of the multimode optical waveguide network to any selected one of multiple out-coupling regions of the multimode optical waveguide network.

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