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(54) Title: THREE-DIMENSIONAL OPTICAL DATA CARRIER AND METHOD OF CORRECTION OF TRACKING ERRORS

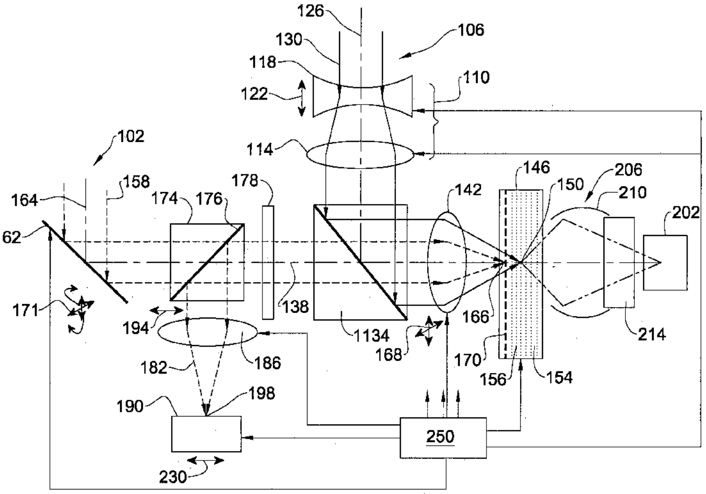

FIG. 11

(57) Abstract: A method and system are presented for use in at least reading data in a three-dimensional optical data carrier having at least one reference layer and at least one data layer. A recording/reading beam and a reference beam are focused onto the optical carrier through a common optical element creating two focal spots in different optical planes. Movement of at least said optical element is controlled such that the focal spot of said reading/recording beam tracks a data track in an addressed data layer, said controlling comprising identifying a change in an error signal from the reference layer during the reference beam tracking the reference layer, thereby adjusting a tracking target for control of the movement of the reference beam.

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THREE-DIMENSIONAL OPTICAL DATA CARRIER AND METHOD OF CORRECTION OF TRACKING ERRORS

FIELD OF THE INVENTION

The present invention is generally in the field of optical data storage and relates to a three-dimensional optical data carrier and a method of correction of tracking errors in an optical storage system.

BACKGROUND OF THE INVENTION

Some optical disks have, in addition to information marks written on them, so-called servo or formatting marks. Servo marks are embossed or optically recorded marks or symbols having a certain pattern that indicates the coordinates of the optical pick-up head relative to a nominal track. Knowledge of the coordinates allows synchronized or guided information recording, reading and erasing. Conventional optical storage carriers typically comprise one or a few partially reflective data layers in which data and servo marks are recorded in a certain order. Diffraction limited spots track the data layer directly and record or retrieve data therefrom. Tracking methods include imaging the spot or a split beam on a position sensitive detector (PSD) and 2D sampled servo.

In recent years, for the purpose of further increasing recording density, recording media have been proposed that include recording in multiple virtual recording layers. Such carriers represent an optically monolithic disk-like plate of a photochromic material (active plate), or a number of plates adhered to each other, in the depth of which the data in the form of a three-dimensional pattern of spaced-apart data marks is recorded. Typically, the marks are organized to form nominally, almost planar, patterns. Data is recorded in the form of marks on circular or spiral tracks, the radial distance between which is about 0.8 microns and the spacing between the virtual layers may be 2 to 10 microns. In addition to data layers, such carriers include at least one servo or reference layer that indicates the location of the reading/recording beam. Data recording in such a multi-layer optical recording medium requires precise control of size and location of the recording/reading spot in the thickness direction of the medium, or in the axial optical pick-up unit (OPU) direction (i.e. in the direction of the optical axis of the OPU).

In optical storage media such as optical disks in general and three-dimensional disks in particular, data is stored in form of a pattern of marks (voxels in three-dimensional disks) and spaces along tracks formed in the bulk of the optical disk. The tracks generally comprise spiral tracks located on and in the vicinity of a nominal position on which the data is to be written and from which the data is to be read. A focused laser beam illuminates these voxels, while the disk is rotated around its axis. Interaction of laser light with disk material results in material change or recording. Interaction of laser light with already recorded disk material produces a luminescent response or a non-linear response that may be detected and the data may be interpreted. It should be noted that the thickness of a monolithic photochromic material disk-like plate may be between 300 and 1200 microns, far exceeding the depth of field of the existing OPUs, therefore the distance between the reference layer and the data layer may be 300 to 1200 microns.

US patent No. 6,738,322 to Amble et al discloses an optical data storage system that comprises an optical medium including a servo plane (i.e. servo layer) and at least one data plane. A first laser is positioned to generate a servo laser beam and address the servo plane with a first servo focal spot. A second laser is positioned to generate a read-write laser beam and address the data plane with a second read-write focal spot. A first servo system is associated with the first laser and is configured to provide focus and tracking error correction according to servo information associated with the servo plane. A second servo system is associated with the second laser and is configured to provide focus and tracking error correction according to servo information associated with the data plane. In addition to a reference layer, the ‘322 patent discloses that a certain servo pattern is embedded into the data layers. This reduces the capacity of the carrier and increases recording complexity. Three-dimensional carriers contain multiple recording layers, the number of which may be few hundred of layers. Recording of servo marks in each of these layers would place a burden on either factory pre-formatting or on formatting in the drive speed.

The recording and reading of data in a three dimensional monolithic carrier is further complicated by disturbances that occur during recording such as run-out, mechanical vibrations and distortions, absence of match between disk recording and reading state, and disk aging. Because of these phenomena, the marks might be recorded at offset above and below and to the left and right of the intended nominal location of a track. US Patent 6,865,142 and International publications WO/2007/069243 and WO/2007/083308, all assigned to the assignee of the present invention, disclose methods of tracking a reading spot moving along a track recorded in the depth of the carrier by making simultaneous oscillatory spot movements in two directions orthogonal to the track. The spot movement supports the reading of marks located on and in the vicinity of a nominal track location.

In order to read data correctly, the coordinates of the focused recording or reading laser beam have to be known precisely. To enable this, disks in addition to reading and recording beams, have a reference or servo layer, which, when scanned by a focused laser beam, allows the focused beam spot to coordinate determination. The location of the reference spot is typically coordinated with the location of the recording or reading beam. Knowledge of the coordinates of the reference beam allows determination of the coordinates of the data-reading beam.

Three-dimensional disks are relatively thick disks (0.3 mm to 6.0 mm thick) and data is recorded about the nominal position of a data track, which means that voxels may be below, above, to the right or left of the track. In addition, mechanical errors such as axial and radial disk run-out, and mechanical vibrations complicate the coordination of the reference and data reading beams locations.

GENERAL DESCRIPTION

There is a need to provide a method and an apparatus adapted for simultaneous scanning reference layer(s) and data layer(s) in a three-dimensional optical carrier using a single OPU. There is also a need in a method for data tracking enabling a reliable coordination of the reference and reading spots.

Moreover, there is a need to correct the different mechanical disturbances that take place during the reading and recording processes.

It should be noted that a three-dimensional optical carrier refers to a medium configured for recording and reading data in the form of a three-dimensional pattern of spaced-apart recorded regions located in multiple planes.

According to one aspect of the invention, there is provided a method for use in at least reading data in a three-dimensional optical data carrier having at least one reference layer and at least one data layer. The method comprises:

a) focusing a recording/reading beam and a reference beam onto said optical carrier through a common optical element creating two focal spots in different optical planes; and,

b) controlling the movement of at least said optical element such that the focal spot of said reading/recording beam tracks a data track in an addressed data layer, said controlling comprising identifying a change in an error signal from the reference layer during the reference beam tracking the reference layer, thereby adjusting a tracking target for control of the movement of the reference beam.

In some embodiments of the invention, the error signal from the reference layer has a spatial frequency bandwidth larger than that of an error signal from the data layer. This enables identification of the change in the error signal from the reference layer.

The method of the invention also provides for at least partially correcting for an error of the reference beam focal position.

In some embodiments, the controlling of the movement of at least said optical element comprises keeping axes of the common optical element and the recording/reading and the reference beams to be coaxial.

Preferably, the recording/reading focal spot and the reference focal spot are coordinated in a predetermined relation. The controlling of the movement of at least said optical element comprises utilizing location of the reference focal spot in the reference layer to locate the recording/reading beam focal spot in a target location in the optical data carrier.

Generally, the controlling of the movement of said optical element can be achieved by at least one of the followings: (a) axes of the reading/recording beam and the reference beam can be kept parallel to the optical axis of the optical element; and (b) the reference beam can be deflected or offset in a radial or tangential direction.

According to another broad aspect of the invention, there is provided a method for use in at least reading data in a three-dimensional optical data carrier having at least one reference layer and at least one data layer. The method comprises:

a) focusing a recording/reading beam and a reference beam onto said optical data carrier through a common optical element creating a recording/reading focal spot and a reference focal spot in different optical planes; and;

b) controlling position of said reference focal spot and reading/recording focal spot by manipulation of an optical path common to both recording/reading and reference beams and by at least one additional manipulation of optical path of one of said beams.

The manipulation of the optical path common to both beams may be carried out by actuating an objective lens system to locate the reference focal spot, tracking a reference track in the tangential direction. The additional manipulation of one of the optical paths may be carried out by actuating a mirror in said one of the optical paths to locate said reference focal spot on the reference track in the radial direction. In these embodiments, the movement of said reference beam and reading/recording beam can be controlled by coupling said objective lens system to a mirror and actuating said objective lens system and said mirror together.

In some embodiments of the invention, the movement of at least one common optical element can be controlled by estimating an anticipated required movement of said common optical element.

The invention in its yet another aspect provides a method for use in at least reading data in a three-dimensional optical data carrier comprising at least one reference layer associated with one or more data layers and having a reference pattern arranged along reference tracks, the method comprising tracking said reference pattern by a reference beam having a focal spot size exceeding a pitch between two adjacent tracks in the reference layer.

The invention also provides a three-dimensional optical data carrier comprising a recording volume associated with at least one reference layer having reference patterns indicative of reference information pieces arranged along reference tracks, wherein said reference patterns are separated from servo patterns located on adjacent tracks in a radial direction, said servo patterns having at least one of the following arrangement: (i) with no angular overlap between the servo patterns located on adjacent tracks; (ii) said separation between the servo patterns of adjacent tracks includes separation in a frequency domain; and (iii) said separation between the servo patterns of adjacent tracks includes separation in a signal domain.

The reference patterns may contain tracking information, and/or clock for data recording and retrieving, and/or carrier format information such as layer, track sectors numbers.

The reference patterns may be embedded as tones or Baker coded or Complementary Code Keying coded.

The recorded volume may comprise one or more data layers including servo patterns embedded as tones in the data layer.

The reference patterns are preferably configured to provide a smooth substantially continuous transition between tracks in the reference layer.

In yet further aspect of the invention, there is provided a three dimensional optical data carrier comprising a recording volume with a plurality of data layers recorded therein, each data layer comprising data pattern arranged along data tracks, a radius of the most external track decreasing from the upper surface of the recording volume towards the lower surface thereof in a direction of propagation of incident light.

Such data carrier may comprise at least one reference layer configured as described above, namely comprising a reference pattern arranged along reference tracks. A distance between the most external reference tracks of the reference layer and an external surface of said volume determines numerical aperture of a reading/recording beam to be used for recording/reading data in/from a data layer coupled to said reference layer and the maximal recording radius in said data layer.

There is also provided a three dimensional optical data carrier comprising at least one reference layer and at least one data layer, wherein the radii of said layers decrease stepwise with the distance from an upper surface of the carrier with respect to a direction of incident light propagation during recording/reading processes.

It should be noted that generally, a data carrier may have a double-sided configuration. The data layers may be arranged in groups, and may be interspaced by group separation intervals. The groups may be defined by virtual base layers.

In yet another aspect of the invention, there is provided an optical system for recording and/or reading in a three-dimensional optical data carrier having at least one reference layer and at least one data layer; said system comprising:

a). a light source system generating a reference beam and a recording/reading beam;

b) a beam combiner combining said beams such that said beams being coaxial and having at least a common optical path section;

c) a common optical element (e.g. an objective lens unit) located on the common optical path section; and

d) a control unit configured and operable for controlling movement of said common optical element such that a focal spot of said reading/recording beam tracks a data track in an addressed data layer, said controlling comprising identifying a change in an error signal from the reference layer during the reference beam tracking the reference layer, thereby adjusting a tracking target for control of the movement of the reference beam.

The common objective lens unit is operable to locate the reference focal spot, and tracking the reference track, in the radial direction and in the tangential direction.

In its yet further aspect, the invention provides an optical system for recording and/or reading in a three-dimensional optical data carrier having at least one reference layer and at least one data layer; said system comprising:

a) a light source system for generating a reference beam and a reading/recording beam;

b) a beam combiner combining said beams such that said beams are coaxial and have at least a common optical path section;

c) a common optical element located on the common optical path section, wherein movement of said optical element being used for controlling the position of both beams;

d) at least one additional optical element located in one of the separate optical paths of said beams, movement of said additional optical element being used for controlling position of one of said beams.

The objective lens system being the common optical element may be actuated to locate the reference beam, and to track the reference track in the tangential direction. The additional optical element may be a mirror actuated to locate the reference beam on the reference track in the radial direction.

The system preferably comprises a detector providing a feedback signal indicative of the position of at least one of the beams, and a control unit configured for receiving the feedback signal and generating a correction signal. The latter is used for affecting the movement of the common optical element, and/or the additional optical element and/or an optical pickup unit.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the method and to see how it may be carried out in practice, embodiments will now be described, by way of non-limiting examples only, with reference to the accompanying drawings, in which:

Fig. 1A and **Fig. 1B** are schematic illustrations of a typical multilayer optical data carrier structure;

Fig. 2A-2C are schematic illustrations of some relative reference and recording/reading spot locations in a data carrier;

Fig. 3 is a schematic illustration of a typical S-curve;

Fig. 4A is a schematic illustration of the present reference surface layout;

Fig. 4B illustrates a simplified block of marks that comprise servo and to some extent additional data information encoded with Barker codes;

Fig. 5 is a schematic illustration of the present reference layer format and tracking method;

Fig. 6 is a schematic illustration of the proportional range generated by different servo tracking methods;

Fig. 7 is a schematic illustration of the overlapping proportional ranges of the present reference surface format;

Fig. 8 is a schematic illustration of a deviation of a data track projected on the reference layer tracks, showing the need for overlapping proportional ranges of the reference layer format;

Fig. 9 is a schematic illustration of a tracking error servo system loop operating according to the present layer principles;

Fig. 10 is a schematic illustration of a focal/axial servo system loop operating according to the principles disclosed;

Fig. 11 is a schematic illustration of an embodiment of an optical system for recording and reading a multilayer three-dimensional optical data carrier;

Fig. 12 is a schematic illustration of a typical multilayer three-dimensional optical data carrier and of some relative reference and recording/reading spot locations in a data carrier;

Figs. 13A-13C are schematic illustrations of an embodiment of the principle of determined relation between the reference and recording/reading focal spots in the optical layout of **Fig. 11**;

Fig. 14 is a schematic illustration of another embodiment of an optical system for recording and reading a multilayer three-dimensional optical data carrier;

Fig. 15 is a schematic illustration of an optical system layout, details of which are shown in Table 1.

Fig. 16 is a schematic illustration of a three-dimensional non-linear optical carrier;

Fig. 17 is a schematic illustration of a problem associated with the use of a high numerical aperture optical system;

Fig. 18 is a schematic illustration of one of the embodiments of the three-dimensional information carrier;

Fig. 19 is a schematic illustration of another embodiment of the three dimensional information carrier;

Fig. 20 is a schematic illustration of an embodiment of a double sided three-dimensional information carrier;

Fig. 21 is a schematic illustration of a further embodiment of the three dimensional information carrier; and;

Figs. 22A-22B are schematic illustrations of another embodiment of the three dimensional information carrier.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

In the following detailed description, reference is made to the accompanying drawings, which form a part thereof. Because the embodiments of the present apparatus and method can be positioned in a number of different orientations, the directional terminology such as "top," "bottom," "base," "upward," horizontal," "vertical," "above," etc., is used for purposes of illustration and is in no way limiting.

Reference is made to **Fig. 1A-1B** showing examples of a three-dimensional optical data carrier structure for recording/reading data in/from multiple data layers. In **Fig. 1A**, the optical data carrier **100** includes a recording volume **104**, having a disk-like shape, located on top of and in direct contact with a flat surface **108** supporting the entire stack. The recording volume **104** may be made of a transparent or translucent polymer material, such as Polymethylmethacrylate (PMMA) and compositions including acrylate and methacrylate monomers. The recording volume **104** may also be made of a non-linear photochromic material in which, upon photochemical excitation of the chromophores, a change of the chromophore's state (e.g. isomerization) occurs (WO 01/73,769; US 5,268,862). Such a change of the chromophore's state is the inscription ("writing") of data. Two flat surfaces **108** and **109** and a rim **116** define the recording volume **104** of the carrier **100**. The recording volume **104** is a bulk monolithic material, e.g. as discussed in WO 06/075327, or may be an assembly of disk like plates made of the same material. In both examples, a reference layer **112** is located on the top of flat surface **108**. In the example of **Fig. 1A**, this reference layer is associated with all the recording planes, while in the example of **Fig. 1B**, an additional reference layer is provided between two groups of recording planes.

It should be understood that, the flat surface/support layer **108** can be associated with (e.g. composed of) a second recording volume, or a second recording volume with a reference layer followed by a third recording volume, and so on. Reference or servo layers may be recorded similarly to data layers, for example, by recording method and systems such as disclosed in International publications WO2005/015552 and/or WO 2006/111972.

The recording volume **104** is configured and operable to record data therein and read the recorded data therefrom, where the data is in the form of a three-dimensional pattern of spaced-apart recorded marks arranged in multiple recording layers. The data may be optically recorded in the carrier **100** in practically any location, although it is convenient to record it on a plurality of "virtual" layers **120** as a series of three dimensional (3D) regular or oblong and tilted data marks. The nominal spacing between adjacent data layers may be 3 to 15 microns.

Generally, the recording volume is configured for recording/reading data arranged in multiple planes, and includes one or more reference layers. In some embodiments of the invention, the reference layer is a structure defining a reflective interface for a reference beam of a certain wavelength range. The reference layer is at least partially reflective for the reference beam and in case it is located in between recording layers it is substantially transparent for recording and reading beams.

In some embodiments of the invention, the reference layer is interposed between a data layer and a non-recording layer. The data layer and non-recording layers have different optical properties with respect to one- or multi-photon interaction used for recording/reading data in the data carrier.

The reference layer preferably has a pattern in the form of spaced-apart pits arranged along a spiral track or multiple concentric rings. The pits may be arranged in a spaced-apart relationship along a groove or grooves.

A reference beam focus or spot **105** is located on reference layer **112**. The intersection of the spot **105** with detectable pits on the reference layer **112** modulates the intensity of the reflected signal. The pits may modulate the signal by several methods such as the formation of refractive interference, or if the reference layer is a recordable photochromic layer, the modulation of the amount of fluorescence (between pits/marks and spaces) at the nominal interface (between the reference layer **112** and the recording volume (plate) **104**) position.

The reference beam or spot **105** is coupled to the recording/reading beam/spot **134** such that the reference surface in reference layer **112** can be used to locate a recording/reading light beam on a desired position in the recording volume **104**, above and/or below the reference layer **112**. It should be understood that the reference layer enables to keep the focal position of the recording/reading beam on the addressed plane, by detecting light response of the reference layer (e.g. reflection of the reference beam); and in case the reference layer is patterned it enables to control the recording/reading beam position while scanning the addressed plane.

Depending on the implementation, beams **105** and **134** may be directed from another direction on the carrier **100**. The recording volume **104** may be composed of a non-linear photochromic medium having a fluorescent property variable on occurrence of one or multi-photon (e.g. two-photon) absorption. Practically, the recording volume may be composed of any medium supporting volumetric recording, such as a recording medium disclosed in US Patent No. 7,011,925 and in International publication WO 2006/075327, all assigned to the assignee of the present application. The surface support layer **108** may serve as a base layer for the reflective reference surface (layer) **112** on which servo patterns (arrangement of spaced-apart pits) for tracking are embossed or optically recorded. The surface **108** is made of at least one transparent material such as polycarbonate, methacrylic resin, or polyolefin. The surface **108** may also comprise a photochromic medium having similar or different properties as the recording volume **104**.

The recording layers **120** in tens or hundreds of layers, can be formed in one recording volume **104**. Methods and appropriate media for extracting the basic signal from the reference layer, methods of calibration of layers location, and methods of tracking the recorded data, and an optical system adapted for this purpose are disclosed in the International Publications WO2007/069243 and WO2007/083308 all assigned to the assignee of the present application and incorporated herein by reference.

As indicated above, the reference layer **112** is characterized by a certain pattern in the form of a plurality of pits/marks arranged in a spaced apart relationship either in nominally concentric circular arrays or nominally along zoned spiral tracks. The surface of the reference layer is a reflecting surface, which may be formed by well-known methods on the pitted/protruded surface **108**. Alternatively, the reference pattern may be formed on the surface of recording volume **104** (e.g. by direct embossing or printing). The reference layer **112** generates a signal indicative of the positional information of the data such that the data can be recorded/read with the aid of the tracking direction position signal in the record/read layers. Generally, depending on the carrier structure, as shown in **Fig. 1B**, the carrier **100** may contain more than one reference layer **112**. Reference layer **112** may be a printed layer or a conventional embossed CD-like stamped layer.

The servo or reference spot **105** follows a reference track and is located slightly above (or below in the plane of the drawing) the reference spot; a read/record spot scans a data layer. The distance along the vertical axis between the recording/reading focal beam/spot **134** and the reference beam foci can range from complete overlap (zero distance) up to 300 - 1500 microns. A calibration procedure that determines the relative location of recording/reading focal spot with respect to the reference beam focal spot within recording volume **104** is carried out, for further controlling the recording/reading spot axial moving distance. As disclosed in the above-indicated WO2007/069243 and WO2007/083308, the calibration procedure utilizes determination of the reflection of the reference beam from the interface surfaces (e.g. the reflective surface of the reference layer **112** or the outer surface of the disk) and change of read signal (e.g. fluorescence) caused by the reading spot interaction with the same interface surfaces.

In order to establish the recording layer location, the recording spot moves upward (in the plane of the drawing) within the carrier **100** in a predetermined motion mode to define and record a recording layer. The reading layer location may be established by moving the reading spot upward (in the plane of the drawing) from the reference layer **112** into the recording volume **104** of the carrier **100**. As the spot moves, it scans the recorded layers and the interaction between the spot and the recorded marks causes a varying response (e.g. fluorescence) to be emitted. The response identifies the location and the distance of the recorded layer from the reference surface of the reference layer **112**.

As disclosed in WO/2007/069243 and WO/2007/083308, the tracking of a reading spot moving along a recorded track may be performed by making simultaneous spot movements in two directions orthogonal to the track (wobbling). However, using this technique, disturbances from spatial frequencies higher than the bandwidth enabled by the corrective movements of the spot, might not be eliminated. Moreover, being an integral part of the disk, the reference layer is subject to mechanical assembly errors, which may cause tilt of the reference layer relative to the optical axis of the beam propagation through the carrier, as well distortions due to thermal and mechanical load, and other errors.

Furthermore, certain time elapses occur between the disk-recording event and the reading of the recorded data. During this time, the disk is subject to aging and other mechanical deformations that may change the spatial relation between the recorded track and the corresponding reference track location.

Reference is made to **Figs 2A-2C**, illustrating different disk distortion examples, where for the sake of comparison **Fig. 2A** illustrates the ideal case in which the carrier surface **200**, the reference layer **204** and the data layer **216** are ideally perpendicular to the optical axis **226** and parallel to the disk surface. The spatial (radial and tangential) location of the reference beam **220** focus or spot **224** and the recording/reading beam **232** and focus or spot **236** are correlated and coaxial. **Fig. 2B** illustrates the same configuration on a tilted carrier, and **Fig. 2C** illustrates the same configuration for a tilted and distorted carrier. In cases of **Figs. 2B** and **2C**, the reference beam **220** and recording/reading beam **232** may remain coaxial, but their relative spatial position along the optical axis is liable to change between the recording process and the data retrieving process due to the mechanical error of the assembly, tilt of the reference layer **204** relative to the disk surface **200** and internal mechanical changes in the disk. The offset **244** shows the difference between the actual position of the reference spot **240** and the recording/reading spot **236**. The beams' refraction by the disk material and the loss of common optical axis (centering) of the reference beam **220** and the recording/reading beam **232** may further contribute to the absence of correlation.

In addition to distortion, the relative location of the data layer **216** with respect to the reference layer **204** is due to the drive-to-drive compatibility or the mechanical and optical tolerances of each drive. Because of such differences, the motion of the recording spot with respect to the servo (reference) spot might not be substantially coaxial. This may result in different, drive dependent data marks locations and adversely affect the disk interchangeability.

The amplitude of the described offset for a disk with tilt tolerance of 2-10 milliradian and thickness of 0.6-2.4 mm may be in the order of microns in either one of axial (focal or tangential) or radial directions. As the offset between the reference beam and the data recording/reading beam increases, the coupling between the reference beam and the data recording/reading beam becomes less accurate, and reading the data track requires compensation for the induced errors. The tilt and the de-center of the rotating carrier, and the carrier shape distortions caused by carrier aging or improper mechanical and thermal load application, might lead to so-called low frequency deformations (in the range of KHz) or errors of the data tracks relative to the reference layer. The errors which are not relative to the reference layer and to the mechanical vibrations of the system cause disturbances that may comprise high frequency disturbances (in the range of MHz). The high frequency disturbances might exceed the bandwidth of the direct position error signals from the recorded data track.

The present invention, in one of its aspects, enables the correction of both high frequency disturbances and low frequency errors caused by any disturbances such as disk distortion. This correction is based on combining high frequency error signal from the reference layer (for correction of high frequency disturbances) with low frequency error signal from the data layer (for correction of low frequency distortions and disturbances). The error signals that could be detected in the optical axis (axial or tangential) direction are termed Focus Error Signals (FESs) and those in the radial direction are termed Tracking Error Signals (TESs). In the OPU, a common objective lens unit is used for focusing the reference and recording/reading beams into the recording volume. The present invention thus also enables the use of the respective error signals (FESs or TESs) associated with the data and reference layers and being thus of different spatial frequencies (high and low frequencies, respectively) to identify a distance between the reference layer and the addressed recording layer and to keep the reference and the recording/reading data beams coaxial.

It should also be noted that the above-mentioned distortions are predominately generators of a low frequency error signal as also is the disk eccentricity. Therefore, high frequency error signals are predominately the result of disturbances, and the tracking errors, as induced by mechanical vibrations and disk eccentricity, are common for both the data layer tracking and the reference layer tracking. The reference beam reflection (reference signal) from the reference layer generated error signal, which is in general a high quality signal with good signal-to-noise ratio. It allows for correction of the errors on both data and reference track. The difference in the relative location (orientation and position) of the data track with respect to the reference (the relative error) track, however, compared to the relative location during the recording process, must be properly detected. The low frequency character of the relative error allows for narrower bandwidth and lower signal-to-noise ratio's detection methods. Furthermore, this error has a dominant periodic component (it repeats every revolution of the disk with the same error pattern.) The error can be detected and learned by a "feed forward" method incorporated to the control of a correcting actuator (as will be described below with reference to Fig. 11). This could eliminate errors caused by disk distortion and disk eccentricity and prevent beam de-centering errors by prevention of large objective offsets. This method further reduces the requirements for reliable detection signal-to-noise ratio of the signal and reduces the loss in data signal quality.

In addition to bandwidth issues, it should be noted that non-linear three dimensional storage carriers require high power, high brightness recording/reading spot. Accordingly, optical systems for data recording/reading are aberration corrected optical systems that keep the optical path of the recording/reading beam with minimal losses. The reference (reflected) signal is typically a stronger signal as compared to the response signal caused by the interaction of the recording/reading spot with the bulk (optically) monolithic material of the carrier. As noticed above, proper design considerations require utilization of a common objective lens unit for both the reference beam and the recording/reading beam. Since proper spherical aberration correction is more simply applied to only one of the spots, it has to be applied to the read/write spot. Under the above considerations, with proper configuration of the reference layer pattern, the reference beam quality is less critical and it may form a relatively large, lower effective NA, aberration tolerant reference pattern scanning spot. Since the same objective lens unit projects both the reference and the reading/recording spots, unavoidable losses and aberrations could be placed in the reference beam path allowing for a diffraction limited recording/reading spot. Moreover, a longer wavelength may be used for the reference beam (the reference pattern scanning spot).

To characterize the properties of a servo signal, an S-curve may be calculated using the output of a position sensor (See "Optical Recording" by A. Marchant, pages 168 – 172, Addison-Wesley 1990, ISBN 0-201-76247-1). Reference is made to **Fig. 3** representing a schematic illustration of a typical S-curve. The range of the linear section of the S-curve **350**, indicated by the horizontal bar **310** determines the more appropriate working range derivable from the servo signal. The accuracy and reliability of the servo signal are conveniently characterized by the slope and noise margins of the S-curve.

Standard radial tracking error signal (TES) generation methods are characterized by a relatively small proportional range S-curve and may have a TES range that is much smaller than 1 micron. These methods should be modified for use in combined tracking error correction using signals from the reference layer tracking and from the layer tracking data.

Although depending on the optical magnification of the OPU and the accumulated aberrations, the size of the spot should be such as to enable reliable error signal S-curve generation. It should be noted that using sampled servo, the size of spot may vary over a relatively wide range (compared to other servo methods such as push-pull tracking), and yet sampled servo tracking error signal (TES) may still be characterized by a reliable and accurate S-curve enabling the determination of the location of the spot. Thus, the exact size of the spot and the strict maintenance of the spot size become less important, allowing a relative freedom in the design of the system and reliable operation.

Reference is made to **Fig. 4A** representing a reference pattern **500** and its associated signal generated by the spot **516** moving along the nominal center of a track. The servo or reference marks (pits or spaces between them) **504** are optically recorded or embossed on tracks A, B, and C. The error signal generated by the difference between the intensities reflected by the marks **504** read by the large spot **516**, equal to (A-B) or (B-C), would not provide a decisive indication on the spot location. The spot **516** may have dimensions larger than the pitch (i.e. the distance **520** between two adjacent tracks). The diagram **528** illustrates the signal generated by the spot movements. Generally, the carrier may rotate and the spot may be static. In this specific non-limiting example, the spot **516** moves along the track B in the direction indicated by arrow **524**. The center of the spot **516** follows track B. When the spot passes the marks **504** on track B, the content reflected signal **532** originating in track A or C is minimal, when passing data marks on tracks C or A, a partial response of the marks from track C or A is detected. By assigning different weights to signals received from spot **516**, the location of the spot between the tracks may be determined and used to track the spot in arbitrary positions within the servo response range. In the example of **Fig. 4A**, the error signal could be expressed as the difference between the signals generated by tracks A and C. In accordance with the present method, the marks **504** of the adjacent tracks in the reference layer are used as sampled servo marks. Despite its size, the reference spot can follow a track, with a high resolution.

It should be noted that mark **504** may be constituted by a single pit/space or by a group of the spaced-apart pits, where a distance between the pit/space within the group **504** is smaller than that between the groups (i.e. between the last pit-space in one group and the first pit/space in the adjacent group. Thus, the block **504** of marks may be a single-mark or multiple-marks block. The blocks of marks **504** are relatively sparse on each of the tracks such that no block of marks angularly overlaps another mark block located on an adjacent track, i.e. there is no overlap between the blocks in a radial direction. Therefore, the relatively large spot **516** will not cover simultaneously marks on the adjacent tracks. Such marks location allows for removing ambiguity or interference that could exist if a relatively large spot, like spot **516**, would overlap marks on all of two (or three) tracks A, B (and C). Further to this, the spot may vary in a relatively large range from two to three track pitches allowing for significant defocusing to be absorbed without affecting the signal.

Reference layer formats having tracks densely populated by reference or servo marks, may have, especially for a low quality (low resolution) spot, relatively significant interference between the tracks signals. This effect may be overcome, for example, by interleaving servo mark and other information (e.g. synchronization bits, sector identification, disk standard, manufacturer's identification, etc.) and by having the servo marks angularly separated from the other information patterns. Preferably, servo signaling marks provide high update frequency (preferably greater than 500 indications per disk rotation, more preferably greater than 1500 indications per disk rotation, and most preferably more than 4500 indications per disk rotation) so that noise may be averaged out.

Alternatively, blocks of marks may spatially overlap each other, if their respective signals are separable in the signal domain such as tone embedding or signal spreading approaches in which generally signals are encoded to practically orthogonal in a certain decoding scheme. It should be understood that the signal domain signifies that different servo marks have different signal contents; and the frequency domain signifies that different servo marks have different frequency contents. **Fig. 4B** illustrates a simplified block of marks that comprise servo marks and to some extent additional information encoded with Barker codes (i.e. sequence of N values of +1 and −1). Each ellipse **540** denotes one clock interval or a minimal mark (which may encode more than one clock event). First reference track **544** is encoded by using 11 digits (+1 +1 +1 −1 −1 −1 +1 −1 −1 +1 −1) for section **548** and 5 digits (+1 +1 +1 −1 +1) Barker codes for section **552.** Second track **556** is encoded using 13 digits (+1 +1 +1 +1 +1 −1 −1 +1 +1 −1 +1 −1 +1) in section **560** and 4 digits (+1 −1 +1 +1) Barker codes in section **564**. This structure requires less coordination (in the radial direction) of the marks' positions with respect to the adjacent track. Any known suitable method for separating signals (in the signal domain), such as the use of Complementary Code Keying, can be used either using one beam for tracking or using splitting optics for data tracking. The signal domain (i.e. different servo marks having different signal content) can be any signal domain. The frequency domain (i.e. different servo marks having different frequency content) and the time-space domain can also be used as well as other domains such as wavelet domains. Servo or data patterns in adjacent tracks are characterized by being substantially orthogonal and/or multiplexed in the space-time, frequency and/or another signal domain. The signals can be considered to be well separated, if the inter-signal interference (interference/signal) is less than -10 dB, preferably less than -15 dB and more preferably less than -20 dB.

Reference is made to **Fig. 5** representing a schematic illustration of a reference layer format according to an example of the present invention. The marks **504** within the reference layer are represented as well as their location on tracks, and the distance (pitch) between the tracks. Blocks **600** of marks **504** could be pre-formatted and recorded/embossed in a way that they would enable an accurate spot location determination. Servo marks or patterns may further comprise additional information such as track position as is indicated schematically by the detailed structure of **610**. For example, a minimum mark-space interval may be 11T (where T denotes the pitch) and each segment (block) is such that 21x11T = 231T. To allow spiral evolution of a continuous track that compares signal from the triplets of segment (in the radial direction), the number of the segments in a carrier revolution should be divided by three. The same is applicable if other track multiplicities in the radial direction are selected for track and tracking design. There would be 2744 segments per carrier revolution. Each mark block **600** contains information on the track address, sector index and possibly additional information.

These reference layer structural features (mark, block sparseness) may also allow tracking with other methods such as split beam imaging on a position sensitive detector, which in principle can be used instead of the sampled servo method.

Thus, each segment contains tracking information, clock for data recording and retrieving, format information on layer, track sectors numbers and specific disk info information. The segments may be formatted in correlation to provide the same synchronization by adjacent tracks.

Reference is made to **Fig. 6** representing a non-limiting example of the proportional ranges generated by different reference layer pattern tracking options. Letters **A**, **B**, and **C** designate tracks. A signal **704** produced by a push-pull servo serves as a reference for comparison with the other options. Horizontal bar **708** indicates the proportional tracking range. The tracking range **708** produced by a push-pull servo is limited. The tracking range **712** of the sampled servo examples below is larger than the one produced by the push-pull servo. It is produced by a sampled servo based on signals (A-B) and (B-C). (The value (A-B) = 0 means that the spot is right in the middle between tracks A and B.) The tracking range **716** produced by the present method (A-C) is substantially larger than the others.

Reference is made to **Fig. 7** representing a schematic illustration of the overlapping proportional ranges of the reference surface format according to the example of the present invention and some possible tracking options (derivation of the tracking error signal). Letters **A-E** designate tracks. Lines **804**, **808**, and **812** indicate different possible tracking signals. The overlap **820** between horizontal bars **816** indicates the proportional tracking range when the reference scanning spot moves from one track to another track, meaning that a tracking option in which the tracking signal is generated by $\text{Track}_n - \text{Trackn}_{+2}$ is feasible. Fine servo capability is achieved by the large overlap denoted **820**. Practically, a large proportional ranges overlap **820** enables a smooth continuous transition between the tracking alternatives including the tracking between the recorded tracks. Servo resolution depends on a number of additional parameters such as signal-to-noise ratio, sampled servo frequency, and others.

Reference is made to **Fig. 8** representing a schematic illustration of a deviation of a data track projected on the reference layer tracks, showing the need for overlapping proportional ranges of the reference layer format. It illustrates a feedback obtained from a reference pattern or a track that has been forced by a low frequency relative disturbance to pass (jump) over more than one reference track. Line **900** indicates a trajectory of the reference spot that must be followed to compensate for example for relative data position and OPU imperfect positioning. At the outset, the spot was in a location where the (high frequency) tracking signal was generated as a difference between the signals (A-C) obtained by detecting the intensity of the reflected beam. As the offset (introduced by the relative error) from the initially defined trajectory increases, the difference between the signals (B-C) obtained by detecting the intensity of the reflected beam becomes the feedback signal. Further increase of offset does not lead to a loss of control. The servo simply switches to the next tracking alternative, and a signal (B-D) generated by the next closest track is generated. In this non-limiting example, the servo gradually returns to the original (A-C) signal, stressing the cyclic partially repeatable nature of disk deformations as a function of angular position.

The structure of the present reference layer offers a number of spot position tracking options that rely on the ability to separate the mark segments (blocks) in the radial direction (e.g. sparseness of marks, if sampled servo is used) and dense mark location in the angular direction (e.g. high repetition frequency if sampled servo is used). The ability to separate mark segments in the radial direction allows for the use of a wide range of spot sizes on the reference layer, while the dense location of marks in angular direction allows for the use of low signal quality e.g. caused by low contrast, defocusing or significant spot aberrations that can be improved by averaging. There is no need for a high tangential data density; the only information to be stored is a high quality clock and position location. The clock can be scaled to the actual data clock. The presented method and system enable to follow spot position even when the spot is located between the tracks and is independent from the fixed tracking track pitch (i.e. the radial distance between scanned virtual/nominal tracks). The method and system also provide a large effective servo offset range. In addition, the tracking error signal detection using sampled servo does not require use of a quadrant detector for spot location determination.

Keeping high quality clock derived from the reference layer is conveniently provided by using encoding for Zoned Constant Angular Velocity (ZCAV) on the reference layer and in turn in the recording layer. ZCAV refers to a servo or data pattern structure in which tracks are groups located into annular zones, wherein each of the zones, the distances between marks, and the lengths of sectors, are kept substantially constant, providing for recording and reading the data in each respective zone at a substantially constant data rate and at a substantially fixed disk rotation speed. A particular advantage of this scheme is that when switching back and forth between tracks in case of offsets between the reference layer and the data layer, clock adaptation is eliminated, thus allowing for higher clock quality.

Reference is made to **Fig. 9** representing a schematic illustration of a tracking error servo system correcting low frequency distortions and disturbances and high frequency disturbances, and operating according to the present invention. In particular, the scheme illustrates how the TES of the reference layer and TES of the data layer are combined. Block **1000** indicates the servo section processing the reflected pattern signal from the reference pattern, and block **1004** indicates the servo section processing the luminescent data signal generated by interaction of the recorded marks with the reading laser spot. It should be noted however, that the TES signal generated by the reference layer has a wider bandwidth range (spatial frequency of the pattern features) allowing the "jump" from tracking one reference layer track to another. The reference layer tracking aims at annihilating the high frequency disturbances and not at correcting distortions, therefore only the direction and the amplitude of the high frequency disturbance are required to be estimated for correction. The use of sampled servo TES that has a large overlap as shown in **Fig. 7** enables determining a TES at any point from at least one track and allows smooth shifting/transition from using high frequency TES derived from one "track" to another track.

Standard focal (axial) error signal (FES) generation methods are characterized by a relatively wide proportional range S-curve and may have a FES range of more than 20 microns. As the relative (reference layer – data layer) tracking errors are typically much smaller, the reference layer may be followed with sufficient offset still enabling to follow the data layer. These methods can also be used for combined axial error correction, using signals from the reference layer tracking and from the data layer tracking.

Reference is made to **Fig. 10** representing a schematic illustration of a servo system correcting high frequency disturbances. Block **400** indicates the servo section processing the reflected signal from the reference pattern, and block **404** indicates the servo section processing the luminescent data signal generated by the interaction of the recorded marks with the reading laser spot. The FES of the reference layer has a long range, but it is an indirect signal as compared to the direct data signal and thus cannot be used for the correction of the distortion of the data track with respect to the reference track. The low frequency tracking of the data layer allows correction of the low frequency distortions and disturbances. The low frequency portion of the reference layer FES allows for adjusting the relative distortions, and the high frequency range of the reference layer FES can be used to indicate the amplitude and the direction of the high frequency disturbances and therefore to correct the high frequency disturbances.

Reference is made to **Fig. 11**, which is a schematic illustration of an embodiment of an optical system for recording and reading a multilayer three dimensional optical data carrier. The optical system has two branches: a branch **102** that provides first or reference beam and a branch **106** that provides a second or reading/recoding beam. The branch **106** includes a beam expander device **110** composed of a positive lens **114** and a negative lens **118**. The negative lens **118**, as shown by an arrow **122** has a freedom of movement along the system optical axis

126 forming a variable magnification beam expander system providing a variable divergence reading or recoding beam. Generally, the beam expander **110** may have a different structure and may, for example, comprise two positive lenses.

A beam combiner **1134** collects the second or recording/reading beam **130** and changes the direction of beam **130** such that it propagates along the optical axis **138** of an objective lens unit **142**. The objective lens **142** focuses the recording/reading beam **130** within the bulk of an optical data carrier **146**, such as for example that described in the present disclosure. Changes in the convergence or divergence of the second or recording/reading beam **130** would move the beam focal spot **150** along the optical axis **138** within the bulk of the data carrier **146**. This allows focusing the beam **130** on any one of hundreds of different data layers **154** populated for example with data voxels **156** recorded within data carrier **146**. The read/write branch **106** of the optical system in combination with the objective lens **142** (when in the fixed position thereof) corrects the spherical aberrations of the variable divergence of reading/recording beam **130** at different focal spot locations in the depth of carrier **146**.

The branch **102** of the system includes a beam expander device (not shown) that collimates the first or reference beam **158** or otherwise finitely conjugates the beam source with a targeted spot depth in the disk. A mirror **162** folds the beam optical path such that the optical axis **164** of the beam after passing the beam combiner **1134** coincides with the folded optical axis **126** of the recording/reading beam optical axis and with the optical axis **138** of objective lens **142**. The beam combiner **1134** combines beams **130** and **158** such that they form a section of a common optical path where the optical axis **138** of the objective lens **142** becomes a common optical axis of both beams.

Beam **158** may be of wavelength different from the wavelength of beam **130**. It should be noted that the reference beam **158** should not interfere with the reading/recording processes, or the signal detection, and that the separation may be achieved, for example, by use of different wavelengths and/or polarizations. For example, the first reference beam **158** may be of wavelength of about 780 nm and the recording/reading beam **130** may be of about 650 nm wavelength (the recording and reading beams may in turn be of the same or different wavelengths). The objective lens **142** focuses the beam **158** into a spot **166** located in the plane of reference or servo layer **170** of the optical data carrier **146**. Since both the beam **130** and the beam **158** are focused by the same objective lens **142**, although in different optical planes, the beams are optically coupled. Any movement of the objective lens **142** in the plane perpendicular to the drawing, as shown by arrows **168** affects location of both focal points **150** and **166** simultaneously. The degree at which each of the beams is affected is different, because they have different wavelength and divergence.

The mirror **162** that folds the first beam **158** has certain freedom of movement for adjustment purposes around axis **164**, as shown by arrows **171** and in direction perpendicular to axis **164**. Located in the optical path of the reference beam **158** are a beam combiner **174** and a quarter-wave plate **178**. The beam combiner **174** folds the light reflected by the reference layer beam **182** and directs it through a focusing lens **186** onto a Position Sensitive Detector **190** (PSD). As indicated by arrow **194**, the focusing lens **186** may be capable of lateral movement in the plane perpendicular to the plane of the drawing. The movement of the focusing lens **186** changes the location of an image **198** of a particular track of a reference layer **170** and a focal spot **166** formed by the lens **186** on the detector **190**. The quarter wave plate **178** rotates the polarization plane of the reflected beam **182** directed towards detector **190** to avoid undesired interference with the original reference beam **158**.

Further included in the system is a detector **202** for reading the fluorescent signal generated by the interaction of the reading beam **130** at focal point **150** with the carrier potentially containing recorded data marks **156**. Generally, the detector **202** may be located on any of the sides of the optical carrier **146**. **Fig. 11** shows a transmission like configuration. The detector **202** may be a Position Sensitive

Detector (PSD), or non-PSD, and may be used to measure the signal and compare its value produced by different sections of the detector.

The fluorescent signal generated by the interaction of the focal point **150** of the reading beam **130** with the recorded data marks pattern **156** and distributed in the depth of the optical carrier **146** is a relatively weak signal and a signal collection system **206** comprising mirrors **210** having curvature of second or higher order and a filter **214** allows a better collection and signal-to-noise reduction of the fluorescent signal.

As noticed above typically, both reading and recording of a three-dimensional optical carrier, such as the one shown in **Fig. 12A**, is performed with at least two beams: a reference beam and a recording/reading beam or first and second beam. The beams are optically coupled and coordinated in a determined relation, such that the location of reference spot **166** in a reference layer **172** could be used to locate a recording/reading beam spot **150** in a desired position in the recording volume of the optical carrier **146**. In the current embodiment, the coupling and the coordination between the beams are achieved by maintaining the objective lens **142** focusing the reference beam **158** and the reading/recording beam **130**, into the focal spots **166** and **150**, in a fixed position with respect to the reference layer **172**. Changes in divergence of the reading/recording beam **130** moves spot **150** from one data layer to another data layer.

Reference is made to **Fig. 13A** which illustrates in detail the effect of offset between the incident axes of a reference beam **163** and a recording/retrieving beam **126** relative to the axis **138** of the objective or an OPU. The offset may be linear or angular or a combination of both of them. In **Fig. 13A**, an ideal positioning is presented in which the focal spots **150** and **166** of the reading beam and of the reference beam respectively overlap and are located along the optical axis **138**. Therefore, there is no offset between the axis **138** of the objective **142** and the reference beam axis **163**, and the recording beam axis **126**, and the beams are coaxial. The spatial (radial and tangential) location of the reference beam focal spot **166** and the recording/reading beam focal spot **150** are correlated and coaxial. In **Fig. 13B-13C**, the focal spots **150** and **166** of the reading beam and reference beam are not along the optical axis **138** and an offset exists between their respective locations, with regard to the axis **138**. In **Fig. 13B**, the lateral movement of the objective lens **142** indicated by the arrow **219**, creates an offset between the incident reference beam axis **163** and the recording/reading beam axis **126**, and the focal spots **150** and **166** focused by the objective lens **142**. The image is laterally shifted by the objective **142** relatively to the optical axes of beams **130** and **158** inducing a shift in the location of the focal points **166** and **150** of the reference **158** and recording **130** beams respectively. As shown, the shift of the focal points **166** and **150** is not identical, i.e. an *offset difference* (because of a change in location of a common optical element) is formed. The numeral **234** marks the optical carrier surface.

This offset may vary, being dependent on the relative spatial position (angular and linear) of the reference beam **158** and the recording beam **130** versus the objective **142**. For example, the beams may have different divergence, an angle may exist between their optical axes, and the beams may not be coaxial with the optical axis **138** of the objective lens. The offset between the foci positions (spots) is dependent on additional factors such as the effective NA and the angle of divergence of the incoming beams. In order to reduce or eliminate the offset and its influence on the recording or reading process, the reference and read/record beam axes and the objective axis should be kept at determined relation.

It is important to note that the process, by which the actuators control the spots, influences the amount of the de-centering of the beams relative to the objective axis and consequently the relative offsets and the quality of data recording and data retrieving processes. The spots offsets can be controlled by limiting the movement of the objective lens actuator and controlling directly the position of the objective (for example, by limiting the voltage on the coil holding the objective), and distributing the required movement to other elements than to the objective lens actuators. The control of the relative position of the two focal points can also be achieved, for example, by use of a galvanometer mirror (or a piezo actuated mirror) deflecting or offsetting the beam in the radial or tangential directions and by altering the beam through the objective pass in a predetermined amount.

Generally, the relative position of the reference beam focal point and of the focal point of the recording/reading beam should be in a determined relation. In particular, the axes of the reading/recording beam and the reference beam may be parallel to the optical axis of the objective lens. However, the beams are not necessarily coaxial. Even if the objective lens and the incident beam are not in a substantially optimal position (coaxial and parallel to the objective optical axis), the two focal points may be in a controlled relative position. The relative position of the spots can be monitored by feedback from the optical system, e.g. by monitoring the voltages at the objective actuators and other actuators, thereby allowing full control on the relative positions of the two focal points. The objective lens movement should vary the location of the recording/reading beam focus, such that the target location of the focal point may be in a determined relation with respect to the focal position of the reference or servo beam. The determined relation should include the difference between the depth of the servo layer and the focused point of the recording/reading beam. Alternatively, to keep the spots in a determined relation, the tilt or offset of the beams can be controlled e.g. by a PZT actuated mirror.

For example, in the optical system disclosed below, if the vertical distance between the focus at the reference layers and the focus of the recording beam in the medium is 500 microns, a lateral movement of the objective lens of 100 microns gives an *offset difference* of 8 microns.

The effect of the change in the location of a common optical element (e.g. objective lens **142**) on the location of the focal spot positions can generally be described by a change ***df1*** of a first focal spot and ***df2*** of a second focal spot and by a function of a change in the location ***dx*** or displacement of a common optical element. The change may be well approximated by a proportion factor ***k*** being a function of the vertical distance (in the direction of the optical axis) between the focal positions. For the example provided above, a ***dx*** displacement of the lens (the common optical element) for the particular case is such that, it will move the closest to the lens spot by a distance ***df1***, and the spot located further from the lens surface by a distance by ***df2 =kdx***, where ***k*** is approximately **0.92**.

The *offset difference* may be attributed to the different beams divergence (e.g. NA differences and the focusing of the beams at different depths in the optical carrier material) and to media dispersion. Typically, the focal position of the beam focused closer to the objective will move to a smaller extent. This difference in the lateral offset of the focal spots may, but not necessarily, be approximated as a bilinear function of the extent of the lateral movement of a first focal position and of the distance along the optical axis between the two focal positions.

The lateral offsets **218** and **222** as shown in **Figs. 13B** and **13C** are dynamic offsets that vary, being dependent on the relative spatial position (angular and linear) of the reference and recording beams versus the dynamic position of the objective **142** and/or of additional common optical elements. The lateral offsets **218** and **222** may also be a function of the optical carrier position relative to the elements of the optical system.

Turning back to **Fig. 11**, as the optical carrier rotates, the radial run-out, the axial run-out, the optical carrier angular deviations and deformations, and the external disturbances, cause changes in the locations of the focal spots **150** and **166** relative to the tracking targets, i.e. a data track and/or a reference layer track. The servo or control system, schematically shown by a controller **250**, dynamically controls the positioning of all the relevant optical elements (as shown by arrows), such that it keeps the reference beam on the reference layer to provide first tracking information and keeps the reading/recording beam on a track in an addressed plane to record a data track or to retrieve data thereof, optionally providing second tracking information.

Dynamic offsets may be formed when tracking in the lateral direction is performed, using optical elements located in the common optical path for example, such as the objective lens **142**. These dynamic offsets may have the following effects (attributed to dynamic offset difference): (*i*) in course of recording, the offsets may cause one record track to cross over and/or overlap a neighbor track; (*ii*) during the reading, they may force the reading beam off-track.

In one embodiment of the system, in the process of recording or reading optical carrier **146**, the focal spot **166** of the reference beam **158** scans the tracks of the reference layer **170**. The reference layer **170** partially reflects the reference beam **158**. The imaging lens **186** collects the reflected beam **182** and forms an image of a section of the reference layer **170** track scanned, on the detector **190**. As the reference spot **166** gets off-track, its image on the detector **190**, which may be a Position Sensitive Detector, gets off the center of detector, and an error feedback signal marking this de-centering may be generated and communicated to the servo controller **250**. The controller **250** generates a correction signal that moves the objective **142** such as to correct the error feedback signal for both reference and reading beams.

In some embodiments, a split beam derives the tracking information from the reference layer. The earlier disclosed tracking principles *are mutatis mutandis* applicable to the use of a split beam for focusing on the reference layer and tracking the reference layer.

In an alternative embodiment, wobble or sampled servo structures on the reference layer are used to derive the tracking information and the tracking error signal without using position sensitive imaging of the reflected beam.

It is necessary to mention that generally, the servo controller **250** may get a tracking signal from either the reference **170** or the data layers **154**. The tracking signal from the data track may de derived for example by methods described in

WO2005/015552 assigned to the assignee of the present application. These methods may be used for extracting the error signal directly from the data track while recording or reading.

The constraints on tracking by the data track and that by the reference layer track are essentially different. When tracking a data track, the beam focal spot is to be positioned on the desired track to be recorded or read without crossing other tracks (recording or reading) and without getting off track (reading). Tracking of the reference layer is basically required for providing an error signal to correct the data in the recording/reading beam position; it does not necessarily require locking onto a specific track, as long as the focal positions are at a determined relation. The second constraint is far less stringent and some of the embodiments of the invention directly leverage this difference.

The radial tracking error signals are processed by the servo controller **250** that generates position correction signals directed to affect the optical elements that influence the beam focal positions. In particular, the position correction signals are directed to the actuator of the common objective **142** and to the actuator of the complete optical pickup unit (OPU) relative to the disk (not shown). The movement of each element and the consequent movement of the recording/reading spot position ***df1*** and the movement of the reference beam focal spot ***df2*** are proportional to the correction signal. However, there is an offset difference $\Delta = (df2 - df1)$, inducing that the determined relation between the focal positions is changed dynamically and the reference layer tracking target should also change dynamically. Therefore, changing dynamically the reference layer tracking target is a kind of forward feedback control. As a response to a tracking error signal, the system anticipates future errors (due to dynamic offset) and by modifying the command (the tracking target on the reference layer), corrects them in advance.

It should be noted that by weighted servo e.g. by using sampled servo with different weights to the 'left' and 'right' mark signals, the tracking target may be changed practically continuously, providing targeting resolution significantly smaller than the track pitch.

For example, in the case described above, a one micron offset of the objective lens **142** would offset the tracking target for the reference layer by approximately 0.08 microns. In other words, if the tracking was initially targeted at a center of an embossed track, the tracking system should now being centered at a position that is offset with respect to the embossed track center by 0.08 microns.

An additional, complementing method to reduce the magnitude of the offset is to smooth out the required objective movements by forward feedback, i.e. to anticipate the required objective movement and to prevent it by an alternative actuation of the optical system in a way that would keep the first and second beams at more appropriate positions relatively to the objective and to other common optical elements. For example, a smooth actuation of the complete OPU can be performed in anticipation of the following of the spiral track shape.

There are several alternatives regarding how to change the tracking target. In one non-limiting example, in the case of the sampled servo tracking of the reference layer, the weights of the sampling servo may be changed appropriately to a predetermined function or by subtracting an offset from the error signal appropriately according to a known (predetermined) error signal curve (behavior).

In one embodiment, the optical system may be configured as a direct correction system in which the correction affects both beams' focal positions in a determined relation in response to an error signal to be used by the beams coupling optical element to move the both beams' focal positions. The determined relation between the focal positions may be changed by variation of the location of an optical element located on the reading/recording optical branch. The offset of the center of the recording beam relative to the axis of the common optical path changes the relation between the focal positions of the reference beam and the reading/recording beam in a determined relation.

In an additional embodiment, the determined relation between the focal positions may be changed by altering the location of an optical element located on the reference optical branch. The offset of the axis of the reference beam **158** relative to the axis of common optical path **138** (the optical axis of the common optical element) changes the relation between the focal positions of the reference beam **166** and the reading/recording beam **150** in a determined relation.

In an alternative embodiment, the optical system may be configured as an indirect correction system in which the correction affects a first beam (coupled to the second beam) in response to a first error signal by means of an intermediate creation of a tracking error in the tracking by the second beam such as to create a second error signal to be used by the beams coupling optical element to move the first beam focal position. In a non-limiting example, the position of the reflected beam **182** relative to the PSD **190** may be shifted, by change of the location of an optical element located along the separate reference beam optical path, e.g. by movement of a beam splitter **174** and associated with it the reflecting surface **176**, or by the movement of the PSD **190**, as shown by arrow **230**. The offset of the center of the reflected reference beam spot **198** relative to the PSD **190** results in a corresponding signal communicated to servo **250**. According to the signal, servo **250** would act to affect the mutual location of the focal spots of the reference **166** and reading/recording **150** beams that are in a determined relation between them.

It should be noted that the offsets of the optical system comprise the dynamic foci offset (due to objective offsets) and deformation like offsets.

More generally the present invention also provides a tracking system and method for eliminating deformation like offsets, by, for example, separating between the disturbance/deformation by use of different frequency regimes. According to this method, the control system **250** comprises two actuator utilities (not shown), each configured for handling a separate beam combination e.g. each moving one optical element in one of the separate optical branches, or having one of the actuator utilities configured for moving an optical element in the common optical path and the other actuator for moving one optical element in one of the separate optical branches.

In a ‘direct’ configuration, a read beam actuator performs small (in the order of 10 microns) movements to correct (low frequency) offsets that are result of the objective offsets (as detailed above) and a second actuator performs the main tracking of the reference layer.

In an "indirect" configuration, as exemplified in **Fig. 11**, two actuators handle the combined tracking. A drive mechanism (not shown) of the movable mirror **162** responds to the tracking signal generated by a respective actuator utility of the controller **250** in accordance with the data tracking detected by detector **202** (in response to the tracking error indication of the data). A drive mechanism of the objective **142** responds to the tracking signal generated by a respective actuator utility of the controller **250** in accordance with the reference layer tracking detected by detector **230**, to move the objective **142** accordingly. Thus, the combined tracking operates as follows:

(*i*) in response to a reference layer tracking error indication, the objective **142** is actuated to correct the error, and as a result both spots move relative to their respective tracks, correcting the common tracking errors; and

(*ii*) in response to a tracking error signal from the data track (lower bandwidth signal), indicating an offset to a first direction, the reference beam is offset by the actuation of e.g. the mirror **162** according to the amount indicated by the tracking error signal, thereby creating an offset of the first reference beam in the same direction as the offset of the data reading beam (relative to the data track).

As a result, by actuation of the objective **142** in response to the reference layer tracking signal indicating the introduced error, both the reference beam and the data read beam are actuated to move to the second direction to correct the first (read beam) offset.

The coupling of the movement of both beams achieved by the actuation of the mirror **162** creates a process which transfers the majority of the movement of the read spot relative to the data track to the movement of the objective (inducing a movement of both beams). This process of transferring the error to the actuation of common elements (and possibly, to the whole OPU relative to the disk) ensures that the mirror would have to correct basically only the non-common tracking errors. Practically, the mirror is required to actuate the beam in a limited range, which is similar to the possible range of the dynamic offset between the beams.

It should be noted that the data track tracking is a critical task. However, typically the tracking of the data track would provide a weaker signal (lower correction range, lower bandwidth, larger lag, lower SNR etc) compared to the reference layer tracking signal. One of the advantages of using two actuators is the capacity to correct dynamically changing offset between data tracks using the tracking of the reference layer.

Reference is made to **Fig. 14** representing a schematic illustration of another embodiment of an optical system for recording and reading a multilayer three-dimensional optical data carrier. The optical layout of this embodiment is somehow similar to the one of **Fig. 11**; however the recoding/reading beam in this case has a constant divergence. To facilitate understanding, the same reference numbers are used for identifying components that are common in the examples of **Fig. 11** and **Fig. 14**. Refocusing between the layers is achieved by changing the divergence of the reference beam **158**. Accordingly, a variable magnification beam expanding device **261**, similar to beam expander **110** is included in the optical branch **102** of the first or reference beam **158**. The beam expander device **261** is composed of a positive lens **264** and a negative lens **268**. Negative lens **268**, as shown by arrow **272** has a freedom of movement along the optical axis **164** forming a variable magnification beam expander system providing a variable divergence reference beam.

Changes in the convergence or divergence of the first or reference beam **158** would move the beam focal spot **166** along the optical axis **138** within the bulk of the optical carrier **146**. This allows focusing beam **130** in different depth within optical carrier **146**. The read/write branch **106** has a fixed beam expansion ratio and the objective **142** focuses it at the same constant plane with respect to the objective **142**.

Since the reference and the reading/recording beams are optically coupled and coordinated in a determined relation, it is possible to focus the recording/reading beam **130** on a data layer and by a change of the divergence of the reference beam **158** to bring its focal spot **166** to the reference layer **172**. Generally, any data layer may be selected for the determination of the distance to the reference layer **172**. However, the selection of a data layer closer or even next to the reference layer **172** could simplify the task. As soon as the recording/reading beam focal spot **150** is located on a data layer, the beam expander **261** is activated to change the divergence of the reference beam **158** such as to locate the reference spot **166** in the reference layer **172**. For transfer to the next data layer, the objective lens **142** moves axially, as indicated by arrow **280**, to relocate the recording/reading focal spot **150** to the next layer in the volume of the optical carrier **146** by a mechanism of indirect correction.

The axial movement of the objective lens **142** introduces spherical aberration at least into the reference beam focused spot **166**. In order to correct this aberration, a compensation plate **290** is introduced in the optical path of both beams.

Reference is made to **Fig. 15** representing a non-limiting example of the parameters of the lenses controlling the shape and the focusing of the beam reading/recording beam **130** after the collimation. The numerals in the drawings correspond to the description of the optical surfaces geometry in **Table 1** and **Table 2** below. The objective lens of this example has a numerical aperture of 0.7. The drawings take into account optical apertures only.

Table 1: Main parameters for surfaces 4, 5, 6, 7, 13 and 14 as designated in **Fig. 15**.

#	Type	Curvature	Thickness	Glass	Semi-Diameter	Conic
4	EVENASPH	-1.86E-01	1.67E+00	S-NSL3M	2.30E+00	3.22E+00
5	STANDARD	-3.01E-02	4.00E+00		2.80E+00	0.00E+00
6	STANDARD	6.78E-02	4.41E+00	S-NSL3M	5.60E+00	-8.18E+00
7	EVENASPH	-5.13E-02	9.39E+00		5.60E+00	1.97E+00
13	EVENASPH	-2.61E-01	-5.79E+00	S-BAL41M	3.30E+00	-4.76E-01
14	EVENASPH	2.85E-01	-1.24E+00		3.30E+00	-8.59E+00

Table 2: Aspherical parameters for surfaces 4, 7, 13 and14 as designated in **Fig. 15**

#	2nd order	4th order	6th order	8th order	10th order	12th order
4	0	2.97E-03	-4.19E-04	2.82E-04	-5.01E-05	4.84E-06
7	0	-2.18E-04	5.78E-06	-9.85E-08	1.81E-09	-1.91E-11
13	0	7.51E-04	-5.95E-05	2.98E-05	-2.78E-06	1.70E-07
14	0	1.45E-03	7.15E-04	-1.23E-04	9.95E-06	-3.33E-07

For sampled servo, the optical requirements are not extremely stringent, and the reference beam is not required to be fully focused to diffraction limit. The reference beam may reach thus the objective **142** with divergence controlled by conventional optical elements.

In an alternative embodiment, the objective **142** may be rigidly coupled with the folding mirror **162** and actuated together. In this configuration, the folded optical axis of the recording/reading beam and the optical axis of the objective lens are collimated or have a very small divergence angle. Therefore, the offsets caused by the movement of the folding mirror **162** and the objective **142** coupled to the folding mirror **162**, will be substantially reduced or eliminated.

In a further embodiment, the whole system responds to the TES by the movement of the sled or as described in the US patent application No. US2007288947 assigned to the present assignee by a rotating swing arm.

The movement of the actuators for the low frequency distortions and disturbances can be smoothed and planned (e.g. by forward Kalman filtering) so as to minimize the lag between the low frequency error and the response and to control and limit the required movement of the actuators directly controlling the objective, and the offsets between the beams and the objective. This may be facilitated by providing servo marks and track addresses at sufficient frequency. Thus, the sampled servo frequency would preferably be greater than 500, more preferably greater than 1500, and most preferably more than 4500 indications per disk rotation (track revolution). The high quality signal would enable high quality feedback, forward feedback, smooth movement of the optical system and minimize the movement of the objective lens, preventing uncontrolled movement of one of the focal points with respect to the other focal point.

The method and system described enable high-resolution data reading and recording using relatively large low-resolution reference scanning spot. The data is recorded on tracks with a pitch of about 0.8 microns and recorded with a diffraction limited spot.

In an additional embodiment, the servo signal may be embedded as tones in the data layers/tracks to assist the positioning of recording/reading focus in the recording volume. Such marks may be also used as data clocks. A combination of the reference pattern presented with servo data embedded in the data layers/tracks as tones provides a highly redundant reading/recording spot location tracking system. Very accurate clock can be derived from the difference between the frequencies of tones in adjacent tracks.

Moreover, it should be noted that the use of a high numerical aperture of the recording beam incidence onto the addressed plane in the carrier causes recording beam truncation at the sections of the optical carrier proximate to the rim (**116** in Figs. 1A and 1B) and to the mounting bore that receives the rotatable support,. This truncation adversely affects the quality of the recording spot, causes significant power losses, and does not allow full utilization of the optical carrier capacity. Therefore, there is a need in the art, in a non-linear optical storage carrier and a method of recording/reading such carrier that would allow better utilization of the carrier volume and accordingly optimize the storage capacity of the carrier.

Reference is made to **Fig. 16**, representing an optical carrier **100** having a peripheral annular section **136** (i.e. the rim of the carrier) and an inner annular section **140**. The inner annular section **140** is the section that is in contact with the rotational support or spindle. The spindle dimensions, although standardized, limit its utilization. Non-linear three-dimensional storage carriers require high power; high brightness recording/reading spot usually achieved by a high numerical aperture (NA) optical system. **Fig. 17** is a schematic illustration of an optical carrier **100** with recorded layers **144** extended into the peripheral **136** and inner annular section **140**. High numerical aperture of the recording beam **151** causes at the peripheral and inner annular sections of the carrier recording/reading beam truncation. This truncation is especially pronounced at the peripheral section **136**, where the interaction with the rim **116** in addition to the truncation may cause beam reflection as shown by arrow **155**. Because of the beam truncation, sections **136** and **140** are not utilized for recording of data or servo marks, reducing the capacity of the carrier, and the actual size of the recorded layer **120** is smaller than it could be. (For simplicity of illustration, **Figs. 17-19** do not take into account the beam refraction by the material of the carrier.)

It should be noted that a similar problem exists with the reference layers that can be close or away from the reference beam source and accordingly, the reference beam is truncated, although the numerical aperture of the reference beam is typically lower than the one of the recording beam.

Fig. 18 is a schematic illustration of one of the embodiments of a three-dimensional information carrier. Data layers **170** begin at the annular peripheral section **136** (i.e. the most external tracks of said data layers) and have their largest size at the sections of the carrier **180** located close to flat surface **108** facing the source of light or OPU. Data layers **172** located at a distance from surface **108** or OPU have smaller size. Typically, the numerical aperture of the recording optical system will define the difference in the dimensions of the layers, and the incremental change of the size of two adjacent layers should be proportional to the numerical aperture.

As indicated above, the reference layer **132** serves for determination of the coordinates of the recording beam **151** in one or more data layers. Thus, the size of the embossed or optically recorded reference layer **132** should be at least equal to the size of the largest data layer or even larger. As indicated above, the numerical aperture of reference beam **160 (Fig. 17**) is smaller than the numerical aperture of the recording beam **151.** As it may be a limiting factor of the size of the reference layer, it is another advantage of the less stringent requirements of the reference beam focus.

Fig 19 is a schematic illustration of another embodiment of the three dimensional information carrier **191**. Carrier **191** has data layers **170** of variable size interspaced by a number of reference layers **175** having different size. Each of reference layers **175** serves as a source of coordinates for a group of data layers **170**. If the carrier is an assembly of plates having for example, embossed reference layers, the size or radii of the reference layers may be equal. Alternatively, each of reference layers **175** may have the size matching the size of the largest data layer **170** of the group of the data layers associated with the particular reference layer.

The size of data layers decreases stepwise away from the recording beam light source.

In some cases the reference layers (or base layers) are optically recorded (virtual reference layers). Some of these layers may be partially recorded in a formatting process as disclosed in WO2005/015552 or WO2006/111972 assigned to the same assignee and in general, in cases where embossed, printed layers or virtual layers are used for recording. The radii of the layers may be substantially continuous and decrease in a stepwise mode away from the source of the recording light or OPU.

Fig. 20 illustrates a double-sided three-dimensional information carrier **211**. The data layers located close to flat surfaces **108** and **109**, or light sources are larger than the data layers located at a distance from these surfaces or light sources. Their radii are stepwise reduced as they depart from the recording light sources.

Fig. 21 illustrates a three-dimensional information carrier **213** having a symmetrical reference layer structure **215** in which, in addition to improved utilization of the active plate volume (i.e. increase of the storage capacity of the carrier), the reference layers are covered by support plates **218** which may be of material different from the active layer material and which may provide mechanical strength. For example, the support plates may be polycarbonate cover plates enabling an accurate reference layer embossing on the polycarbonate plates. Further details of the layer structure of the exemplified disk are provided in a co-pending PCT application PCT/IL2008/000629 incorporated herein by reference. In addition, it should be noted that thin plate production may allow for more stringent thickness tolerances which, as has been noted above in reference to **Fig. 2**, provide for easier reference layer tracking and keeps the determined relation between the focal spots of the reference beam and the reading/recording beam tighter.

Alternatively, films of about 100 micrometer thickness may be used instead of polycarbonate substrates to provide low variation of the reference layer distance from the surface of the disk, mechanical strength, and an efficient active plate recording and volume usage.

Figs. 22A-22B are schematic illustrations of another embodiment of a three dimensional information carrier. The carrier **281** has a structure of a pre-formatted grid **291** (**Fig. 22A**) of variable size interspaced by group separation intervals of different size. Each of group **294** has an embedded grid with position indication marks that serves as a source of coordinates for a group of data layers **291**. Alternatively, the groups may be defined by virtual base layers **295** (**Fig. 22B**) which are used for stepwise recording of grid and/or data layers **299**. The indication marks may be for example sampled servo marks or tone marks as disclosed in WO2005/015552 and WO 2006/111973 assigned to the same assignee.

The present carrier and the recording and reading method allow better utilization of the volume of the carrier available for data storage. The method enables a larger carrier capacity and does not complicate production or exploitation of the carrier.

CLAIMS

1. A method for use in at least reading data in a three-dimensional optical data carrier having at least one reference layer and at least one data layer, said method comprising:

a) focusing a recording/reading beam and a reference beam onto said optical carrier through a common optical element creating two focal spots in different optical planes; and,

b) controlling the movement of at least said optical element such that the focal spot of said reading/recording beam tracks a data track in an addressed data layer, said controlling comprising identifying a change in an error signal from the reference layer during the reference beam tracking the reference layer, thereby adjusting a tracking target for control of the movement of the reference beam.

2. The method of claim 1, wherein said error signal from the reference layer has a spatial frequency bandwidth larger than that of an error signal from the data layer, thereby enabling said identification of the change in the error signal from the reference layer.

3. The method of claim 1 or 2, comprising at least partially correcting for an error of the reference beam focal position.

4. The method of any one of the preceding Claims, wherein said controlling comprising keeping axes of said common optical element and the recording/reading and the reference beams to be coaxial.

5. The method of any one of the preceding Claims, wherein said recording/reading focal spot and said reference focal spot are coordinated in a determined relation, said controlling comprising using location of the reference focal spot in said reference layer to locate the recording/reading beam focal spot in a target location in the optical data carrier.

6. The method of any one of the preceding Claims, wherein said controlling of the movement of said optical element is achieved by at least one of the followings: (a) keeping axes of the reading/recording beam and the reference beam parallel to the optical axis of the optical element; and (b) deflecting or offsetting the reference beam in a radial or tangential direction.

7. A method for use in at least reading data in a three-dimensional optical data carrier having at least one reference layer and at least one data layer, said method comprising:

a) focusing a recording/reading beam and a reference beam onto said optical data carrier through a common optical element creating a recording/reading focal spot and a reference focal spot in different optical planes; and;

b) controlling position of said reference focal spot and reading/recording focal spot by manipulation of an optical path common to both recording/reading and reference beams and by at least one additional manipulation of optical path of one of said beams.

8. The method of Claim 7, wherein said manipulation of the optical path common to both beams comprises actuating an objective lens system to locate said reference focal spot, tracking a reference track in the tangential direction; and said additional manipulation of one of the optical paths comprises actuating a mirror in said one of the optical paths to locate said reference focal spot on the reference track in the radial direction.

9. The method of Claim 8, wherein said controlling of the movement of said reference beam and reading/recording beam is provided by coupling said objective lens system to a mirror and actuating said objective lens system and said mirror together.

10. The method of Claim 1 or 7, wherein said controlling of the movement of at least one common optical element comprises estimating an anticipated required movement of said common optical element.

11. A method for use in at least reading data in a three-dimensional optical data carrier comprising at least one reference layer associated with one or more data layers and having a reference pattern arranged along reference tracks, the method comprising tracking said reference pattern by a reference beam having a focal spot size exceeding a pitch between two adjacent tracks in the reference layer.

12. A three-dimensional optical data carrier comprising a recording volume associated with at least one reference layer having reference patterns indicative of reference information pieces arranged along reference tracks, wherein said reference patterns are separated from servo patterns located on adjacent tracks in a radial direction, said servo patterns having at least one of the following arrangement: (i) with no angular overlap between the servo patterns located on adjacent tracks; (ii) said separation between the servo patterns of adjacent tracks includes separation in a frequency domain; and (iii) said separation between the servo patterns of adjacent tracks includes separation in a signal domain.

13. The optical data carrier of claim 12, wherein said reference patterns contain at least one of the following: tracking information, clock for data recording and retrieving, carrier format information such as layer, track sectors numbers.

14. The carrier of claim 12 or 13, wherein said reference patterns are embedded as tones or Baker coded or Complementary Code Keying coded.

15. The carrier of any one of claims 12 to 14, wherein said recorded volume comprises at least one data layer including servo patterns embedded as tones in the data layer.

16. The carrier of claim 12, wherein said reference patterns are configured to provide a smooth substantially continuous transition between tracks in the reference layer.

17. A three dimensional optical data carrier comprising a recording volume with a plurality of data layers recorded therein, each data layer comprising data pattern arranged along data tracks, a radius of the most external track decreasing from the upper surface of the recording volume towards the lower surface thereof in a direction of propagation of incident light.

18. The data carrier according to claim 17, comprising at least one reference layer comprising a reference pattern arranged along reference tracks, a distance between the most external reference tracks of the reference layer and an external surface of said volume determining numerical aperture of a reading/recording beam to be used for recording/reading data in/from a data layer coupled to said reference layer and the maximal recording radius in said data layer.

19. A three dimensional optical data carrier comprising at least one reference layer and at least one data layer, wherein the radii of said layers decrease stepwise with the distance from an upper surface of the carrier with respect to a direction of incident light propagation during recording/reading processes.

20. The carrier according to claim 18 or 19, having a double-sided configuration.

21. The carrier according to claim 19, wherein said data layers are arranged in groups, and are interspaced by group separation intervals.

22. The carrier according to claim 21, wherein the groups are defined by virtual base layers.

23. An optical system for recording and/or reading in a three-dimensional optical data carrier having at least one reference layer and at least one data layer; said system comprising:

a) a light source system generating a reference beam and a recording/reading beam;

b) a beam combiner combining said beams such that said beams being coaxial and having at least a common optical path section;

c) a common optical element located on the common optical path section; and

d) a control unit configured and operable for controlling movement of said common optical element such that a focal spot of said reading/recording beam tracks a data track in an addressed data layer, said controlling comprising identifying a change in an error signal from the reference layer during the reference beam tracking the reference layer, thereby adjusting a tracking target for control of the movement of the reference beam.

24. The system of Claim 23, wherein said common optical element is an objective lens unit operable to locate said reference focal spot, tracking the reference track, in the radial direction and in the tangential direction.

25. An optical system for recording and/or reading in a three-dimensional optical data carrier having at least one reference layer and at least one data layer; said system comprising:

a) a light source system for generating a reference beam and a reading/recording beam;

b) a beam combiner combining said beams such that said beams are coaxial and have at least a common optical path section;

c) a common optical element located on the common optical path section, wherein movement of said optical element being used for controlling the position of both beams;

d) at least one additional optical element located in one of the separate optical paths of said beams, movement of said additional optical element being used for controlling position of one of said beams.

26. The system of Claim 25, wherein said common optical element is an objective lens system actuated to locate the reference beam, tracking the reference track, in the tangential direction; and said additional optical element is a mirror actuated to locate said reference beam on the reference track in the radial direction.

27. The system of Claim 25, comprising: a detector providing a feedback signal indicative of the position of at least one of the beams, and a control unit configured for receiving said feedback signal and generating a correction signal, said correction signal affecting the movement of at least one of the following: said common optical element, said additional optical element and an optical pickup unit.

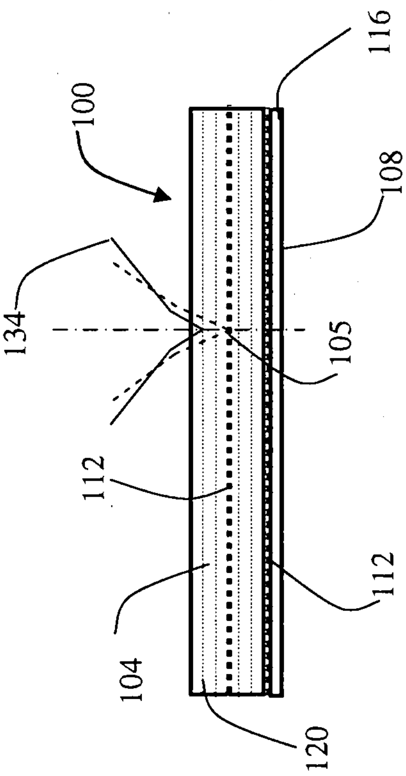
100
116
108
134
105
112
112
104
120

FIG. 1B

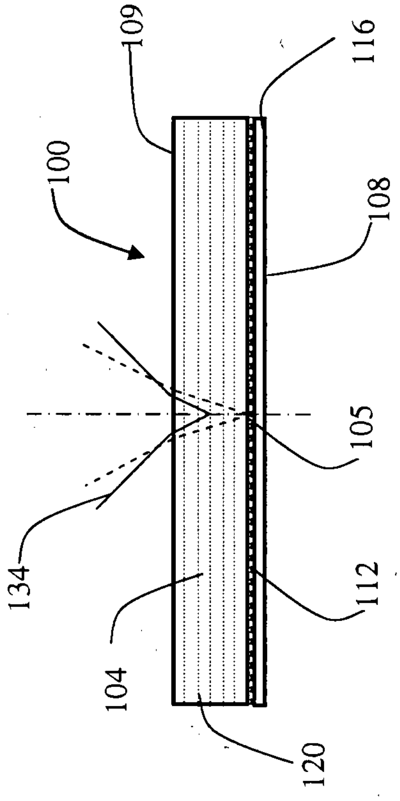
109
116
100
108
105
134
112
104
120

FIG. 1A

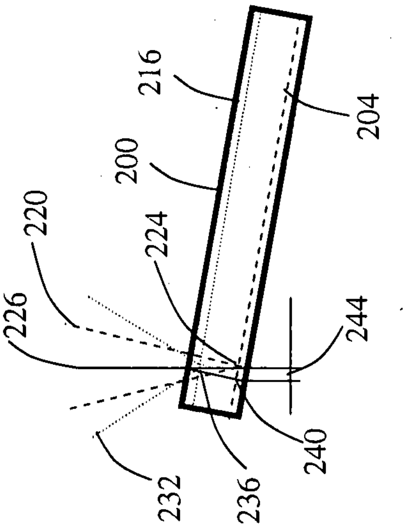

FIG. 2B

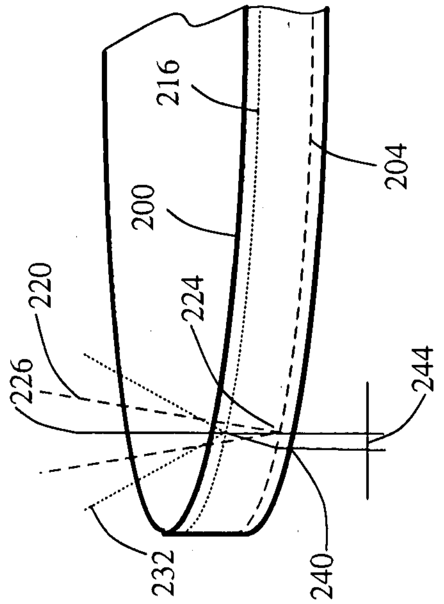

FIG. 2C

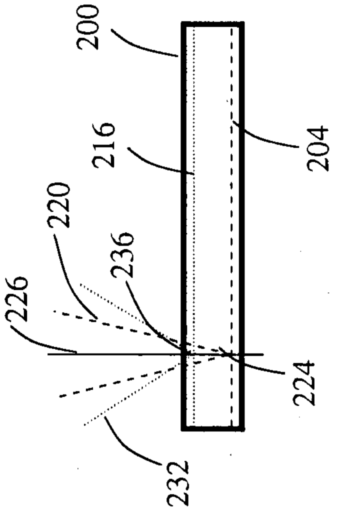

FIG. 2A

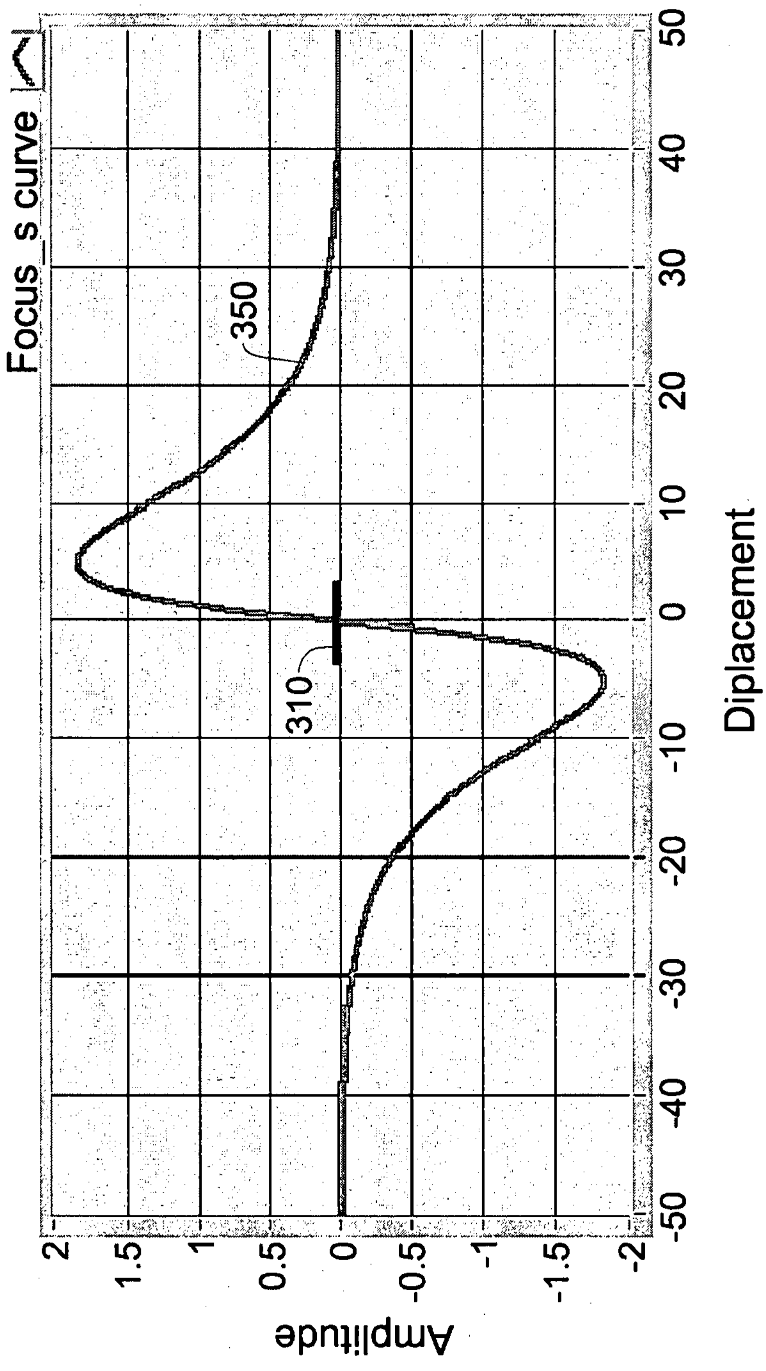
Focus_s curve
350
310
Amplitude
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-50
-40
-30
-20
-10
0
10
20
30
40
50
Diplacement

FIG. 3

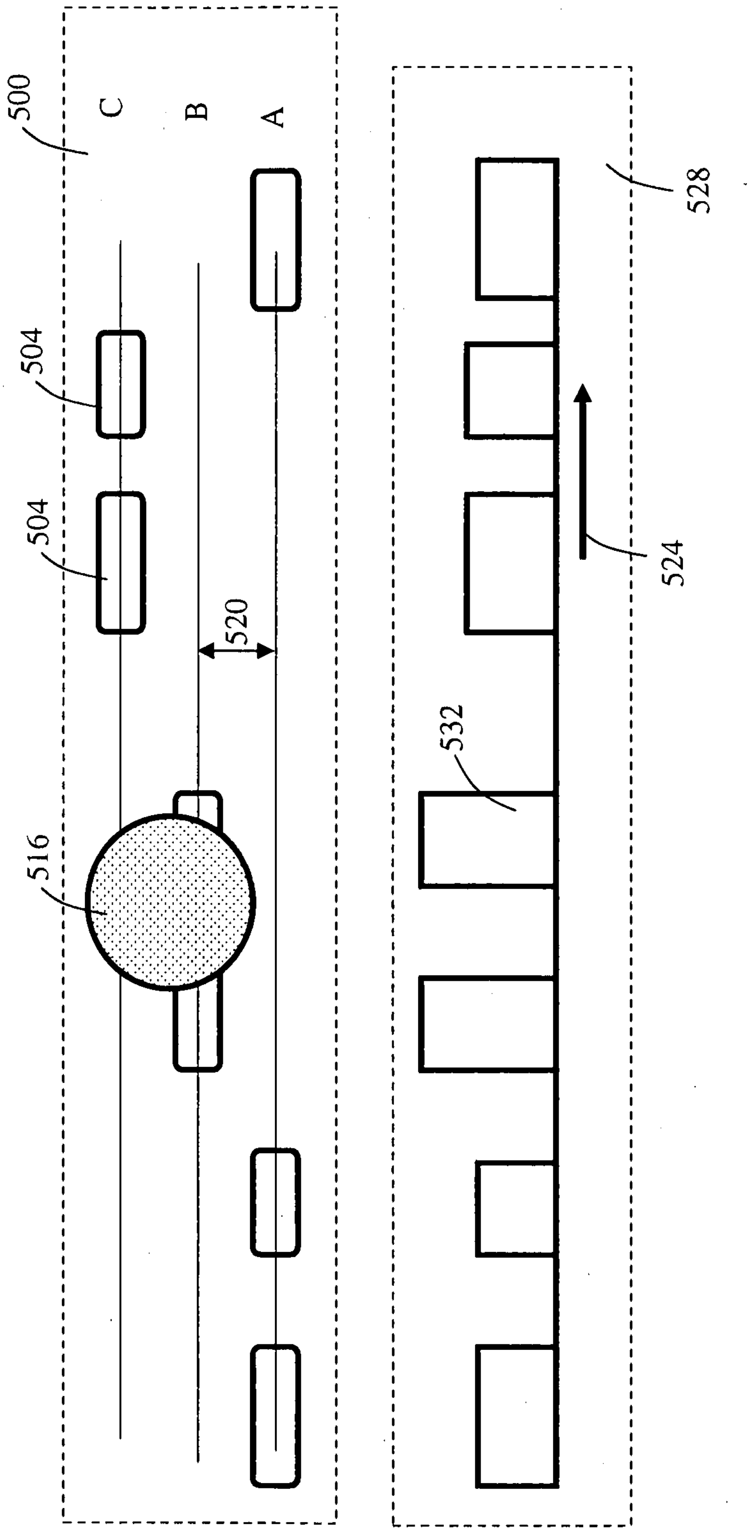

FIG. 4A

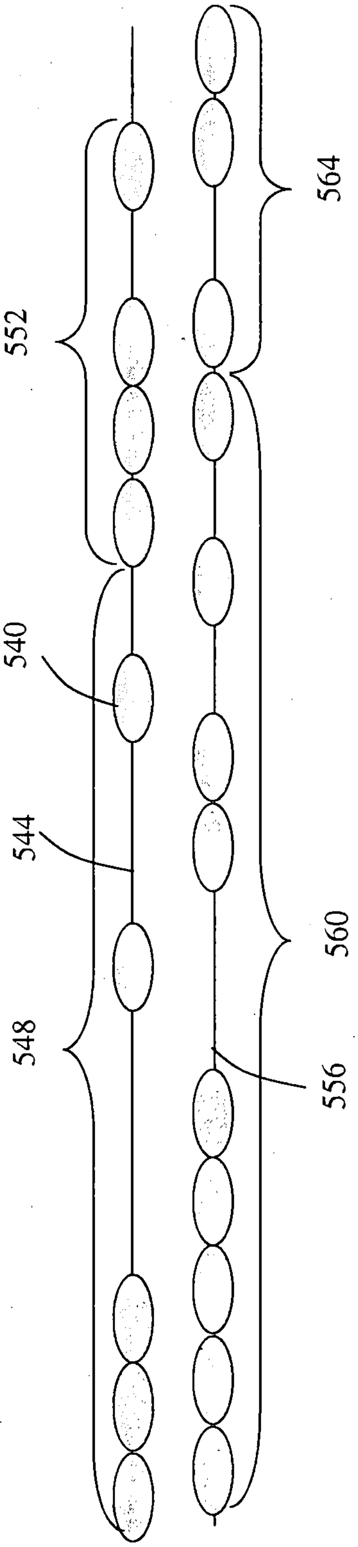

FIG. 4B

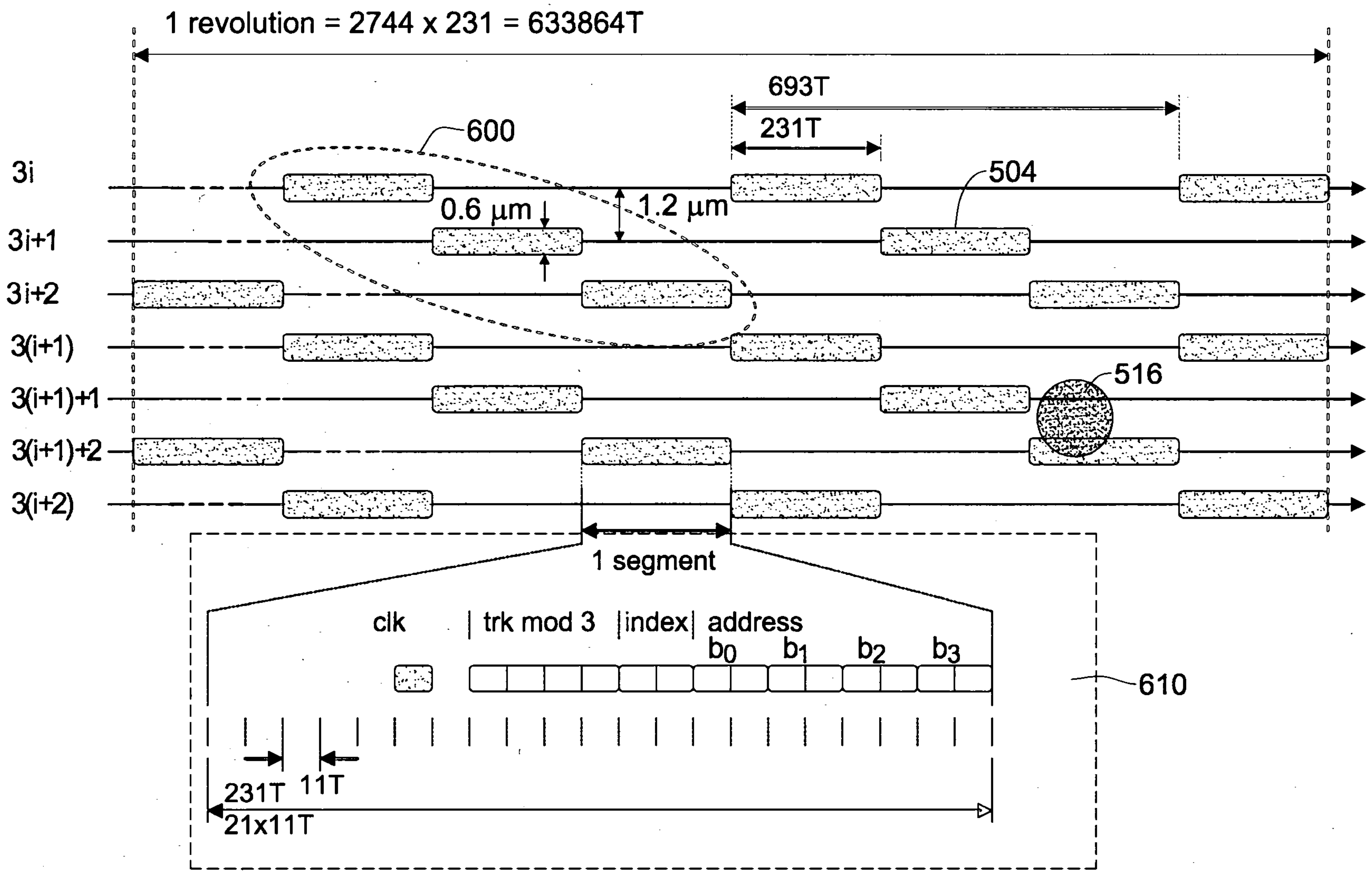
1 revolution = 2744 x 231 = 633864T
693T
231T
600
504
0.6 μm
1.2 μm
3i
3i+1
3i+2
3(i+1)
3(i+1)+1
3(i+1)+2
3(i+2)
516
1 segment
clk
trk mod 3
index
address
b_0
b_1
b_2
b_3
610
231T
11T
21x11T

FIG. 5

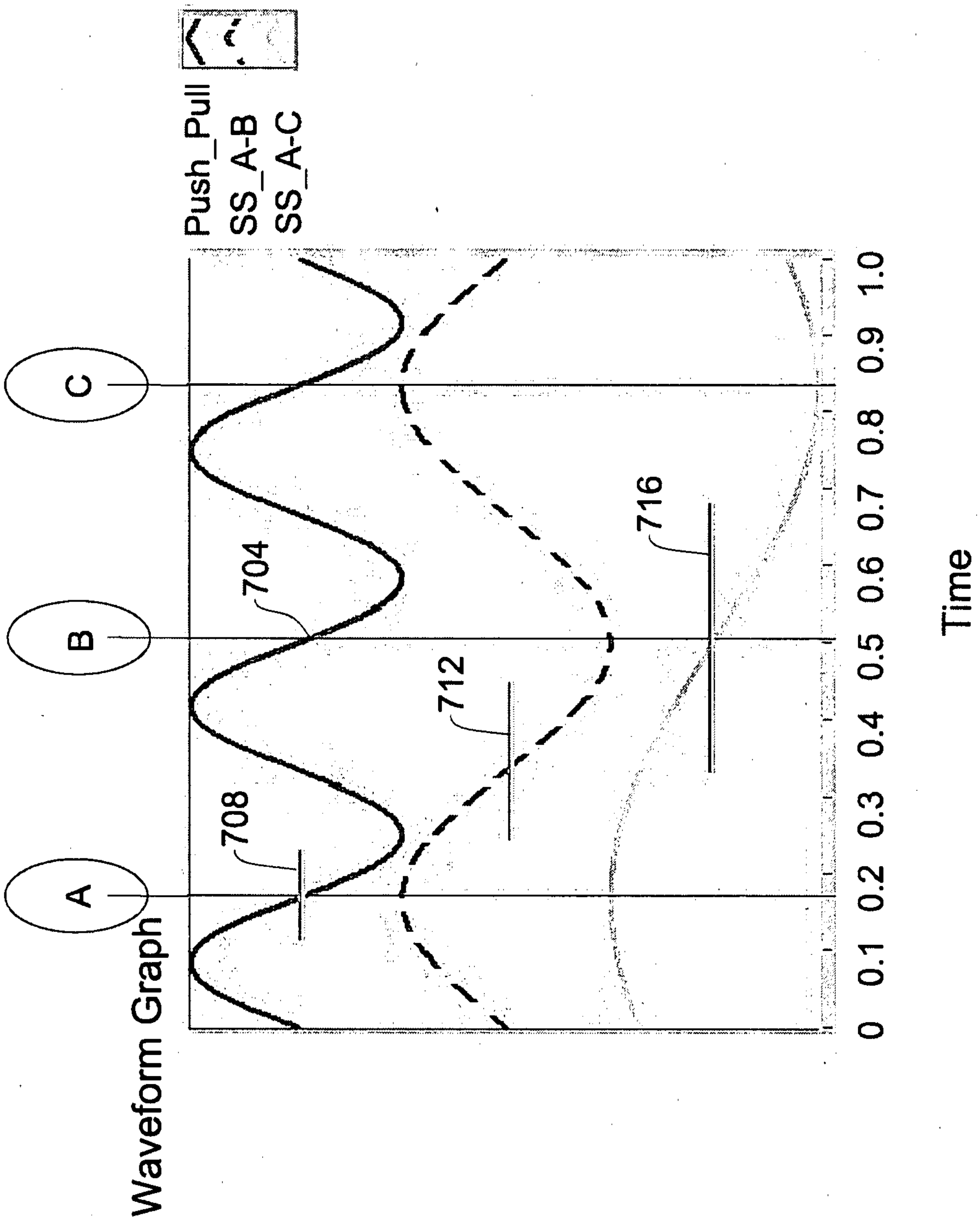
Waveform Graph
Push_Pull
SS_A-B
SS_A-C
A
B
C
708
704
712
716
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Time

FIG.6

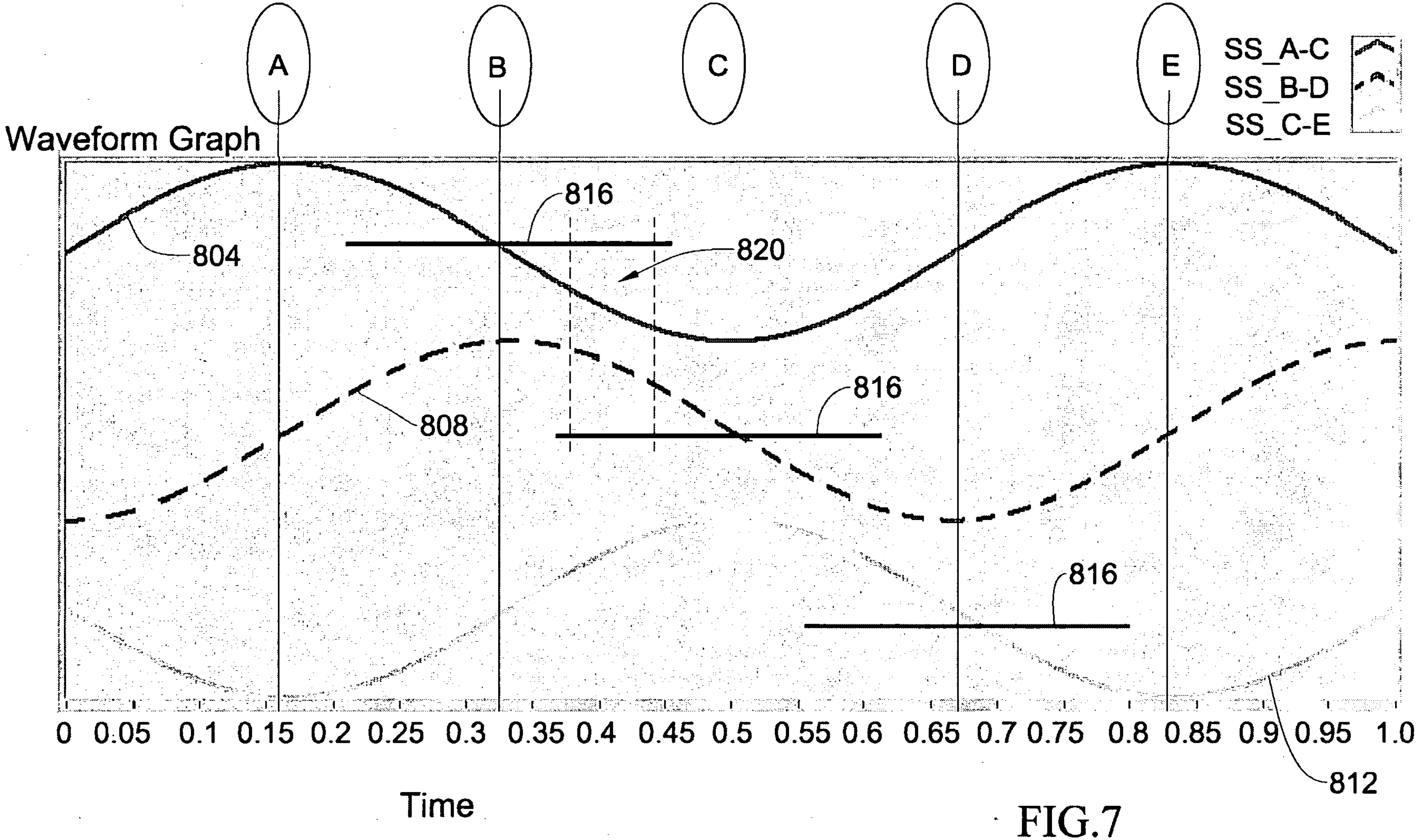
A
B
C
D
E
SS_A-C
SS_B-D
SS_C-E
Waveform Graph
816
820
804
808
816
816
812
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1.0
Time

FIG.7

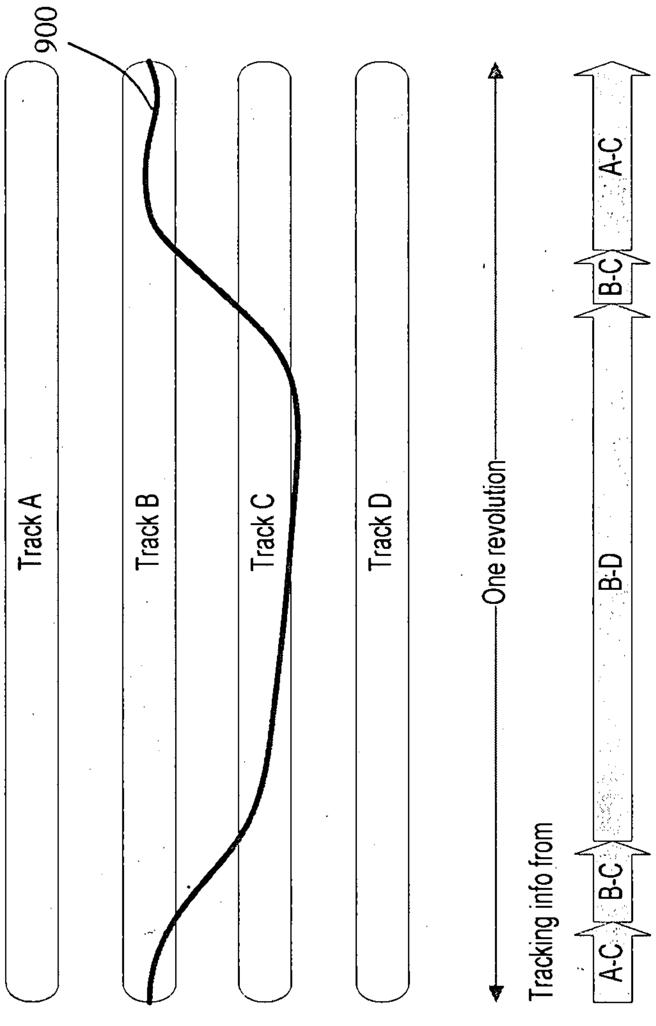
900
Track A
Track B
Track C
Track D
One revolution
Tracking info from
A-C
B-C
B-D
B-C
A-C

FIG. 8

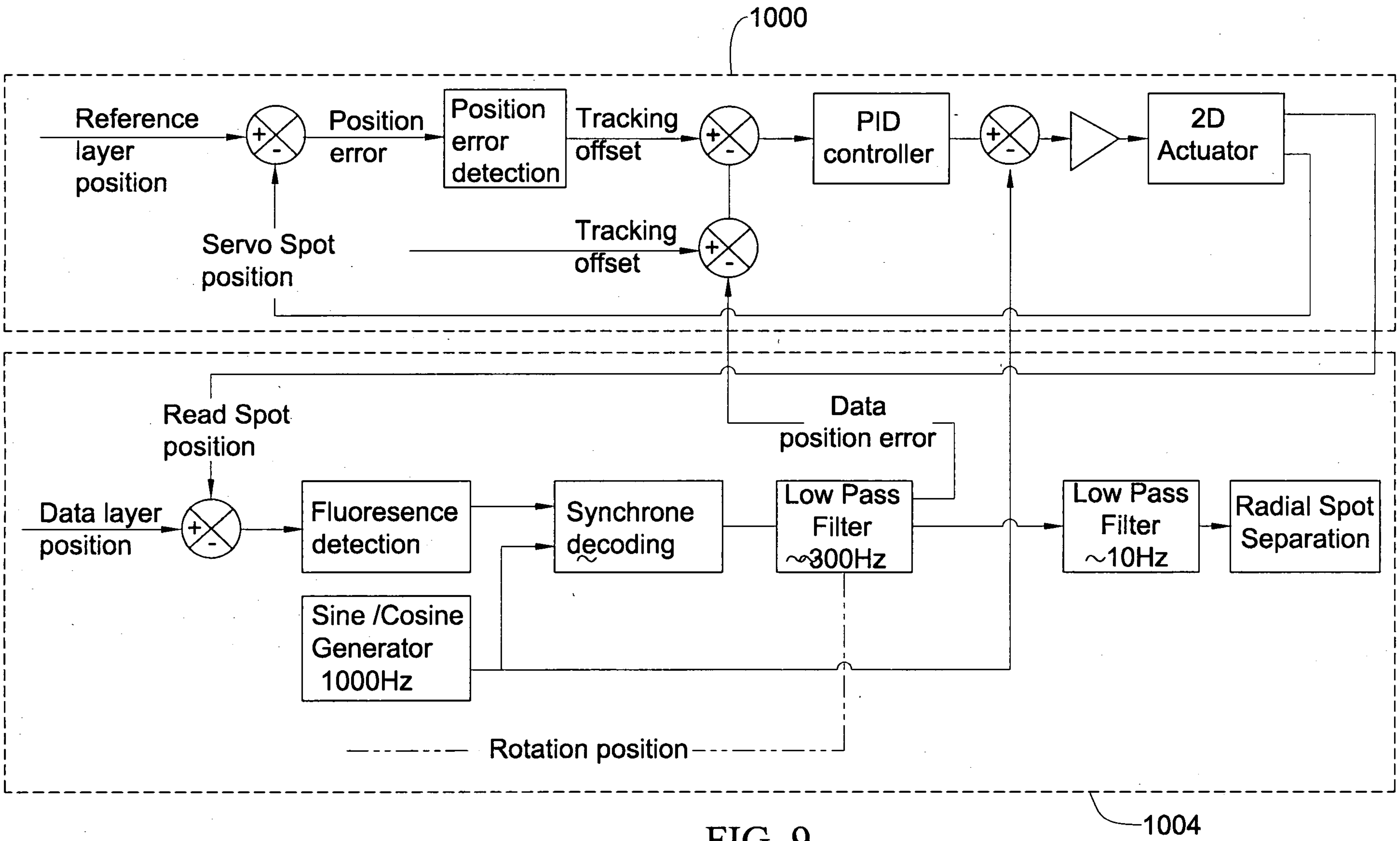
1000
Reference layer position
+
-
Position error
Position error detection
Tracking offset
+
-
PID controller
+
-
2D Actuator
Servo Spot position
Tracking offset
+
-
Read Spot position
Data position error
Data layer position
+
-
Fluoresence detection
Synchrone decoding
Low Pass Filter ~300Hz
Low Pass Filter ~10Hz
Radial Spot Separation
Sine /Cosine Generator 1000Hz
Rotation position
1004

FIG. 9

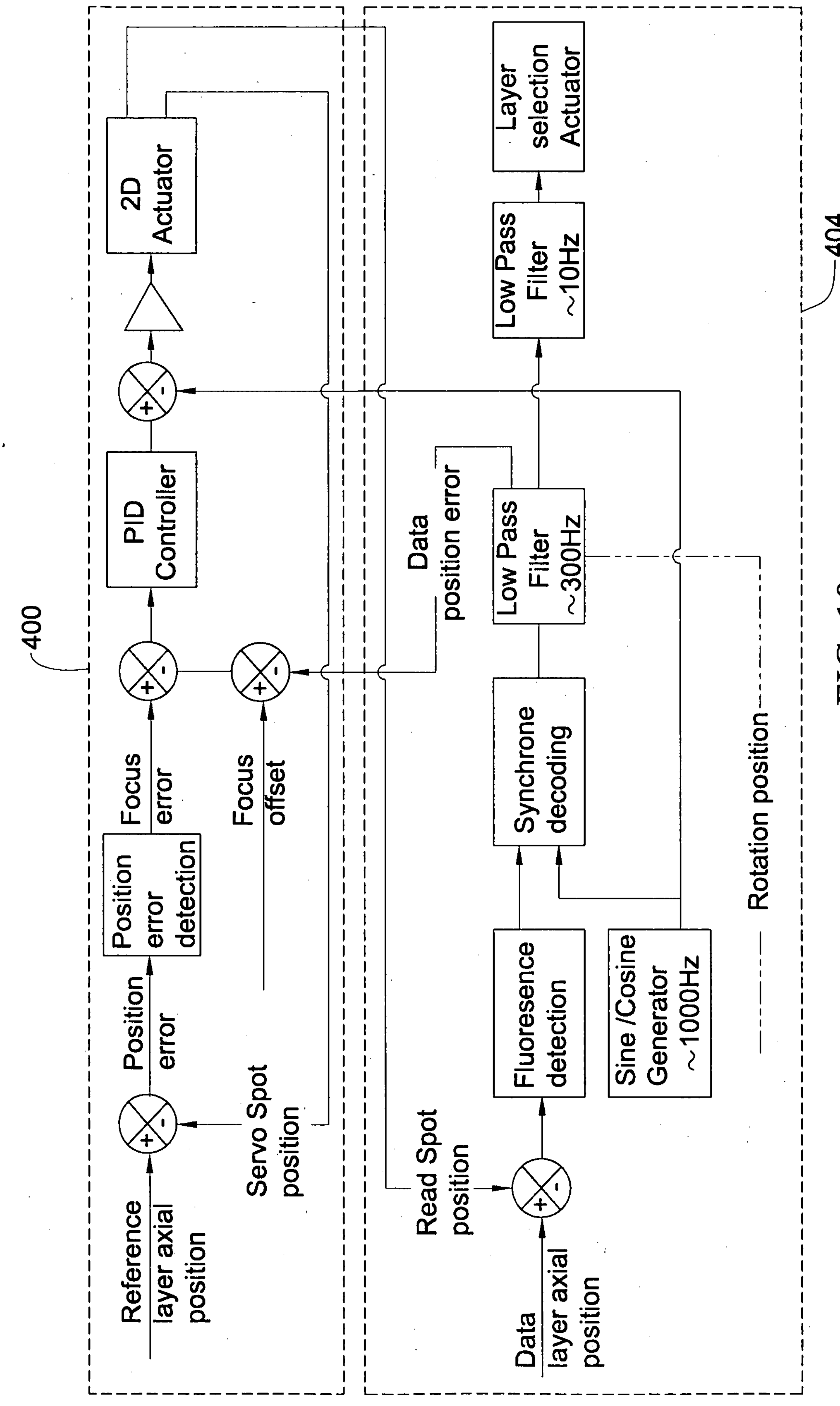
400
Reference layer axial position
Servo Spot position
Position error
Position error detection
Focus error
Focus offset
PID Controller
2D Actuator
Data position error
Read Spot position
Data layer axial position
Fluoresence detection
Sine /Cosine Generator ~1000Hz
Synchrone decoding
Low Pass Filter ~300Hz
Low Pass Filter ~10Hz
Layer selection Actuator
Rotation position
404
+
-

FIG. 10

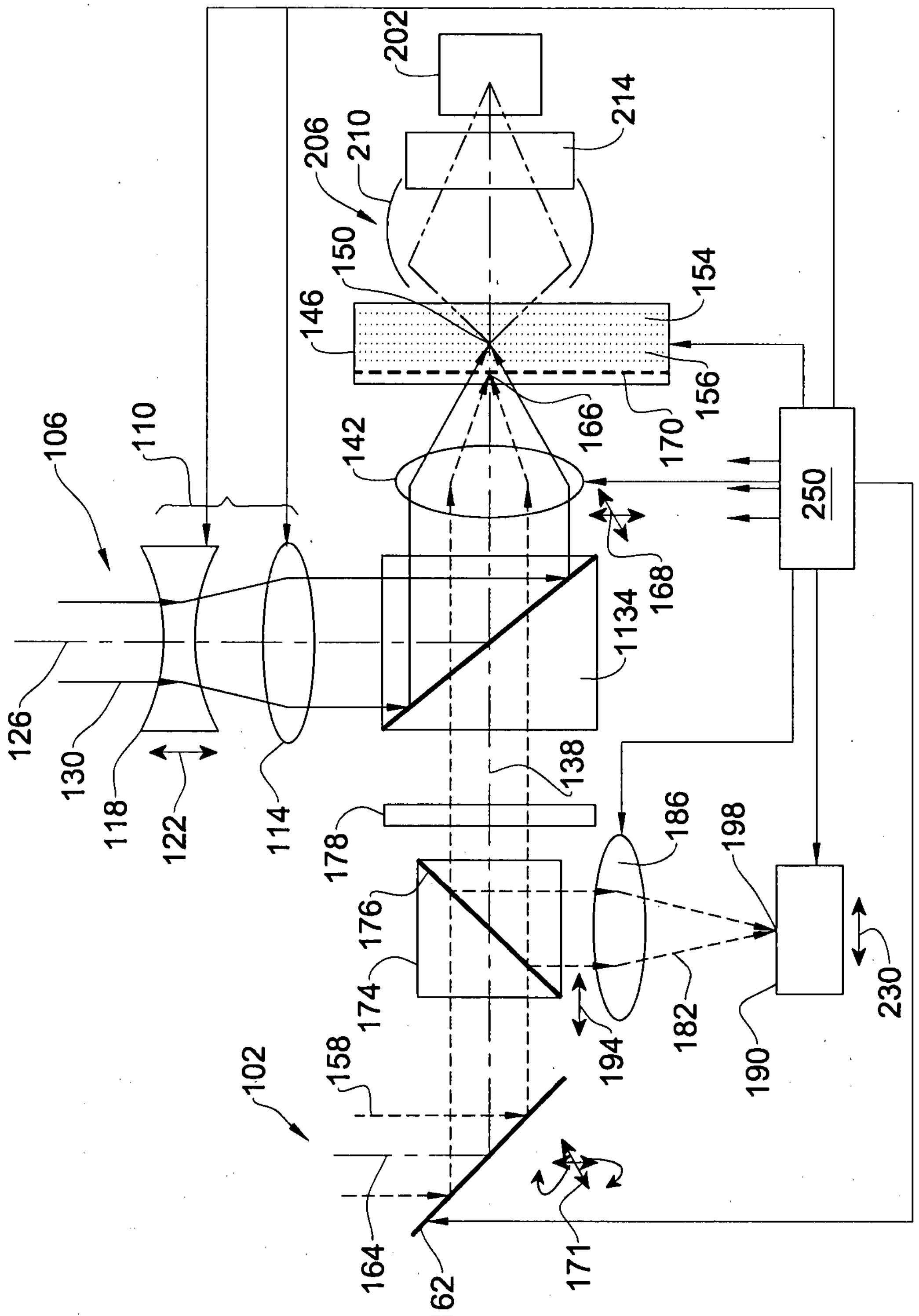
106
110
126
130
118
122
114
202
206
210
214
150
146
154
156
166
170
142
168
1134
250
138
178
176
174
186
198
194
182
190
230
102
158
164
162
171

FIG. 11

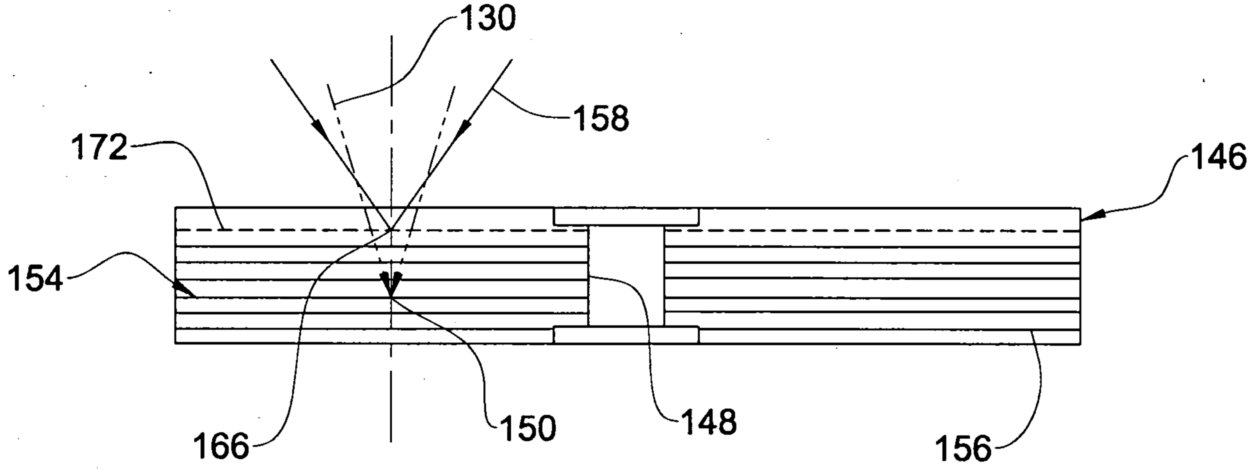

FIG. 12

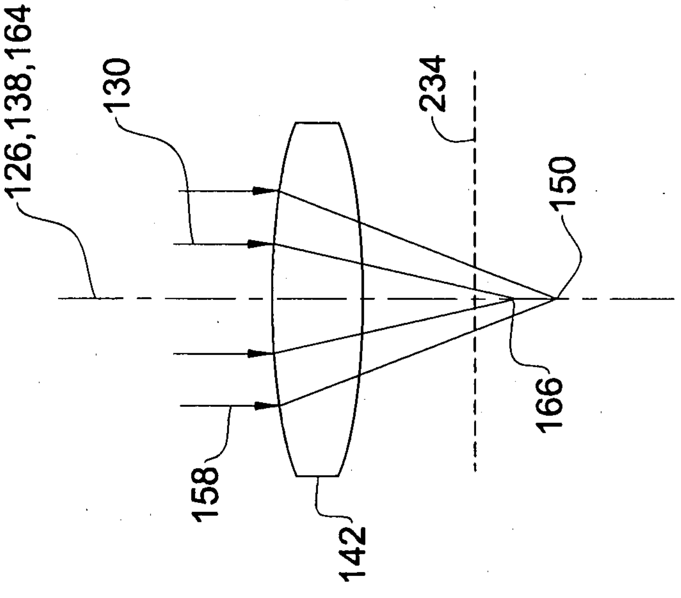

FIG. 13A

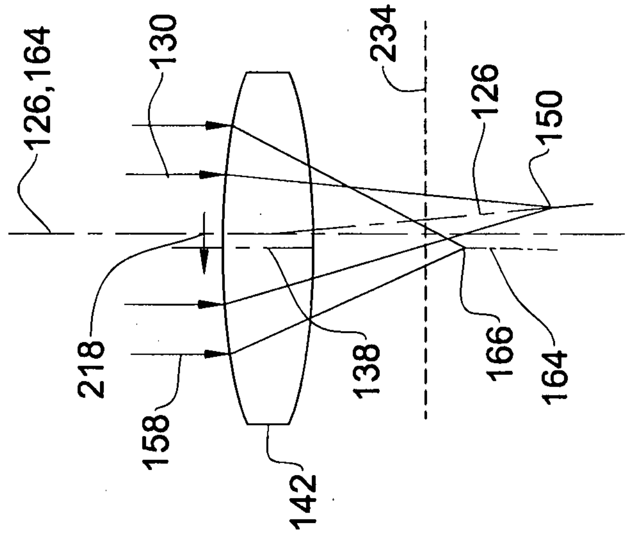

FIG. 13B

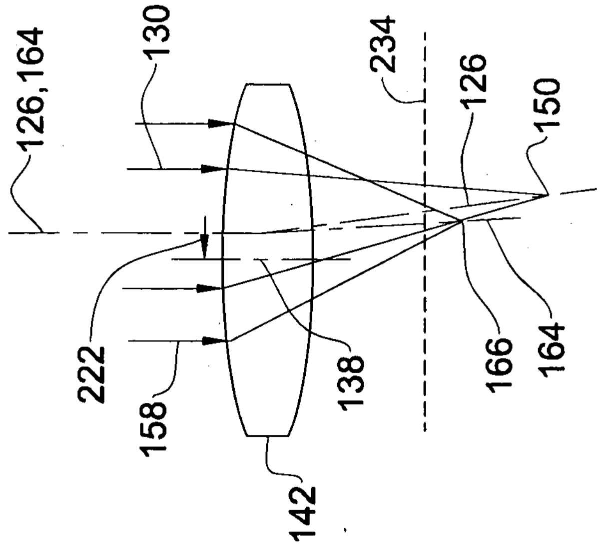

FIG. 13C

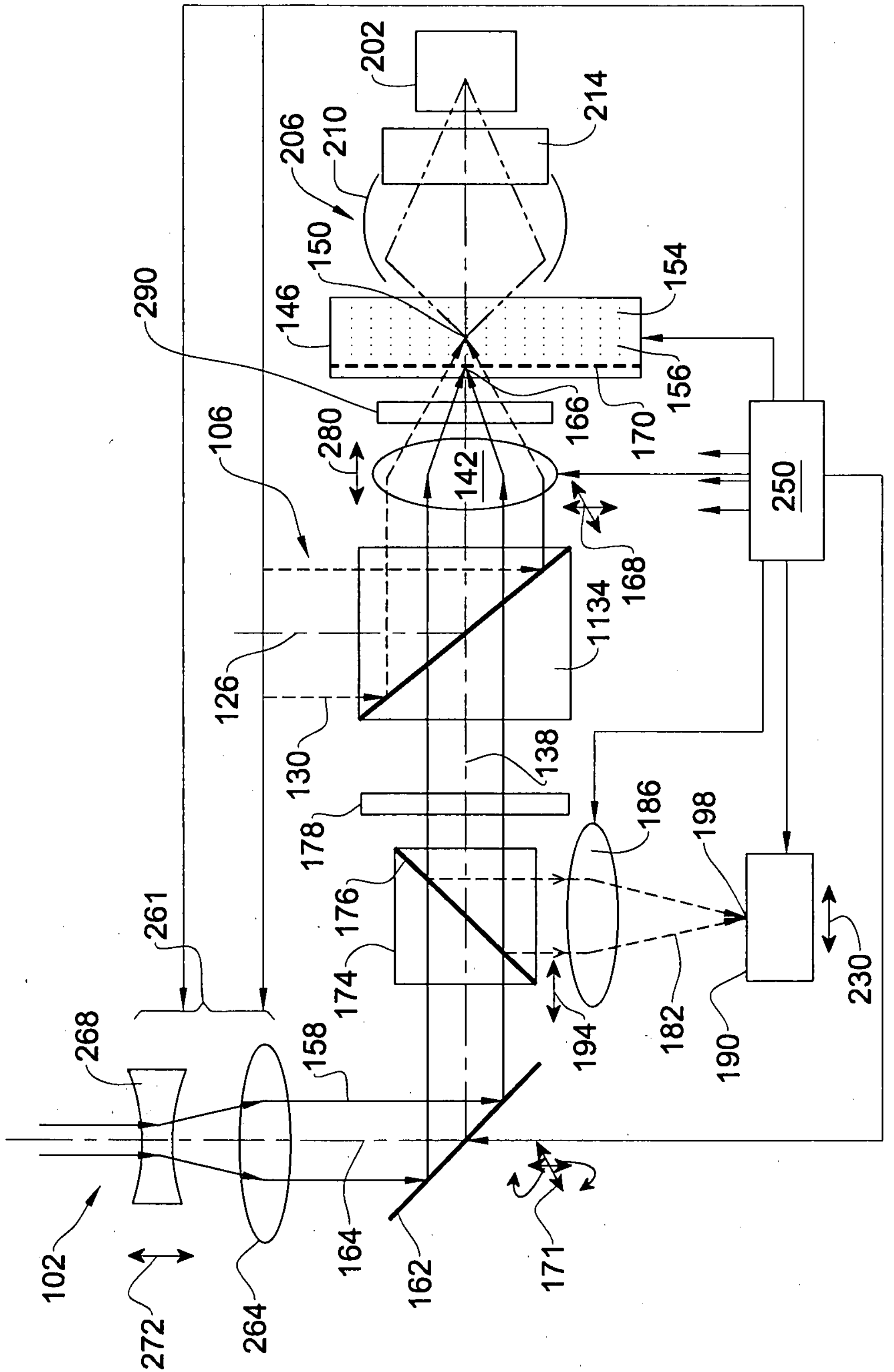
102
272
268
264
164
158
162
171
261
174
176
178
194
182
190
230
198
186
130
126
138
1134
168
106
280
142
250
290
166
170
156
146
150
154
206
210
214
202

FIG. 14

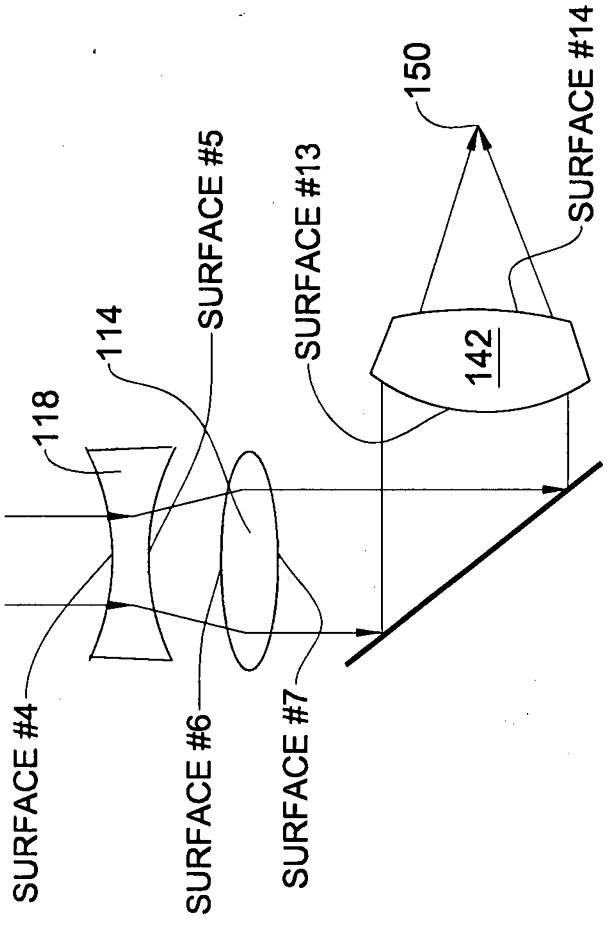
SURFACE #4
SURFACE #6
SURFACE #7
118
114
SURFACE #5
SURFACE #13
142
150
SURFACE #14

FIG. 15

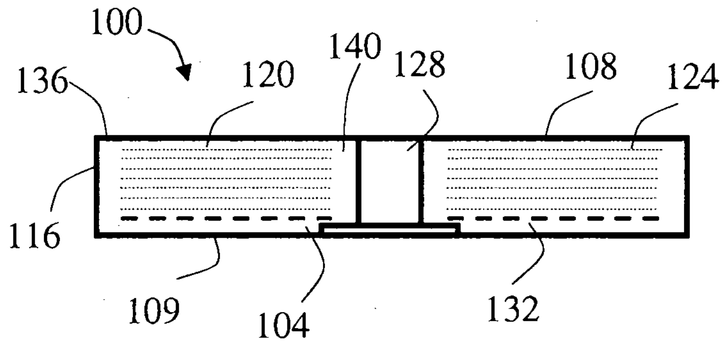
100
136
120
140
128
108
124
116
109
104
132

FIG. 16

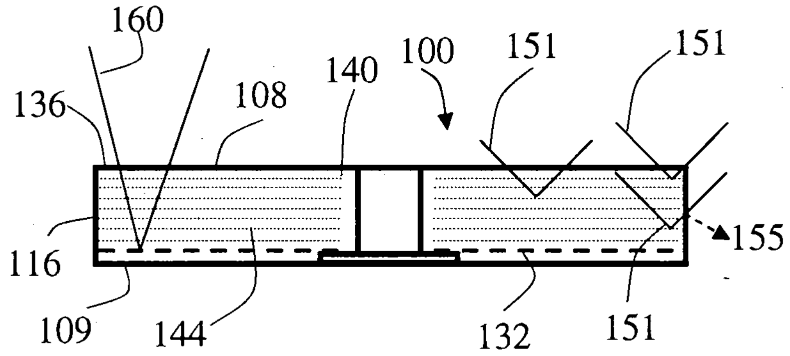
160
136
108
140
100
151
151
116
155
109
144
132
151

FIG. 17

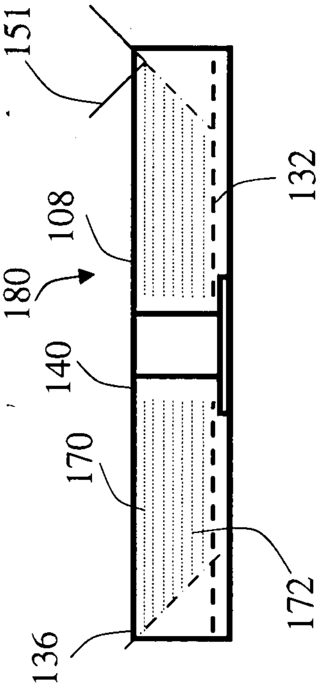

FIG. 18

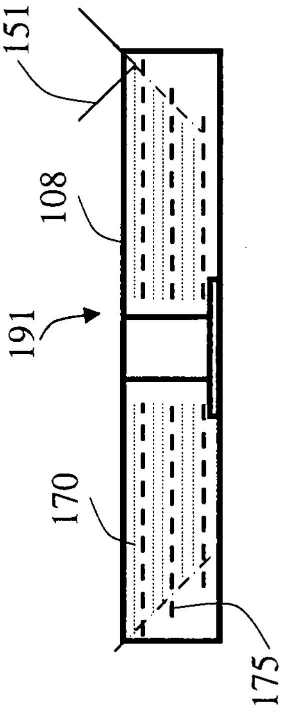

FIG. 19

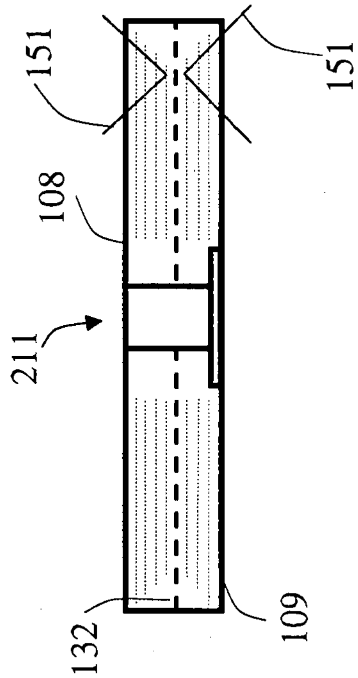

FIG. 20

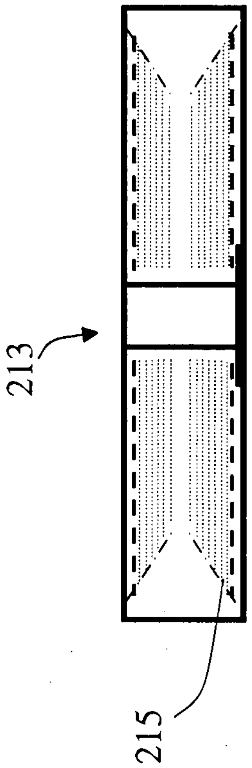

FIG. 21

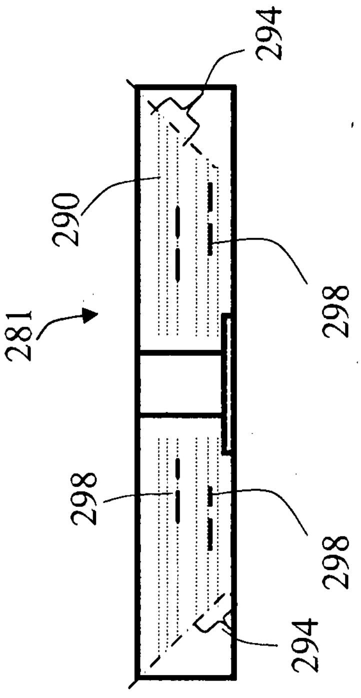

FIG. 22A

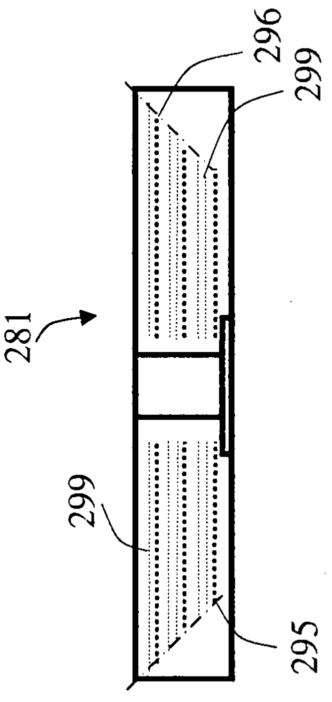

FIG. 22B