Title: FOCUS ERROR SIGNAL GENERATION USING CONFOCALLY FILTERED DETECTION

Abstract: A focus error signal generator device including first and second optical lenses (136 and 142) disposed in the respective paths of first and second light beams (122 and 124) derived from the return read beam (130) wherein the first and second optical lens (136 and 142) have corresponding points of focus (150), and first and second detectors (140 and 146) disposed in the corresponding paths of the first and second light beams (122 and 124) located after the points of focus (150). First and second pinholes (126 and 128) are disposed in the corresponding paths of the first and second light beams (122 and 124) after the corresponding optical lens (136 and 142) and before the corresponding detector (140 and 146), and an electrical differencing circuit (148) having inputs to the first and second detectors (140 and 146) and an output to an optical head servo system.
For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.
SPECIFICATION

FOCUS ERROR SIGNAL GENERATION USING
CONFOCALLY FILTERED DETECTION

1. Field of the Invention

The present invention relates to the generation of focus error signals for use in the auto-focussing of optical data storage and retrieval systems. More specifically, the present invention relates to a method and apparatus for generating focus error signals based upon confocally filtering a return read beam having two distinct focal planes through a pinhole and deriving a focus error signal based upon the difference in location of the two focal planes in relation to the location of the pinhole.

2. Background

As a prerequisite to successful optical data storage, the optical head containing the focussing optics must be positioned properly within the storage layer of the optical storage medium. When recording or retrieving optical data it is essential that the optical head be positioned precisely at the desired storage point. Proper positioning of the optical head is typically carried out through auto-focusing techniques implemented by a servo system within the optical head. The signals that drive the auto-focussing process are generated by Focus Error Signal (FES) generator devices that are incorporated into the overall scheme of the optical delivery and detection system.

FES generator devices within optical delivery and detection systems have typically only been required to provide signals in instances where data storage is limited to a single or to a few layers within the optical storage medium. Current technology is generally limited to performing optical data storage on a minimal number of layers within the optical storage medium. In most instances, these layers have, generally, about 60 micron separation between adjacent layers. When such a pronounced distance separates the layers, the current FES generator devices are sufficient because layer separation does not present an issue.
However, as technological advances in data storage are made, the capability presents itself to store data on numerous layers within the storage medium. See for example U.S. Patent Application Ser. No. 09/016,382 filed on January 30, 1998, in the name of inventor Hesselink et. al. (assigned to the assignors of the present invention) entitled “Optical Data Storage by Selective Localized Alteration of a Format Hologram” for a detailed discussion of layer definition by format hologram grating structures. That disclosure is hereby expressly incorporated herein by reference as if set forth fully herein.

When data storage is performed on multiple layers the distance separating such layers is minimized. As the separation between the layers shrinks to the about 3 to about 10 micron ranges, the ability to separate out these layers during focus error signal detection becomes more of a concern. The prior art methods are not capable of delineating between layers that are packed so closely together. The present invention serves to provide an FES generator device and a method for FES generation that is capable of differentiating the layers in optical storage medium that have numerous tightly packed layers separated at distances comparable to the Rayleigh range of the illuminating beam. Additionally, the FES generator device and the method of FES generation described herein can be used with a data storage device having multiple storage layers residing at discrete media layers spaced at distances that can be comparable to or substantially longer than the Rayleigh range.

**BRIEF DESCRIPTION OF THE INVENTION**

Briefly, and in general terms, one embodiment of the present invention comprises an improved focus error signal generator device including first and second optical lenses disposed in the respective paths of first and second light beams derived from the return read beam wherein the first and second optical lens have corresponding points of focus, and first and second detectors disposed in the corresponding paths of the first and second light beams located after the points of focus. First and second pinholes are disposed in the corresponding paths of the first and second light beams after the corresponding optical lens and before the corresponding detector, and an
electrical differencing circuit having inputs to the first and second detectors and an output to an optical head servo system.

Another aspect of the present invention comprises a method for focus error signal generation including the steps of focusing first and second light beams derived from a return read beam at corresponding first and second points of focus; providing for first and second detectors disposed in the path of corresponding first and second light beams after corresponding first and second points of focus; providing for first and second pinholes in the path of corresponding first and second light beams; and generating a focus error signal related to the difference between the output of the first detector and an output of the second detector.

Additionally, another embodiment of the present invention comprises an optical data delivery and detection system comprising a laser source emitting a light beam, an optical head that receives the light beam, optical lenses within the optical head that focus the light beam on an optical storage media, a data detector that receives the light beam on the beam’s return path and provides data signals and a focus error generator device.

Another embodiment of the present invention comprises an improved focus error signal generator device including an optical lens disposed in the path of a return read beam and a birefringent plate disposed in the path of the return beam of light after the optical lens, wherein the birefringent plate provides for a first and second focal plane of corresponding first and second polarization. A pinhole is disposed in the path of the return read beam after the birefringent plate and in close proximity to first and second focal planes. A polarizing beam splitter is positioned after the second focal plane and serves to split the return read beam into two light beams of first and second polarization. First and second detectors are disposed in the path of corresponding first and second polarization light beams. The detectors are connected to the inputs of an electrical differencing circuit that has an output to an optical head servo system.

Another aspect of the present invention comprises a method for focus error signal generation including the steps of focusing a return read light beam, providing
for a birefringent plate disposed in the path of the read light beam that results in a first and second focal plane of corresponding first and second polarizations, providing for a pinhole disposed in the path of the read light beam after the birefringent plate and in close proximity to the first and second focal planes, providing for a polarizing beam splitter disposed in the path of the read light beam after the second focal plane that splits the read light beam into first and second polarization light beams, providing for first and second detectors, respectively, in the paths of the corresponding first and second polarization light beams, and generating a focus error signal related to the difference between the output of the first detector and an output of the second detector.

Additionally, another embodiment of the present invention comprises an optical data delivery and detection system comprising a laser source emitting a light beam, an optical head that receives the light beam, optical lenses within the optical head that focus the light beam on an optical storage media, a data detector that receives the light beam on the beam's return path and provides data signals and a focus error generator device.

Another embodiment of the present invention comprises an improved focus error signal generator device including two optical lenses in series; a birefringent optical lens followed by a standard optical lens, the lenses being disposed in the path of a return read beam wherein the birefringent optical lens has a first and second focal plane and the standard optical lens serves to minimize the focal lengths. A pinhole is disposed in the path of the return read beam in close proximity to the first and second focal planes. A polarizing beam splitter is positioned after the second focal plane and serves to split the return read beam into two light beams of polarization associated with the first and second focal planes. First and second detectors are positioned so as to read the two light beams signals output from the polarizing beam splitter and the detectors are connected to an electrical differencing circuit having an output to an optical head servo system.

Another aspect of the present invention comprises a method for focus error signal generation including the steps of focussing a return read beam at first and second points of focus; providing a pinhole in the path of a return read beam located in
close proximity to the first and second points of focus; providing for a polarizing beam splitter disposed in the path of the return read beam after the second point of focus that splits the return read beam into first and second polarization beams; providing for first and second detectors, respectively, in the paths of the corresponding first and second polarization beams; and generating a focus error signal related to the difference between the output of the first detector and an output of the second detector.

Additionally, another embodiment of the present invention comprises an optical data delivery and detection system comprising a laser source emitting a light beam, an optical head that receives the light beam, optical lenses within the optical head that focus the light beam on an optical storage media, a data detector that receives the light beam on the beam's return path and provides data signals and a focus error generator device.

Another embodiment of the present invention comprises an improved focus error signal generator device including an optical lens disposed in the path of a return read light beam, and first and second polarizers of corresponding first and second polarizations having corresponding first and second pinholes formed therein wherein the polarizers are spaced apart, disposed in the path of the read light beam after the optical lens. A polarizing beam splitter is disposed in the path of the read light beam after second polarizer and serves to split the read light beam into a first light beam of first polarization and a second light beam of second polarization. First and second light beams are received by corresponding first and second optical detectors and an electrical differencing circuit having inputs to the first and second detectors and an output to an optical head servo system generates a focus error signal.

Another aspect of the present invention comprises a method for focus error signal generation including the steps of focussing the read light beam at a point of focus within a focal plane; providing for first and second polarizers of corresponding first and second polarization having corresponding pinholes formed therein, wherein first and second polarizers are disposed sequentially in the path of the read light beam in close proximity to the point of focus; providing for a polarizing beam splitter disposed in the path of the read light beam after the second polarizer that splits the read
light beam into first and second light beams of corresponding first and second polarizations; providing for first and second detectors, respectively, in the paths of the corresponding first and second light beams; and generating a focus error signal related to the difference between the output of the first detector and the output of the second detector.

Additionally, another embodiment of the invention comprises an optical data delivery and detection system comprising a laser source emitting a light beam, an optical head that receives the light beam, optical lenses within the optical head that focus the light beam on an optical storage media, a data detector that receives the light beam on the beam's return path and provides data signals and a focus error generator device as described herein.

**BRIEF DESCRIPTION OF THE FIGURES**

FIG. 1A is an illustration of a simple format hologram grating structure being written by exposing holographic storage medium to two beams of mutually coherent light.

FIG. 1B is an illustration of a complex format hologram grating structure having layer definition generated by superimposing two planar hologram gratings whose vectors are perpendicular to the storage medium surface.

FIGS. 2A and 2B are cross sectional views of format hologram grating structures having two and four constituent holograms, respectively, for track and layer definition.

FIGS. 3A and 3B are cross sectional views of the optical storage devices containing the format hologram grating structures depicted in FIGS. 2A and 2B, respectively.
FIG. 4A is a schematic diagram of an optical head of an optical delivery and detection system in relation to a grating envelope of a depth only format hologram grating structure.

FIG. 4B is a schematic drawing of an optical head of an optical delivery and detection system in relation to a grating envelope of a depth and radial format hologram grating structure.

FIG. 5 is a schematic drawing of an optical delivery and detection system in relation to a grating envelope of a depth only format hologram grating structure.

FIG. 6 is a schematic drawing of a focus error signal generator device, in accordance with a presently preferred embodiment of the present invention.

FIG. 7A is an illustration of an example of ideal positioning of the points of focus in relation to the pinholes, in accordance with a presently preferred embodiment of the present invention.

FIG. 7B is an illustration of an example of point of focus positioning in relation to the pinholes when the light beam is focused too deeply within the storage medium, in accordance with a presently preferred embodiment of the present invention.

FIG. 7C is an illustration of an example of point of focus positioning in relation to the pinholes when the light beam is focused too shallowly within the storage medium, in accordance with a presently preferred embodiment of the present invention.

FIG. 8 is a schematic drawing of a focus error signal generator device having only one set of optical lenses, in accordance with a presently preferred embodiment of the present invention.
FIG. 9A is a graphical representation of signal intensity versus depth of optical focus for two detectors, in accordance with a presently preferred embodiment of the present invention.

FIG. 9B is a graphical representation of the strength of the focus error signal versus depth of optical focus, in accordance with a presently preferred embodiment of the present invention.

FIG. 10 is a schematic drawing of an optical head showing the general effect on the light beams when the head is not focused properly.

FIGS. 11A, 11B and 11C, respectively, are graphical representations of the strength of the reflected signal as a function of the vertical and transverse dimension within the optical storage medium; the strength of the reflected signal as a function of transverse dimension for two adjacent layers within the optical storage medium; and, the strength of the reflected signal as a function of the vertical dimension for two adjacent track positions within the optical storage medium, respectively.

FIG. 12 is a schematic drawing of a focus error signal generator device, in accordance with a presently preferred embodiment of the present invention.

FIG. 13A is an illustration of an example of ideal positioning of the point of focus in relation to the pinholes, in accordance with a presently preferred embodiment of the present invention.

FIG. 13B is an illustration of an example of point of focus positioning in relation to the pinholes when the light beam is focussed too deeply within the storage medium, in accordance with a presently preferred embodiment of the present invention.

FIG. 13C is an illustration of an example of point of focus positioning in relation to the pinholes when the light beam is focussed too shallowly within the
storage medium, in accordance with a presently preferred embodiment of the present invention.

FIG. 14 is a schematic drawing of a focus error signal generator device, in accordance with a presently preferred embodiment of the present invention.

FIG. 15A is an illustration of an example of ideal positioning of the point of focus in relation to the pinholes, in accordance with a presently preferred embodiment of the present invention.

FIG. 15B is an illustration of an example of point of focus positioning in relation to the pinholes when the light beam is focussed too deeply within the storage medium, in accordance with a presently preferred embodiment of the present invention.

FIG. 15C is an illustration of an example of point of focus positioning in relation to the pinholes when the light beam is focussed too shallowly within the storage medium, in accordance with a presently preferred embodiment of the present invention.

FIG. 16 is a schematic drawing of a focus error signal generator device, in accordance with a presently preferred embodiment of the present invention.

FIG. 17A is an illustration of an example of ideal positioning of the point of focus in relation to the pinholes, in accordance with a presently preferred embodiment of the present invention.

FIG. 17B is an illustration of an example of point of focus positioning in relation to the pinholes when the light beam is focussed too deeply within the storage medium, in accordance with a presently preferred embodiment of the present invention.
FIG. 17C is an illustration of an example of point of focus positioning in relation to the pinholes when the light beam is focussed too shallowly within the storage medium, in accordance with a presently preferred embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Those of ordinary skill in the art will realize that the following description of the present invention is illustrative only and is not intended to be in any way limiting. Other embodiments of the invention will readily suggest themselves to such skilled persons from an examination of the within disclosure.

Referring to FIG. 1A, a simple format volume hologram 10 is written by exposing a holographic material to two beams of mutually coherent light. In particular, two plane waves incident from opposing sides generate a planar reflection hologram, whose orientation and spatial frequency are governed by the wavelength and angles of incidence of the beams. For example, Beam 12 and Beam 14 are incident on opposite sides of the material. For optimal reflection, the hologram is Bragg-matched at the readout to a range of angles within the cone of the focused readout beam. This property is the basis of data storage by selective localized alteration of a format hologram grating structure. Confocal detection isolates the light reflected from the focus. The selective localized alteration serves to change the reflectivity at the waist of a focused beam that can be measured using confocal detection; in this manner, data are represented by the localized changes in reflectivity of the format hologram. A variety of complex format holograms can be generated, including layer definition by superimposing two planar hologram gratings whose vectors are perpendicular to the medium surface, as shown schematically in FIG. 1B.

FIGS. 2A and 2B and corresponding FIGS. 3A and 3B are presented here as examples of storage medium that have multiple storage layers, closely spaced, at distances comparable to the Rayleigh range of the illuminating beam. In particular, FIGS 2A and 2B and corresponding FIGS. 3A and 3B illustrate multiple storage layers within a bulk storage medium. The Rayleigh range storage media that is similar
to the one shown here will benefit greatly from the Focus Error Signal (FES) Generator device of the present invention. Further, the present invention will also perform with storage medium having multiple storage layers residing at separate depths in the storage media spaced at distances that can be substantially longer than the Rayleigh range. The Rayleigh range of an illuminating beam is defined as the depth of focus, i.e. the distance over which the point of focus is within twice its minimum diameter. The Rayleigh range is well known by those of ordinary skill in the art.

Referring now to FIG. 2A and FIG. 2B, format hologram grating structures having complex structures for layer and track definition are shown. FIG. 2A shows a cross sectional view of a format hologram grating structure 20 having two constituent holograms for track and layer definition. The radius of the format hologram grating structure is represented by the horizontal axis 22 and the depth of the format hologram grating structure is represented by the vertical axis 24. FIG. 2B shows a format hologram grating structure 30 having four constituent hologram gratings for track and layer definition. These constituent holograms exist throughout the entire volume and locally interfere to produce a reflection hologram grating structure with a spatially varying envelope, as shown in FIGS. 2A and 2B. Methods for generating such format hologram grating structures are omitted from this disclosure in order to avoid overcomplicating the disclosure. For a detailed disclosure of generating two and four constituent format holograms and format hologram grating structures see, for example, U.S. Patent Application Ser. No. 09/016,382 filed on January 30, 1998, in the name of inventors Hesselink et. al., entitled “Optical Data Storage by Selective Localized Alteration of a Format Hologram” and U.S. Patent Application Ser. No. __________ (atty. docket SIROS-98034) filed on January 12, 1999, in the name of inventors Daiber et. al., entitled “Volumetric Track Definition for Data Storage Media Used to Record Data by Selective Alteration of a Format Hologram”.

FIG. 3A is a cross-sectional view of storage device 40 corresponding to the format hologram grating structure of FIG. 2A. A transparent top cover layer 42 and a transparent bottom cover layer 44 that are typically formed from glass or a polymeric material enclose the holographic storage medium 46 in FIG. 2A. FIG. 3A shows the envelope of the local index perturbation of holographic storage medium 46, for which
the carrier frequencies have been removed. Generally a reflected signal from a focused beam will be strongest when it is centered on a peak.

FIG. 3B is a cross-sectional view of storage device 50 corresponding to the format hologram grating structure of FIG. 2B. A transparent top cover layer 52 and a transparent bottom cover layer 54 serve to enclose the holographic storage medium 56. Similar to FIG. 3A, FIG. 3B shows the envelope of the local index perturbation of holographic storage medium 56, for which the carrier frequencies have been removed. The magnitude profiles depicted in FIGS. 3A and 3B are a general indication of the expected reflectivity for a high numerical aperture, diffraction-limited beam focused into the holographic storage medium. The features of the format hologram grating structure and the relative thickness of the storage layer and cover layers are not to scale. The number of layers illustrated here is by way of example.

FIG. 2A and 2B and corresponding FIG. 3A and 3B illustrate format hologram grating structures that can be utilized for focusing and tracking using a variety of data writing methods, including data writing by selective alteration of the structure itself and data writing by affecting an optical property of the material without substantially affecting the underlying hologram grating structure.

Referring now to FIG. 4A, a schematic of the optical head 62 component of an overall optical delivery and detection system 60 is shown. The optical head 62 can be moved radially, as shown by arrow 64, and in depth, as shown by arrow 66, to access different portions of a holographic storage medium 68. The illustrated holographic storage medium 68 has a format hologram grating structure stored therein. Other details of the structure of an optical head 62 for measuring intensity at a particular depth are not necessary for an understanding of the present invention and are omitted to avoid overcomplicating the disclosure. The construction of an optical head for measuring the intensity at a particular depth of the material can be found in U.S. Patent Application Ser. No. 09/016,382 filed on January 30, 1998, in the name of inventor Hesslink et. al., entitled "Optical Data Storage by Selective Localized Alteration of a Format Hologram", previously expressly incorporated herein by reference.
In the case of a disk, rotation brings different angular portions of the holographic storage medium 68 into optical communication with the optical head 62. In the case of a medium formed in card or tape (not shown in FIG. 4A), linear motion brings different lateral portions of the holographic storage medium to the optical head. FIG. 4A illustrates the position of the optical head 62 in relation to a grating envelope of a depth only format hologram grating structure. The top layer 70 and the bottom layer 72 of the holographic storage device 74 can comprise glass or a polymeric material. As a function of the vertical position of the focus, the reflected intensity is greatest when the focus is positioned at the center of a layer, and least when positioned between the layers. By way of example, focus servo can be achieved by wobbling the head vertically, measuring the change in intensity, and directing the head to be positioned where the reflection is highest.

FIG. 4B illustrates an optical head 62 in relation to a grating envelope of a depth and radial format hologram grating structure. Layer selection may be achieved using the same simple focus servo; a tracking servo can be similarly achieved by wobbling the optical head 62 transversely, measuring the change in intensity, and directing the head to be positioned where the reflection is highest.

FIG. 5 illustrates an optical delivery and detection system 80. A laser 82 illuminates a beam 84 that is expanded by beam expansion optics 86 and directed towards the holographic storage medium 88. Once the beam is expanded it passes through a polarizing beam splitter 90 where it is directed towards a first corner turning mirror 92 located within the optical head 94 and then directed towards an objective lens 96. Variable spherical aberration correction (SAC) optics 98 can be used in conjunction with an objective lens 96 to focus on different layers within the holographic storage medium 88. The use of SAC optics 98 is particularly important when trying to reach depths within the storage medium 88 in excess of approximately 100 microns. On the beam’s forward and return paths, light passes through a quarter wave plate 100 that serves to change the polarization of the beam. The use of the polarizing beam splitter 90 and the quarter wave plate 100 serves to increase the efficiency of the overall system 80. Alternatively, a standard 50/50 beam splitter can be used in place of the polarizing beam splitter 90 and the quarter wave plate 100.
Once the polarization has been changed, the beam passes through the polarizing beam splitter 90. The polarizing beam splitter 90 recognizes the change in polarization and directs the beam towards several operational paths. A fraction of the light is split in the direction of each path. A standard 50/50-beam splitter 102 directs a portion of the light in a data path 104 towards a data detector 106 and additional optional detectors (not shown in FIG. 4). The portion of light not directed toward the data path 104 is directed towards a second 50/50-beam splitter 108 that serves to direct a portion of the light in a tracking path 110 toward a tracking error detector 112. The portion of light not directed toward the tracking path 110 is directed towards optional second corner turning mirror 114. Finally, the light is reflected off the corner turning mirror 114 in an autofocus path 116 toward a focus error detector 118.

A presently preferred embodiment of the present invention is illustrated in FIG. 6. Shown in FIG. 6 is an improved focus error signal (FES) generator device 120 comprising two optical paths 122 and 124, and corresponding pinholes 126 and 128. With the present invention, an optical head (not shown in FIG. 6) focuses light onto a data layer in a data storage medium that has multiple layers of data storage and, in particular, bulk monolithic holographic storage media with a format hologram grating stored therein to define layers.

Light beam 130 is shown as a read beam on a return path from an optical storage medium. The optical storage medium may, preferably, have a format hologram grating structure stored therein to define data layers (not shown in FIG. 6), although the present invention can be used with media having a single data layer. Light beam 130 is directed towards a beam splitter 132 from which a fraction of the light proceeds along path 122 and the remaining beam is directed towards a corner turning mirror 134 where it is reflected and results in path 124. The implementation of beam splitter 132 is not an essential element of the presently preferred embodiment of the present invention. The beam splitter 132 serves to split light beam 130 into two distinct light paths: path 122 and path 124. Any other manner of splitting light beam 130 into two distinct light paths can also be implemented and will still be within the inventive concept herein disclosed.
Path 122 light travels through optical lens 136, pinhole 126 and optical lens 138 before light beam 122 contacts detector 140. Path 124 light travels through optical lens 142, pinhole 128 and optical lens 144 before light beam 124 contacts detector 146. Optical lens 136 and optical lens 142 are, typically, standard glass or plastic optical lenses that share similar focal lengths. Pinholes 126 and 128 are, typically, formed in a glass plate that is coated with a metal foil. Those skilled in the art will realize that the pinhole formation can be accomplished in a variety of manners. The pinhole configuration that is shown here is by way of example only and is not intended to be in any way limiting.

The size of the pinhole is dependent upon the focal length of optical lenses 136 and 142, the beam diameter and the beam wavelength. By way of example, the pinhole size may be sized so that 90% of the intensity of the light beam passes through the pinhole when the pinhole is positioned at the beam focus. The pinhole may typically range in size from about 1 micron in diameter to about 50 microns in diameter, and is typically about 8 microns in diameter. Optical lens 138 and optical lens 144 are, typically, standard glass optical lenses that share similar focal lengths. The lenses that are chosen as optical lenses 138 and 144 should be able to ensure that the light beams emitted from optical lenses 138 and 144 are collected efficiently by the corresponding detector 140 or detector 146.

Detector 140 and detector 146 may be standard photodiodes that serve to convert light beam photons to electrical signals in the form of electrons (an electrical current). The electrical signal is then provided to electronic differencing circuit 148 that generates a focus error signal. A servo system (not shown in FIG. 6) uses the focus error signal to direct the position of the objective lens in the optical head, thus completing the auto-focus procedure. Servo systems are well known in the art.

In contrast, in a prior-art data detection arm (shown in FIG. 5 at 106), a pinhole is generally used for confocal depth selection, and is generally situated so that light reflected from the desired depth - the focus of the read beam - comes to a focus in the plane of the pinhole, passing efficiently through it. For the device shown in FIG. 6, the pinholes are positioned in the separate arms so that they are displaced to either side of
this focus when the beam is focused at the center of the layer. Thus, when the optical head is focused on a layer, the point of focus 150 in FES generator device 120 occurs before pinhole 126 for path 122 and after pinhole 128 for path 124. Point of focus 150 occurs within the focal plane (not shown in FIG. 6) of the corresponding optical lens 136 and 142. For this configuration, the intensities of the beams propagating through the paths 122 and 124 are the same.

The plates containing the pinholes are characteristically mounted within a FES generator device housing (not shown in FIG. 6) with the aid of a precision alignment fixture. Use of such alignment fixtures to position elements such as pinhole plates are well known by those of ordinary skill in the art.

The positioning of the point of focus in relation to the pinholes is instrumental in determining proper auto-focus. The ideal positioning of the point of focus is shown in FIG. 7A. This ideal positioning is achieved when the optical head is properly focused on the desired layer within the storage medium with respect to the depth of a data layer or layer center. Path 170 point of focus 172 occurs slightly before pinhole 174 and path 176 point of focus 172 occurs slightly after pinhole 178.

FIGS. 7B and 7C illustrate light beams that are focused either too deeply or too shallowly within the storage medium with respect of the depth of a layer or layer center. FIG. 7B gives an example of focusing too deeply within the storage medium. If the optical head is focused too deeply into the medium, point of focus 180 in the FES generator device is shifted towards the detectors (not shown in FIG. 7B) for both paths 182 and 184. For moderate perturbations, point of focus 180 is more tightly focused at pinhole 186 in path 182 and is less tightly focused at pinhole 188 in path 184. Therefore, more light is transmitted through pinhole 186 in path 182 than pinhole 188 in path 184 and therefore more light is detected by the detector corresponding to pinhole 186 than the detector corresponding to pinhole 188. FIG. 7C provides an example of the optical head being focused too shallowly into the medium, resulting in point of focus 190 in the FES generator device being shifted away from the detector for both paths 192 and 194. For moderate perturbations, it is more tightly focused at pinhole 196 in path 194 and less tightly focused at pinhole 198 in path 192. Therefore,
more light is transmitted throughout pinhole 196 in path 194 than pinhole 198 in path 192 and therefore more light is detected by the detector corresponding to pinhole 196 than the detector corresponding to pinhole 198. Thus, a simple difference in the intensities of the light indicates in which direction the optical head is out of focus.

When the focal lengths of the lenses focusing the light to the pinholes are large, lateral pinhole positioning tolerances are reduced. It is particularly advantageous in this case to modify the arrangement shown in FIG. 6 so that the detectors are adjacent to the pinholes, as illustrated in FIG. 8, a diagram showing another presently preferred embodiment of the present invention comprising a FES generator device 200 that eliminates the need for a second set of optical lenses. In this embodiment the first set of optical lenses 202 and 204 have a characteristically large focal length. The large focal lengths of optical lenses 202 and 204 dictate that plates 206 and 208 containing pinholes 210 and 212 be placed at a greater distance from optical lenses 202 and 204 than was observed in the embodiment depicted in FIG. 6. Detector 214 and detector 216 must be placed close enough to pinholes 210 and 212 that nearly all light from pinholes 210 and 212 irradiates detector 214 and detector 216.

A simple differencing circuit can be employed to generate a focus error signal in the present invention. Detector A outputs a current which is converted to a voltage A, and detector B outputs a current that is converted to a voltage B. Current-to-voltage techniques are well known in the art. The focus error signal \((A - B)\) is positive when the focus is too deep, and negative when the focus is too shallow. Furthermore, the signal \((A - B)\) is stronger as the beam is further out of focus. The focus error signal can be further normalized to the total strength \((A + B)\) in order to compensate e.g. for fluctuations in laser strength. The focus error signal can be used to position the optical head so that it focuses on a layer e.g. by defining the minimum and maximum tolerable value limits \(D1 < (A - B) \div (A + B) < D2\); where \(D1\) is the minimum limit and \(D2\) is the maximum limit. When the normalized focus error signal \((A - B) \div (A + B)\) falls outside this range, the head is moved in the appropriate direction to bring it within this range, thus focusing on a particular layer.
Referring now to FIG. 9A, signal intensities for detector A and detector B are shown as a function of depth of the material. The vertical line 220 indicates a particular depth of a formatted layer. At this depth, detector A and detector B provide the same output voltage that corresponds to the same signal strength. Referring now to FIG. 9B, the value of the focus error signal (A - B) is shown as a function of depth of the material. If the beam from the optical head is focused too deeply with respect to the nearest layer, then the focus error signal (A - B) is positive, and therefore the normalized focus error signal (A - B) ÷ (A + B) is positive. If the beam from the optical head is focused too shallowly with respect to the nearest layer, then the focus error signal (A - B) is negative, and therefore the normalized focus error signal (A - B) ÷ (A + B) is negative. Both the value of the focus error signal (A - B) and its slope can be used together to determine the direction and distance the optical head must be moved to restore focus to the nearest layer. Alternatively, the value of the normalized focus error signal and its slope can be used together to determine the direction and distance the optical head must be moved to restore focus to the nearest layer. Furthermore, the value of the focus error signal (A - B) and its slope can be used to supplement the evaluations based on a normalized focus error signal. Layer selection is accomplished by keeping track of the number of layers crossed as the optical head passes from the first layer it encounters to the others.

The strength of the focus error signal defined by (A - B) in FIG. 9B is proportional to the phase shift of the two signals A and B, illustrated in FIG. 9A. This relationship can be understood by referring to FIG. 10, which shows the general effect on the light beams when the head is not focused on a layer. FIG. 10 does not include all critical parts of the optical head, such as a spherical aberration corrector, but illustrates the effects of out-of-focus head position. For clarity, the figure does not illustrate effects of the index of refraction of the material; these effects would be apparent to those skilled in the art of optical sciences. In FIG. 10, the layer is indicated by a single reflecting surface for illustration purposes only.

A light beam 230 passes through the objective lens 232, is reflected by the layer 234, turns through the objective lens 232, passes through the beam splitter 236, and is then focused by the detection lens 238. The focal position of the light returning
to the objective lens 232 is shifted by twice the depth positioning error. As would be apparent to those skilled in the optical sciences, the focus position in the detection optics therefore shifts by \( \Delta z_2 = (\Delta z_1/n)(f_1/f_2)^2 \). In this equation \( n \) is the index of refraction of the material, \( f_1 \) is the focal length of objective lens 232, \( f_2 \) is the focal length of the detection lens 238, \( \Delta z_1 \) is the depth positioning error, and \( \Delta z_2 \) is the focal shift in the FES generator. An axial pinhole displacement \( \Delta z_2 \) therefore results in a detected phase shift of \( \Delta z_1 = (n/2)\Delta z_2(f_1/f_2)^2 \) as illustrated in FIG. 9A.

The strongest focus error signal (A - B) is achieved when the axial pinhole displacement is set such that the displacement of the pinhole from the point of focus for path A is adjusted to optionally detect a depth positioning error of \( \Delta z_{1A} = (1/4)\Delta z \), and for path B is adjusted to optionally detect a depth positioning error of \( \Delta z_{1B} = (1/4)\Delta z \), where \( \Delta z \) is the spacing of the layers as measured by the optical focus displacement (FIG. 9B). For data detection, however, it is generally preferred that the pinhole reside near the point of focus of the beam, for which the displacement would be less than the Rayleigh range of the optical focus in the material (e.g., \( \Delta z_{1A} = \Delta z_{1B} = (1/2)z_R \), where \( z_R \) is the Rayleigh range of the beam focused in the material). Thus, it is generally preferred that the data detection and focus error generation optics described herein are in separate arms/paths (as shown in FIG. 5).

Equivalently, the condition for strongest focus error signal can be cast in terms of the pinhole placement with respect to the layer spacing imaged by the detection lens 238. In these terms, the strongest focus error signal (A - B) is achieved when the axial pinhole displacement from the point of focus for path A is \( \Delta z_{2A} = (1/4)\Delta z' \), and for path B is \( \Delta z_{2B} = -(1/4)\Delta z' \), where \( \Delta z' = (2\Delta z/n)(f_1/f_2)^2 \) which is the spacing of the layers as measured by the optical focus displacement (FIG. 9B). If it is required that the two signals A, B be in focus (e.g. to detect data), then the phase shift should be reduced to less than the Rayleigh range of the optical focus of the detection lens (e.g., \( \Delta z_{1A} = \Delta z_{1B} = (1/2)z_R \), where \( z_R \) is the Rayleigh range of the beam focused by the detection lens).

In an alternative preferred embodiment of the present invention, a focus error signal (B-A) can be generated to keep the beam focused on the nulls between data
layers. This may be advantageous for data recording that does not utilize selective localized alteration of a format hologram.

Due to the properties of confocal detection, the pinhole diameter should be less than or equal to the diameter of the optical beam reflected from the material for optimal rejection of out-of-focus signals from other layers. In contrast, for maximum signal strength and positioning tolerance, the pinhole diameter should be greater than or equal to the optical beam diameter. A particular choice that balances these constraints is to set the pinhole size to just pass nearly all of the optical intensity of the non-aberrated beam. By way of example, the pinhole size can be selected so that 90% of intensity of the light beam passes through the pinhole when the pinhole is positioned at the beam focus.

The present invention can also be practiced to keep an optical head focused on tubular format regions (tubular format cross-sectional regions are illustrated in the storage medium of FIGS. 2B, 3B and 4B). The round cross sections sweep out tubular format regions throughout the radius of the material that result from complex format hologram grating structures. In this case, the reflected light detected by the system is relatively small between the tubes. Thus, the beam must be kept radially positioned on the data tube in order to remain focused on a particular data layer. Some tracking methods used for single layer and multiple media layer storage devices can be adapted for use in this invention as disclosed. By way of example, one such method of tracking comprises wobbling the focused spot radially, measuring the change in intensity, and directing the head to be positioned where the reflection is highest which correspond to the track centers. The operation of the focus error generator device of the present invention is otherwise the same.

Referring now to FIGS. 11A, 11B and 11C, data are shown for the strength of light reflected off a format hologram grating structures that defines layers and tracks which together define tubular format regions. FIG. 11A shows the strength of the reflected signal as a function of the depth (vertical dimension) and the radius (transverse dimension) within the storage medium at a fixed angular position. FIG. 11B shows the strength of the reflect signal as a function of radius (transverse
dimension) for two adjacent layers within the storage medium. Note that adjacent tracks are shifted in phase by half a period. FIG. 11C shows the strength of the reflected signal as a function of depth (vertical dimension) for two adjacent track positions. Note that these layers may be placed as closed as only a few times the depth of field of the readout optical beam.

Another presently preferred embodiment of the present invention is illustrated in FIG. 12. Shown in FIG. 12 is an improved focus error signal (FES) generator device 320 comprising lens 322, birefringent plate 324 and pinhole 326. An optical head (not shown in FIG. 12) focuses light onto a data layer in a data storage medium. The data storage medium, by way of non-limiting example, may be comprised of either multiple layers of data storage or a bulk, monolithic holographic storage medium that has a format hologram grating stored therein to define layers. Read beam 328 enters FES generator device 320 on a return path from the data storage medium. Read beam 328 passes through first optical lens 322 that serves to focus read beam 328. First optical lens 122 is typically formed from glass or a polymeric material. First optical lens 322 should have a working distance that slightly exceeds the distance between first optical lens 322 and birefringent plate 324.

Once read beam 328 passes through first optical lens 322 it is focused towards birefringent plate 324. Birefringent plate 324 characteristically has two indices of refraction that result in two separate focal planes (not shown in FIG. 12) associated with two corresponding polarizations 340 and 342. Generally first polarization 340 and second polarization 342 will be separated by 90 degrees. Each focal plane has a corresponding point of focus, shown in FIG. 12 as first point of focus 330 and second point of focus 332. By example, birefringent plate 324 may be formed from crystal calcite or any other birefringent material may be used to form birefringent optical plate 324. The amount of shift in the indices of refraction may be an appropriate consideration when choosing the birefringent material that will form birefringent optical plate 324.

FIG. 12 shows, by way of example, birefringent plate 324 adjacent to plate 334 with pinhole 326 formed therein. FES generator device 320 is not limited to a
configuration having birefringent plate 324 adjacent to plate 334. FES generator
device 320 may be configured so that birefringent plate 324 is located at any distance
between first optical lens 322 and plate 334. In the illustrated embodiment, plate 334
may be physically attached to birefringent plate 324 using, for example, an adhesive
compound or any other fastening mechanism. Additionally, a mounting mechanism
may be implemented when birefringent plate 324 and plate 334 are located in close
proximity to one another.

Pinhole 326 serves to confocally filter read beam 328 as it departs birefringent
plate 324. Pinhole 326 is, typically, formed in a glass plate that is coated with a metal
foil. The size of pinhole 326 is dependent upon the working distance of first optical
lens 322, the diameter of read beam 328 and the wavelength of read beam 328. By
way of example, pinhole 326 may be sized so that 90% of intensity of the read beam
passes through the pinhole when the pinhole is positioned at a point of focus. The
pinhole may typically range in size from about 1 micron in diameter to about 50
microns in diameter, and is typically about 8 microns in diameter. Those skilled in the
art will realize that the pinhole can be formed in a variety of manners. The pinhole
configuration that is shown here is by way of example only and is not intended to be in
any way limiting.

After read beam 328 has been filtered through pinhole 326 and resulting first
point of focus 330 and second point of focus 332 have formed, read beam 328 is
transmitted through second optical lens 336. Second optical lens 336 is, typically, a
standard glass or polymeric lens. Second optical lens 336 serves maximize the
performance of polarizing beam splitter 338 by directing read beam 328 towards
polarizing beam splitter 338. Second optical lens 336 is an optional element of FES
generator device 320. It is possible and within the inventive concept herein disclosed
to configure FES generator device 320 without second optical lens 336 in instances
where the focal length and beam diameter of read beam 328 are such that the use of
second optical lens 336 would not be required.

Polarizing beam splitter 338 separates the light of first polarization 340 from
the light of second polarization 342. The use of a polarizing beam splitter is well
known by those of ordinary skill in the art. Light of first polarization 340 is directed towards detector 344 and light of second polarization 342 is directed towards detector 346.

Detector 344 and detector 346 may be standard photodiodes that serve to convert light beam photons to electrical signals in the form of electrons (an electrical current). The electrical signal is then provided to electronic differencing circuit 348 that generates a focus error signal. A servo system (not shown in FIG. 12) uses the focus error signal to direct the position of the objective lens in the optical head, thus completing the auto-focus procedure. Servo systems are well known in the art.

In contrast, in a prior-art data detection arm, a pinhole is generally used for confocal depth selection, and is generally situated so that light reflected from the desired depth - the focus of the read beam - comes to a focus in the plane of the pinhole, passing efficiently through it. For the FES generator device 320 shown in FIG. 12, when the optical head is focused on a layer within the storage medium first polarization 340 will form first point of focus 330 before pinhole 326 and second polarization 342 will form second point of focus 332 after pinhole 326.

The birefringent plate 324 and plate 334, having pinhole 326 formed therein, are characteristically mounted within a FES generator device housing (not shown in FIG. 12) with the aid of a precision alignment fixture. Use of such alignment fixtures to position elements, such as pinhole plates or birefringent plates, are well known by those of ordinary skill in the art.

The positioning of the points of focus in relation to the pinhole is instrumental in determining proper auto-focus. The ideal positioning of the points of focus are shown in FIG. 13A. This ideal positioning is achieved when the optical head is properly focused on the desired layer within the storage medium with respect to the depth of a data layer or layer center. First polarization 340 has first point of focus 330 slightly before pinhole 326 and second polarization 342 has second point of focus 332 slightly after pinhole 326. For this configuration, the intensities detected for first polarization 340 and second polarization 342 are equivalent.
FIGS. 13B and 13C illustrate light beams that are focused either too deeply or too shallowly within the storage medium with respect of the depth of a layer or layer center. FIG. 13B gives an example of focusing too deeply within the storage medium. If the optical head is focused too deeply into the medium, first point of focus 330 and second point of focus 332 in the FES generator device are shifted towards the detectors (not shown in FIG. 13B). For moderate perturbations, at pinhole 326, the read beam is more tightly focused for first polarization 340 and less tightly focused for second polarization 342. Therefore, more light is transmitted via first polarization 340 than second polarization 342 and, thus, more light is detected by the detector associated with first polarization 340 than the detector associated with second polarization 342.

FIG. 13C provides an example of the optical head being focused too shallowly into the medium, resulting in first point of focus 330 and second point of focus 332 being shifted away from the detectors (not shown in FIG. 13C). For moderate perturbations, at pinhole 326, the read beam is more tightly focused for second polarization 342 and less tightly focused for first polarization 340. Therefore, more light is transmitted via second polarization 342 than first polarization 340 and, thus, more light is detected by the detector associated with second polarization 342 than the detector associated with first polarization 340. Thus, a simple difference in the intensities of the light indicates in which direction the optical head is out of focus.

As noted above, simple differencing circuit can be employed to generate a focus error signal in the present invention. For example, a first detector A outputs a current which is converted to a voltage A, and a second detector B outputs a current that is converted to a voltage B. Current-to-voltage techniques are well known in the art. The focus error signal (A - B) is positive when the focus is too deep, and negative when the focus is too shallow. Furthermore, the signal (A - B) is stronger as the beam is further out of focus. The focus error signal can be further normalized to the total strength (A + B) in order to compensate e.g. for fluctuations in laser strength. The focus error signal can be used to position the optical head so that it focuses on a layer e.g. by defining the minimum and maximum tolerable value limits D1 < (A - B) / (A + B) < D2; where D1 is the minimum limit and D2 is the maximum limit. When the
normalized focus error signal \((A - B) \div (A + B)\) falls outside this range, the head is moved in the appropriate direction to bring it within this range, thus focusing on a particular layer.

Referring again to FIG. 9A, signal intensities for first detector A and second detector B are shown as a function of depth of the material. The vertical line 220 indicates a particular depth of a formatted layer. At this depth, first detector A and second detector B provide the same output voltage that corresponds to the same signal strength. Referring to FIG. 9B again, the value of the focus error signal \((A - B)\) is shown as a function of depth of the material. If the beam from the optical head is focused too deeply with respect to the nearest layer, then the focus error signal \((A - B)\) is positive, and therefore the normalized focus error signal \((A - B) \div (A + B)\) is positive. If the beam from the optical head is focused too shallowly with respect to the nearest layer, then the focus error signal \((A - B)\) is negative, and therefore the normalized focus error signal \((A - B) \div (A + B)\) is negative. Both the value of the focus error signal \((A - B)\) and its slope can be used together to determine the direction and distance the optical head must be moved to restore focus to the nearest layer. Alternatively, the value of the normalized focus error signal and its slope can be used together to determine the direction and distance the optical head must be moved to restore focus to the nearest layer. Furthermore, the value of the focus error signal \((A - B)\) and its slope can be used to supplement the evaluations based on a normalized focus error signal. Layer selection is accomplished by keeping track of the number of layers crossed as the optical head passes from the first layer it encounters to the others.

The strength of the focus error signal defined by \((A - B)\) in FIG. 9B is proportional to the phase shift of the two signals A and B, illustrated in FIG. 9A. This relationship can be understood by referring again to FIG. 10, which shows the general effect on the light beams when the head is not focused on a layer. FIG. 10 does not include all critical parts of the optical head, such as a spherical aberration corrector, but illustrates the effects of out-of-focus head position, as noted above. For clarity, the figure does not illustrate effects of the index of refraction of the material; these effects would be apparent to those skilled in the art of optical sciences. In FIG. 10, the layer is indicated by a single reflecting surface for illustration purposes only.
In FIG. 10, a light beam 230 passes through the objective lens 232, is reflected by the layer 234, turns through the objective lens 232, passes through the beam splitter 236, and is then focused by the detection lens 238. The focal position of the light returning to the objective lens 232 is shifted by twice the depth positioning error. As would be apparent to those skilled in the optical sciences, the focus position in the detection optics therefore shifts by \( z_\sigma = (z_i/n)\left(f_1/f_2\right)^2 \). In this equation \( n \) is the index of refraction of the material, \( f_1 \) is the focal length of objective lens 232, \( f_2 \) is the focal length of the detection lens 238, \( z_i \) is the depth positioning error, and \( z_\sigma \) is the focal shift in the FES generator. An axial pinhole displacement \( z_\sigma \) therefore results in a detected phase shift of \( z_\phi = (n/2)\left(z_i/f_1\right)^2 \) as illustrated in FIG. 9A.

Equivalently, the condition for strongest focus error signal can be cast in terms of the pinhole placement with respect to the layer spacing imaged by the detection lens. The strongest focus error signal (A - B) is achieved when the axial pinhole displacement is set such that the displacement of the pinhole from the point of focus for polarization A is adjusted to optionally detect a depth positioning error of \( z_{iA} = (1/4)z \), and for polarization B is adjusted to optionally detect a depth positioning error of \( z_{iB} = -(1/4)z \), where \( z \) is the spacing of the layers as measured by the optical focus displacement (FIG. 9B). For data detection, however, it is generally preferred that the pinhole reside equal distance from the points of focus of the beam, for which the displacement would be less than the Rayleigh range of the optical focus in the material (e.g., \( z_{iA} = z_{iB} = (1/2)z_R \) where \( z_R \) is the Rayleigh range of the beam focused in the material). Thus, it is generally preferred that the data detection and focus error generation optics described herein are in separate arms/paths (as shown in FIG. 5).

Equivalently, the condition for strongest focus error signal can be cast in terms of the pinhole placement with respect to the layer spacing imaged by the detection lens 238. In these terms, the strongest focus error signal (A - B) is achieved when the axial pinhole displacement from the point of focus for polarization A is \( z_{iA} = (1/4)z' \), and for polarization B is \( z_{iB} = -(1/4)z' \), where \( z' = (z/n)(f_1/f_2)^2 \), which is the spacing of the layers as measured by the optical focus displacement (FIG. 9B). If it is required
that the two signals A, B be in focus (e.g. to detect data), then the phase shift should be reduced to less than the Rayleigh range of the optical focus of the detection lens (e.g. 
\[ -z_{2A} = -z_{2B} = (1/2)z_R, \]
where \( z_R \) is the Rayleigh range of the beam focused by the detection lens).

In yet another alternative preferred embodiment of the present invention, a focus error signal (B-A) can be generated to keep the beam focused on the nulls between data layers. This may be advantageous for data recording that does not utilize selective localized alteration of a format hologram.

Due to the properties of confocal detection, the pinhole diameter should be less than or equal to the diameter of the optical beam reflected from the material for optimal rejection of out-of-focus signals from other layers. In contrast, for maximum signal strength and positioning tolerance, the pinhole diameter should be greater than or equal to the optical beam diameter. A particular choice that balances these constraints is to set the pinhole size to just pass nearly all of the optical intensity of the non-aberrated beam. By way of example, the pinhole size can be selected so that 90% of intensity of the light beam passes through the pinhole when the pinhole is positioned at the beam focus.

The present invention can also be practiced to keep an optical head focused on tubular format regions (tubular format cross-sectional regions are illustrated in the storage medium of FIGS. 2B, 3B and 4B and described above). The round cross sections sweep out tubular format regions throughout the radius of the material that result from complex format hologram grating structures. In this case, the reflected light detected by the system is relatively small between the tubes. Thus, the beam must be kept radially positioned on the data tube in order to remain focused on a particular data layer. Some tracking methods used for single layer and multiple media layer storage devices can be adapted for use in this invention as disclosed. By way of example, one such method of tracking comprises wobbling the focused spot radially, measuring the change in intensity, and directing the head to be positioned where the reflection is highest which correspond to the track centers. The operation of the focus error generator device of the present invention is otherwise the same.
Referring again to FIGS. 11A, 11B and 11C, data are shown for the strength of light reflected off a format hologram grating structures that defines layers and tracks which together define tubular format regions. FIG. 11A shows the strength of the reflected signal as a function of the depth (vertical dimension) and the radius (transverse dimension) within the storage medium at a fixed angular position. FIG. 11B shows the strength of the reflect signal as a function of radius (transverse dimension) for two adjacent layers within the storage medium. Note that adjacent tracks are shifted in phase by half a period. FIG. 11C shows the strength of the reflected signal as a function of depth (vertical dimension) for two adjacent track positions. Note that these layers may be placed as closed as only a few times the depth of field of the readout optical beam.

Another presently preferred embodiment of the present invention is illustrated in FIG. 14. Shown in FIG. 14 is an improved focus error signal (FES) generator device 120 comprising birefringent optical lens 122 and pinhole 124. An optical head (not shown in FIG. 14) focuses light onto a data layer in a data storage medium. The data storage medium, by way of non-limiting example, may be comprised of either multiple layers of data storage or a bulk, monolithic holographic storage medium that has a format hologram grating stored therein to define layers. Read beam 426 enters FES generator device 420 on a return path from the data storage medium. Read beam 426 travels through birefringent optical lens 422 and first standard optical lens 428. As is known by those of ordinary skill in the art, birefringent optical lens 422 has two indices of refraction. Birefringent optical lens 422 may be formed from, for example, crystal calcite or any other birefringent material. The amount of shift in the indices of refraction may be an appropriate consideration when choosing the birefringent material that will form birefringent optical lens 422.

First standard optical lens 428 is an optional element of FES generator device 420 that is used to further define the focal lengths of the two indices of refraction resulting from birefringent optical lens 422. First standard optional lens 428 is used to adjust the average center focal length to a value convenient to the physical constraints of the FES generator device 420. It is possible and within the inventive concept herein
disclosed to configure FES generator device 420 without first standard optical lens 428. First standard optical lens 428 is typically formed from glass or a polymeric material.

Once read beam 426 has passed through birefringent optical lens 422 and first standard optical lens 428, read beam 426 will comprise a first polarization portion 430 and a second polarization portion 432. First polarization portion 430 has a corresponding first point of focus 434 within an associated first focal plane (not shown in FIG. 14). Second polarization portion 432 has a corresponding second point of focus 436 within an associated second focal plane (not shown in FIG. 14).

Positioned in close proximity to first point of focus 434 and second point of focus 436 is a plate 438 with pinhole 424 formed therein. Pinhole 424 is disposed within plate 438 so that it lies in the path of first polarization portion 430 and second polarization portion 432. Pinhole 424 serves to confocally filter read beam 426 (i.e. first polarization portion 430 and second polarization portion 432). Pinhole 424 is, typically, formed in a glass plate that is coated with a metal foil. The size of pinhole 424 is dependent upon the effective focal length of the combination of birefringent optical lens 422 and first standard optical lens 428, the diameter of the read beam 426 and the wavelength of read beam 426. By way of example, pinhole 424 may be sized so that 90% of intensity of the read beam passes through the pinhole when the pinhole is positioned at a point of focus. The pinhole may typically range in size from about 1 micron in diameter to about 50 microns in diameter, and is typically about 8 microns in diameter. Those skilled in the art will realize that the pinhole formation can be accomplished in a variety of manners. The pinhole configuration that is shown here is by way of example only and is not intended to be in any way limiting.

After read beam 426 has been filtered through pinhole 424 it is transmitted through second standard optical lens 440. Second standard optical lens 440 is, typically, a standard glass or polymeric lens. Second standard optical lens 440 serves maximize the performance of the polarizing beam splitter 442 by directing read beam 426 towards polarizing beam splitter 442. Second standard optical lens 440 is an optional element of FES generator device 420. It is possible and within the inventive
concept herein disclosed to configure FES generator device 420 without second standard optical lens 440 in instances where the focal length and beam diameter of read beam 426 are such that the use of second standard optical lens 440 would not be required. Polarizing beam splitter 442 separates the light of first polarization portion 430 from the light of second polarization portion 432. Light of first polarization portion 430 is directed towards detector 444 and light of second polarization portion 432 is directed towards detector 446.

Detector 444 and detector 446 may be standard photodiodes that serve to convert light beam photons to electrical signals in the form of electrons (an electrical current). The electrical signal is then provided to electronic differencing circuit 448 that generates a focus error signal. A servo system (not shown in FIG. 14) uses the focus error signal to direct the position of the objective lens in the optical head, thus completing the auto-focus procedure. Servo systems are well known in the art.

In contrast, in a prior-art data detection arm, a pinhole is generally used for confocal depth selection, and is generally situated so that light reflected from the desired depth - the focus of the read beam - comes to a focus in the plane of the pinhole, passing efficiently through it. For the FES generator device 420 shown in FIG. 14, when the optical head is focused on a layer within the storage medium first polarization portion 430 will form first point of focus 434 before pinhole 424 and second polarization portion 432 will form second point of focus 436 after pinhole 424.

The plate containing the pinhole is characteristically mounted within a FES generator device housing (not shown in FIG. 14) with the aid of a precision alignment fixture. Use of such alignment fixtures to position elements, such as pinhole plates, are well known by those of ordinary skill in the art.

The positioning of the points of focus in relation to the pinhole is instrumental in determining proper auto-focus. The ideal positioning of the points of focus are shown in FIG. 15A. This ideal positioning is achieved when the optical head is properly focused on the desired layer within the storage medium with respect to the depth of a data layer or layer center. First polarization portion 430 has first point of focus 434 slightly before pinhole 424 and second polarization portion 432 has second point of focus 436 slightly after pinhole 424. For this configuration, the intensities
detected for first polarization portion 430 and second polarization portion 432 are equivalent.

FIGS. 15B and 15C illustrate light beams that are focused either too deeply or too shallowly within the storage medium with respect of the depth of a layer or layer center. FIG. 15B gives an example of focusing too deeply within the storage medium. If the optical head is focused too deeply into the medium, first point of focus 434 and second point of focus 436 in the FES generator device are shifted towards the detectors (not shown in FIG. 15B). For moderate perturbations, at pinhole 424, the read beam is more tightly focused for first polarization portion 430 and less tightly focused for second polarization portion 432. Therefore, more light is transmitted via first polarization portion 430 than second polarization portion 432 and, thus, more light is detected by the detector associated with first polarization portion 430 than the detector associated with second polarization portion 432.

FIG. 15C provides an example of the optical head being focused too shallowly into the medium, resulting in first point of focus 434 and second point of focus 136 being shifted away from the detectors (not shown in FIG. 15C). For moderate perturbations, at pinhole 424, the read beam is more tightly focused for second polarization portion 432 and less tightly focused for first polarization portion 430. Therefore, more light is transmitted via second polarization portion 432 than first polarization portion 430 and, thus, more light is detected by the detector associated with second polarization portion 432 than the detector associated with first polarization portion 430. Thus, a simple difference in the intensities of the light indicates in which direction the optical head is out of focus.

A simple differencing circuit can be employed to generate a focus error signal in the present invention. For example, a first detector A outputs a current which is converted to a voltage A, and a second detector B outputs a current that is converted to a voltage B. Current-to-voltage techniques are well known in the art. The focus error signal (A - B) is positive when the focus is too deep, and negative when the focus is too shallow. Furthermore, the signal (A - B) is stronger as the beam is further out of focus. The focus error signal can be further normalized to the total strength (A + B) in order to compensate e.g. for fluctuations in laser strength. The focus error signal can be used to position the optical head so that it focuses on a layer e.g. by defining the
minimum and maximum tolerable value limits \( D_1 < (A - B) \div (A + B) < D_2 \); where \( D_1 \) is the minimum limit and \( D_2 \) is the maximum limit. When the normalized focus error signal \( (A - B) \div (A + B) \) falls outside this range, the head is moved in the appropriate direction to bring it within this range, thus focusing on a particular layer.

Referring again to FIG. 9A, signal intensities for first detector A and second detector B are shown as a function of depth of the material. The vertical line 220 indicates a particular depth of a formatted layer. At this depth, first detector A and second detector B provide the same output voltage that corresponds to the same signal strength. Referring again to FIG. 9B, the value of the focus error signal \( (A - B) \) is shown as a function of depth of the material. If the beam from the optical head is focused too deeply with respect to the nearest layer, then the focus error signal \( (A - B) \) is positive, and therefore the normalized focus error signal \( (A - B) \div (A + B) \) is positive. If the beam from the optical head is focused too shallowly with respect to the nearest layer, then the focus error signal \( (A - B) \) is negative, and therefore the normalized focus error signal \( (A - B) \div (A + B) \) is negative. Both the value of the focus error signal \( (A - B) \) and its slope can be used together to determine the direction and distance the optical head must be moved to restore focus to the nearest layer. Alternatively, the value of the normalized focus error signal and its slope can be used together to determine the direction and distance the optical head must be moved to restore focus to the nearest layer. Furthermore, the value of the focus error signal \( (A - B) \) and its slope can be used to supplement the evaluations based on a normalized focus error signal. Layer selection is accomplished by keeping track of the number of layers crossed as the optical head passes from the first layer it encounters to the others.

The strength of the focus error signal defined by \( (A - B) \) in FIG. 9B is proportional to the phase shift of the two signals A and B, illustrated in FIG. 9A. This relationship can be understood by referring to FIG. 10, which shows the general effect on the light beams when the head is not focused on a layer. FIG. 10 does not include all critical parts of the optical head, such as a spherical aberration corrector, but illustrates the effects of out-of-focus head position. For clarity, the figure does not illustrate effects of the index of refraction of the material; these effects would be apparent to those skilled in the art of optical sciences. In FIG. 10, the layer is indicated by a single reflecting surface for illustration purposes only.
In FIG. 10, a light beam 230 passes through the objective lens 232, is reflected by the layer 234, turns through the objective lens 232, passes through the beam splitter 236, and is then focused by the detection lens 238. The focal position of the light returning to the objective lens 232 is shifted by twice the depth positioning error. As would be apparent to those skilled in the optical sciences, the focus position in the detection optics therefore shifts by \( z_2 = \frac{(n_2)(f_1/f_2)^2}{n} \). In this equation \( n \) is the index of refraction of the material, \( f_1 \) is the focal length of objective lens 232, \( f_2 \) is the focal length of the detection lens 238, \( z_1 \) is the depth positioning error, and \( z_2 \) is the focal shift in the FES generator. An axial pinhole displacement \( z_2 \) therefore results in a detected phase shift of \( z_1 = (n/2)(f_1/f_2)^2 \) as illustrated in FIG. 9A.

Equivalently, the condition for strongest focus error signal can be cast in terms of the pinhole placement with respect to the layer spacing imaged by the detection lens. The strongest focus error signal (A - B) is achieved when the axial pinhole displacement is set such that the displacement of the pinhole from the point of focus for polarization A is adjusted to optionally detect a depth positioning error of \( z_{1A} = (1/4)z \), and for polarization B is adjusted to optionally detect a depth positioning error of \( z_{1B} = -(1/4)z \), where \( z \) is the spacing of the layers as measured by the optical focus displacement (FIG. 9B). For data detection, however, it is generally preferred that the pinhole reside equal distance from the points of focus of the beam, for which the displacement would be less than the Rayleigh range of the optical focus in the material (e.g., \( z_{1A} = z_{1B} = (1/2)z_R \), where \( z_R \) is the Rayleigh range of the beam focused in the material). Thus, it is generally preferred that the data detection and focus error generation optics described herein are in separate arms/paths (as shown in FIG. 5).

Equivalently, the condition for strongest focus error signal can be cast in terms of the pinhole placement with respect to the layer spacing imaged by the detection lens 238. In these terms, the strongest focus error signal (A - B) is achieved when the axial pinhole displacement from the point of focus for polarization A is \( z_{2A} = (1/4)z' \), and for polarization B is \( z_{2B} = -(1/4)z' \), where \( z' = (2z/n)(f_1/f_2)^2 \), which is the spacing of the layers as measured by the optical focus displacement (FIG. 9B). If it is required that the two signals A, B be in focus (e.g. to detect data), then the phase shift should be
reduced to less than the Rayleigh range of the optical focus of the detection lens (e.g. \( z_{2A} = -z_{2B} = (1/2)z_R \), where \( z_R \) is the Rayleigh range of the beam focused by the detection lens).

In an alternative preferred embodiment of the present invention, a focus error signal (B-A) can be generated to keep the beam focused on the nulls between data layers. This may be advantageous for data recording that does not utilize selective localized alteration of a format hologram.

Due to the properties of confocal detection, the pinhole diameter should be less than or equal to the diameter of the optical beam reflected from the material for optimal rejection of out-of-focus signals from other layers. In contrast, for maximum signal strength and positioning tolerance, the pinhole diameter should be greater than or equal to the optical beam diameter. A particular choice that balances these constraints is to set the pinhole size to just pass nearly all of the optical intensity of the non-aberrated beam. By way of example, the pinhole size can be selected so that 90% of intensity of the light beam passes through the pinhole when the pinhole is positioned at the beam focus.

The present invention can also be practiced to keep an optical head focused on tubular format regions (tubular format cross-sectional regions are illustrated in the storage medium of FIGS. 2B, 3B and 4B). The round cross sections sweep out tubular format regions throughout the radius of the material that result from complex format hologram grating structures. In this case, the reflected light detected by the system is relatively small between the tubes. Thus, the beam must be kept radially positioned on the data tube in order to remain focused on a particular data layer. Some tracking methods used for single layer and multiple media layer storage devices can be adapted for use in this invention as disclosed. By way of example, one such method of tracking comprises wobbling the focused spot radially, measuring the change in intensity, and directing the head to be positioned where the reflection is highest which correspond to the track centers. The operation of the focus error generator device of the present invention is otherwise the same.

Referring again to FIGS. 11A, 11B and 11C, data are shown for the strength of light reflected off a format hologram grating structures that defines layers and tracks which together define tubular format regions. FIG. 11A shows the strength of the reflected signal as a function of the depth (vertical dimension) and the radius
(transverse dimension) within the storage medium at a fixed angular position. FIG. 11B shows the strength of the reflect signal as a function of radius (transverse dimension) for two adjacent layers within the storage medium. Note that adjacent tracks are shifted in phase by half a period. FIG. 11C shows the strength of the reflected signal as a function of depth (vertical dimension) for two adjacent track positions. Note that these layers may be placed as closed as only a few times the depth of field of the readout optical beam.

A presently preferred embodiment of the present invention is illustrated in FIG. 16. Shown in FIG. 16 is an improved focus error signal (FES) generator device 520 comprising first pinhole 522 and second pinhole 524 that are in the path of read beam 526 returning from an optical data storage medium (not shown in FIG. 16). Unlike conventional pinholes that are formed in materials such as glass or polymers, first pinhole 522 and second pinhole 524 of the present invention are formed in corresponding, first polarizer 528 and second polarizer 530. By way of non-limiting example, the first polarizer 528 and second polarizer 530 may be a dichroic sheet polarizer or any other suitable polarizer material, known by those of ordinary skill in the art, may be used. The size of first pinhole 522 and second pinhole 524 is dependent upon the focal length of first optical lens 532, the diameter of the read beam 526 and the wavelength of read beam 526. By way of example, first and second pinholes 522, 524 may be sized so that 90% of intensity of the read beam passes through the pinholes when the pinholes are positioned at the point of focus. The pinholes may typically range in size from about 1 micron in diameter to about 50 microns in diameter, and is typically about 8 microns in diameter. In this embodiment first pinhole 522 and second pinhole 524 will have similar diameters. Those skilled in the art will realize that the pinhole configuration can be accomplished in a variety of manners. The pinhole configuration that is shown here is by way of example only and is not intended to be in any way limiting.

An optical head (not shown in FIG. 16) focuses light onto a data layer in a data storage medium. By way of example, the data storage medium may be comprised of either multiple layers of data storage or a bulk, monolithic holographic storage medium that has a format hologram grating stored therein to define layers. Read beam 526 enters FES generator device 520 on a return path from the data storage medium. Read
beam 526 travels through first optical lens 532 that provides for point of focus 534. First optical lens 532 is, typically, a standard glass or plastic optical lens.

First polarizer 528 and second polarizer 530 are situated within the FES generator device 520 so that they result in cross polarization. The polarization state of this incident beam may therefore be considered to be made up of two independent polarizations each oriented parallel to the transmission direction of one of the two polarizers 528 and 530. As read beam 526 encounters first polarizer 528, the portion of read beam 526 parallel to the transmission direction of first polarizer 528 passes through first polarizer 528 with minimal loss. The read beam 526 then encounters second polarizer 530 which blocks all of the light parallel to the transmission direction of first polarizer 528 except in the region of second pinhole 524. Accordingly, the portion of read beam 526 parallel to the transmission direction of second polarizer 530 is blocked at first polarizer 528 except in the region of first pinhole 522. As the portion of read beam 526 parallel to the transmission direction of second polarizer 530 encounters second polarizer 530, this portion of read beam 526 passes through second polarizer 530 with minimal loss. The net effect of the polarizers is that, when a layer within the storage medium is in focus, first polarizer 528 is before point of focus 534 and second polarizer 530 is after point of focus 534.

After read beam 526 has been transmitted through second polarizer 530 and second pinhole 524, read beam 526 is transmitted through second optical lens 536. Second optical lens 536 is, typically, a standard glass or polymeric lens. Second optical lens 536 serves to direct read beam 526 towards polarizing beam splitter 538. Second optical lens 536 is an optional element of FES generator device 520. It is possible and within the inventive concept herein disclosed to configure FES generator device 520 without second optical lens 536 in instances where the focal length and beam diameter of read beam 526 are such that the use of second optical lens 536 would not be required. Polarizing beam splitter 538 separates the light into a first light beam 540 of first polarization and a second light beam 542 of second polarization. First light beam 540 is directed towards first detector 544 and second light beam 542 is directed towards second detector 546.

First Detector 544 and second detector 546 may be standard photodiodes that serve to convert light beam photons to electrical signals in the form of electrons (an electrical current). The electrical signal is then provided to electronic differencing
circuit 548 that generates a focus error signal. A servo system (not shown in FIG. 16) uses the focus error signal to direct the position of the objective lens in the optical head, thus completing the auto-focus procedure. Servo systems are well known in the art.

In contrast, in a prior-art data detection arm (shown in FIG. 5 at 106), a pinhole is generally used for confocal depth selection, and is generally situated so that light reflected from the desired depth - the focus of the read beam - comes to a focus in the optical pickup and passes efficiently through the pinhole. For the device shown in FIG. 16, the pinholes are displaced to either side of the point of focus 534 of read beam 526. Thus, when the optical head is focused on a layer, the point of focus 534 in FES generator device 520 occurs after first pinhole 522 and before second pinhole 524. Point of focus 534 occurs within the focal plane (not shown in FIG. 16) of first optical lens 532. For this configuration, the intensities of first polarization and second polarization that propagate through first and second pinholes 522 and 524, and are detected at corresponding first and second detectors 544 and 546, are equivalent.

First polarizer 528 and second polarizer 530 are, generally, plates that are characteristically mounted within a FES generator device housing (not shown in FIG. 16) with the aid of a precision alignment fixture. Use of such alignment fixtures to position elements such as pinhole plates are well known by those of ordinary skill in the art.

The positioning of the point of focus in relation to the pinholes is instrumental in determining proper auto-focus. The ideal positioning of the point of focus is shown in FIG. 17A. This ideal positioning is achieved when the optical head is properly focused on the desired layer within the storage medium with respect to the depth of a data layer or layer center. Point of focus 662 of read beam 660 occurs at about a midway point between first pinhole 664 and second pinhole 666.

FIGS. 17B and 17C illustrate light beams that are focused either too deeply or too shallowly within the storage medium with respect of the depth of a layer or layer center. FIG. 17B gives an example of focusing too deeply within the storage medium. If the optical head is focused too deeply into the medium, point of focus 668 of read beam 670 is shifted towards the detectors (not shown in FIG. 17B). For moderate perturbations, read beam 670 is more tightly focused for second pinhole 672 of second polarizer 674 and is less tightly focused for first pinhole 676 of second polarizer 678.
Thus, more light is transmitted through second polarizer 674 than first polarizer 678 and, therefore more light is detected by the detector corresponding to the polarization of second polarizer 674 than the detector corresponding to the polarization of first polarizer 678. FIG. 17C indicates an example of the optical head being focused too shallowly into the medium, resulting in point of focus 680 of read beam 682 being shifted away from the detectors (not shown in FIG. 17C). For moderate perturbations, read beam 682 is more tightly focused for first pinhole 684 of first polarizer 686 and is less tightly focused for second pinhole 688 of second polarizer 690. Thus, more light is transmitted throughout first polarizer 686 than second polarizer 690 and therefore more light is detected by the detector corresponding to the polarization of first polarizer 686 than the detector corresponding to the polarization of second polarizer 690. Thus, a simple difference in the intensities of the light indicates in which direction the optical head is out of focus.

A simple differencing circuit can be employed to generate a focus error signal in the present invention. For, example, first Detector A outputs a current which is converted to a voltage A, and second detector B outputs a current that is converted to a voltage B. Current-to-voltage techniques are well known in the art. The focus error signal \( A - B \) is positive when the focus is too deep, and negative when the focus is too shallow. Furthermore, the signal \( A - B \) is stronger as the beam is further out of focus. The focus error signal can be further normalized to the total strength \( A + B \) in order to compensate e.g. for fluctuations in laser strength. The focus error signal can be used to position the optical head so that it focuses on a layer e.g. by defining the minimum and maximum tolerable value limits \( D1 < (A - B) \div (A + B) < D2 \); where \( D1 \) is the minimum limit and \( D2 \) is the maximum limit. When the normalized focus error signal \( (A - B) \div (A + B) \) falls outside this range, the head is moved in the appropriate direction to bring it within this range, thus focusing on a particular layer.

Referring again to FIG. 9A, signal intensities for first detector A and second detector B are shown as a function of depth of the material. The vertical line 220 indicates a particular depth of a formatted layer. At this depth, first detector A and second detector B provide the same output voltage that corresponds to the same signal strength. Referring now to FIG. 8B, the value of the focus error signal \( A - B \) is shown as a function of depth of the material. If the beam from the optical head is focused too deeply with respect to the nearest layer, then the focus error signal \( A - B \)
is positive, and therefore the normalized focus error signal \((A - B) \div (A + B)\) is positive. If the beam from the optical head is focused too shallowly with respect to the nearest layer, then the focus error signal \((A - B)\) is negative, and therefore the normalized focus error signal \((A - B) \div (A + B)\) is negative. Both the value of the focus error signal \((A - B)\) and its slope can be used together to determine the direction and distance the optical head must be moved to restore focus to the nearest layer. Alternatively, the value of the normalized focus error signal and its slope can be used together to determine the direction and distance the optical head must be moved to restore focus to the nearest layer. Furthermore, the value of the focus error signal \((A - B)\) and its slope can be used to supplement the evaluations based on a normalized focus error signal. Layer selection is accomplished by keeping track of the number of layers crossed as the optical head passes from the first layer it encounters to the others.

The strength of the focus error signal defined by \((A - B)\) in FIG. 8B is proportional to the phase shift of the two signals A and B, illustrated in FIG. 8A. This relationship can be understood by referring to FIG. 10, which shows the general effect on the light beams when the head is not focused on a layer. FIG. 10 does not include all critical parts of the optical head, such as a spherical aberration corrector, but illustrates the effects of out-of-focus head position. For clarity, the figure does not illustrate effects of the index of refraction of the material; these effects would be apparent to those skilled in the art of optical sciences. In FIG. 10, the layer is indicated by a single reflecting surface for illustration purposes only.

In FIG. 10, light beam 230 passes through the objective lens 232, is reflected by the layer 234, turns through the objective lens 232, passes through the beam splitter 236, and is then focused by the detection lens 238. The focal position of the light returning to the objective lens 232 is shifted by twice the depth positioning error. As would be apparent to those skilled in the optical sciences, the focus position in the detection optics therefore shifts by \(\_Z_2 = (2\_Z_1/n)(f_1/f_2)^2\). In this equation \(n\) is the index of refraction of the material, \(f_1\) is the focal length of objective lens 232, \(f_2\) is the focal length of the detection lens 238, \(\_Z_1\) is the depth positioning error, and \(\_Z_2\) is the focal shift in the FES generator. An axial pinhole displacement \(\_Z_2\) therefore results in a detected phase shift of \(\_Z_1 = (n/2)\_Z_2(f_1/f_2)^2\), as illustrated in FIG. 9A.

The strongest focus error signal \((A - B)\) is achieved when the axial pinhole displacement is set such that the displacement of the pinhole from the point of focus
for polarization A is adjusted to optionally detect a depth positioning error of \( z_{1A} = (1/4)_z \), and for polarization B is adjusted to optionally detect a depth positioning error of \( z_{1B} = -(1/4)_z \), where \( _z \) is the spacing of the layers as measured by the optical focus displacement (FIG. 9B). For data detection, however, it is generally preferred that the pinholes reside equal distance from the point of focus of the beam, for which the displacement would be less than the Rayleigh range of the optical focus in the material (e.g., \( z_{1A} = z_{1B} = (1/2)z_R \), where \( z_R \) is the Rayleigh range of the beam focused in the material). Thus, it is generally preferred that the data detection and focus error generation optics described herein are in separate arms/paths (as shown in FIG. 5).

Equivalently, the condition for strongest focus error signal can be cast in terms of the pinhole placement with respect to the layer spacing imaged by the detection lens 238. In these terms, the strongest focus error signal (A - B) is achieved when the axial pinhole displacement from the point of focus for polarization A is \( z_{2A} = (1/4)z' \), and for polarization B is \( z_{2B} = -(1/4)z' \), where \( z' = (2z/h)(f_1/f_2)^2 \), which is the spacing of the layers as measured by the optical focus displacement (FIG. 9B). If it is required that the two signals A, B be in focus (e.g. to detect data), then the phase shift should be reduced to less than the Rayleigh range of the optical focus of the detection lens (e.g. \( z_{2A} = z_{2B} = (1/2)z_{R'} \), where \( z_{R'} \) is the Rayleigh range of the beam focused by the detection lens).

In an alternative preferred embodiment of the present invention, a focus error signal (B-A) can be generated to keep the beam focused on the nulls between data layers. This may be advantageous for data recording that does not utilize selective localized alteration of a format hologram.

Due to the properties of confocal detection, the pinhole diameter should be less than or equal to the diameter of the optical beam reflected from the material for optimal rejection of out-of-focus signals from other layers. In contrast, for maximum signal strength and positioning tolerance, the pinhole diameter should be greater than or equal to the optical beam diameter. A particular choice that balances these constraints is to set the pinhole size to just pass nearly all of the optical intensity of the non-aberrated beam. By way of example, the pinhole size can be selected so that 90% of intensity of the light beam passes through the pinhole when the pinhole is positioned at the beam focus.
The present invention can also be practiced to keep an optical head focused on tubular format regions (tubular format cross-sectional regions are illustrated in the storage medium of FIGS. 2B, 3B and 4B). The round cross sections sweep out tubular format regions throughout the radius of the material that result from complex format hologram grating structures. In this case, the reflected light detected by the system is relatively small between the tubes. Thus, the beam must be kept radially positioned on the data tube in order to remain focused on a particular data layer. Some tracking methods used for single layer and multiple media layer storage devices can be adapted for use in this invention as disclosed. By way of example, one such method of tracking comprises wobbling the focused spot radially, measuring the change in intensity, and directing the head to be positioned where the reflection is highest which correspond to the track centers. The operation of the focus error generator device of the present invention is otherwise the same.

Referring once again to FIGS. 11A, 11B and 11C, data are shown for the strength of light reflected off a format hologram grating structures that defines layers and tracks which together define tubular format regions. FIG. 11A shows the strength of the reflected signal as a function of the depth (vertical dimension) and the radius (transverse dimension) within the storage medium at a fixed angular position. FIG. 11B shows the strength of the reflect signal as a function of radius (transverse dimension) for two adjacent layers within the storage medium. Note that adjacent tracks are shifted in phase by half a period. FIG. 11C shows the strength of the reflected signal as a function of depth (vertical dimension) for two adjacent track positions. Note that these layers may be placed as closed as only a few times the depth of field of the readout optical beam.

Although illustrative presently preferred embodiments and applications of this invention are shown and described herein, many variations and modifications are possible which remain within the concept, scope and spirit of the invention, and these variations would become clear to those skilled in the art after review of this disclosure. The invention, therefore is not limited except in spirit of the appended claims.
What is Claimed is:

1. An apparatus for generating a focus error signal from a read light beam returning from an optical storage media comprising:
   a first optical lens disposed in the path of a first light beam derived from said read light beam, said first optical lens having a first focal plane;
   a second optical lens disposed in the path of a second light beam derived from said read light beam, said second optical lens having a second focal plane;
   a first optical detector disposed in the path of said first light beam, said first optical detector after said first focal plane;
   a second optical detector disposed in the path of said second light beam after said second focal plane;
   a first pinhole disposed in the path of said first light beam after said first optical lens and before said first optical detector;
   a second pinhole disposed in the path of said second light beam after said second optical lens and before said second optical detector; and
   an electrical differencing circuit having a first input coupled to said first optical detector, a second input coupled to said second optical detector and an output.

2. An apparatus in accordance with claim 1, wherein said electrical differencing circuit generates a focus error signal related to the difference between the output of said first optical detector and the output of said second optical detector.

3. An apparatus in accordance with claim 1, wherein said electrical differencing circuit generates a focus error signal related to the difference between the distance from said first focal plane to said first pinhole and the distance from said second focal plane to said second pinhole.

4. An apparatus in accordance with claim 1, further comprising a beam splitter disposed in the path of said read beam returning from an optical storage media, said beam splitter splitting said read light beam returning from an optical storage media into said first light beam and said second light beam.
5. An apparatus in accordance with claim 1, further comprising:

a third optical lens disposed in the path of said first light beam after said first focal plane and before said first optical detector; and

a fourth optical lens disposed in the path of said second light beam after said second focal plane and before said second optical detector.

6. An apparatus in accordance with claim 1, wherein said first and second pinholes have diameters that allows for the passage of about 90% of the intensity of said first and second beams of light, respectively, when said first and second pinholes are positioned at their respective points of focus.

7. An apparatus for generating a focus error signal from a read light beam returning from an optical storage media:

means for focussing a first light beam derived from said read light beam at a first point of focus within a first focal plane;

means for focussing a second light beam derived from said read light beam at a second point of focus within a second focal plane spaced apart from said first point of focus;

means for first optical detection in the path of said first light beam after said first focal plane;

means for second optical detection in the path of said second light beam after said second focal plane;

means for a first confocal light beam filtration in the path of said first beam of light before said means for first optical detection;

means for a second confocal light beam filtration in the path of said second light beam before said means for second optical detection; and

means for generating a focus error signal related to the difference between an output from said means for first optical detection and an output from said means for second optical detector.

8. A method for generating a focus error signal from a read light beam returning from an optical storage media comprising the steps of:
focussing a first light beam derived from the read light beam at a first point of focus within a first focal plane;

focussing a second beam of light derived from said read light beam at a second point of focus within a second focal plane;

providing a first optical detector in the path of said first light beam after said first focal plane;

providing a second optical detector in the path of said second light beam after said second focal plane;

providing a first pinhole in the path of said first beam of light before said first optical detector;

providing a second pinhole in the path of said second light beam before said second optical detector; and

generating a focus error signal related to the difference between an output from said first optical detector and an output from said second optical detector.

9. A method in accordance with claim 8, wherein the step of generating a focus error signal further comprises generating a focus error signal related to the difference between the distance from said first point of focus to said first pinhole and the distance from said second point of focus to said second pinhole.

10. A method in accordance with claim 8, further comprising the step of splitting said read light beam returning from an optical storage media into said first light beam and said second light beam.

11. A method in accordance with claim 10, further comprising the substep of providing a beam splitter to receive said read light beam returning from an optical storage media, said beam splitter outputting said first light beam and said second light beam.

12. A method in accordance with claim 8, further comprising the steps of:

providing a first optical lens through which said first light beam passes to create said first point of focus within said first focal plane; and
providing a second optical lens through which said second light beam passes to create said second point of focus within said second focal plane.

13. A method in accordance with claim 8 further comprising the steps of:
providing a third optical lens through which said first light beam passes after said first focal plane and before said first optical detector; and
providing a fourth optical lens through which said second light beam passes after said second focal plane and before said second optical detector.

14. A method in accordance with claim 8, further comprising the steps of:
positioning said first pinhole before said first focal plane; and
positioning said second pinhole after said second focal plane.

15. A method in accordance with claim 8, further comprising the steps of:
positioning said first pinhole after said first focal plane; and
positioning said second pinhole before said second focal plane.

16. A method in accordance with claim 8 further comprising the steps of:
providing said first pinhole with a diameter that allows for passage of about 90% of the intensity of said first beam of light when said first pinhole is positioned at said first point of focus; and
providing said second pinhole with a diameter that allows for passage of about 90% of the intensity of said second beam of light when said second pinhole is positioned at said second point of focus.

17. A system for optical delivery and detection comprising:
a laser source that emits a first light beam;
an optical head that receives said first light beam;
an optical lens within said optical head that focuses said first light beam on a location within a storage media;
a data detector that receives said first light beam returning from said storage media and provides data signals;
a tracking error detector that receives said first light beam returning from said storage media and provides a tracking error signal to said optical head; and

a focus error signal generator that receives said first light beam returning from said optical storage media and provides a focus error signal to said optical head, said focus error signal generator including:

a first optical lens disposed in the path of a second light beam derived from said first light beam, said first optical lens having a first focal plane;

a second optical lens disposed in the path of a third light beam derived from said first light beam, said second optical lens having a second focal plane;

a first optical detector disposed in the path of said second light beam after said first focal plane;

a second optical detector disposed in the path of said third light beam after said second focal plane;

a first pinhole disposed in the path of said second light beam after said first optical lens and before said first optical detector;

a second pinhole disposed in the path of said third light beam after said second optical lens and before said second optical detector; and

an electrical differencing circuit having a first input coupled to said first optical detector, a second input coupled to said second optical detector and an output.

18. A system in accordance with claim 18, wherein said storage media has layer separation ($\Delta z$), said layer separation having a corresponding spacing ($\Delta z'$) as measured by an optical focus displacement and wherein said first pinhole is placed $(1/4) \Delta z'$ from said first focal plane and said second pinhole is placed $-(1/4) \Delta z'$ from said second focal plane.

19. An apparatus for generating a focus error signal from a read light beam returning from an optical storage media comprising:

a first optical lens disposed in the path of said read light beam;

a birefringent plate disposed in the path of said read light beam after said first optical lens, said birefringent plate creating a first focal plane of a first polarization and a second focal plane of a second polarization for said read light beam;
a pinhole disposed in the path of said read light beam after said birefringent plate and in close proximity to said first and second focal planes;

a polarizing beam splitter disposed in the path of said read light beam after said second focal plane, said polarizing beam splitter creating a first polarization beam and a second polarization beam from said read light beam;

a first optical detector disposed in the path of said first polarization beam;

a second optical detector disposed in the path of said second polarization beam;

and

an electrical differencing circuit having a first input coupled to said first optical detector, a second input coupled to said second optical detector and an output.

20. An apparatus in accordance with claim 19, wherein said electrical differencing circuit generates a focus error signal related to the difference between the output of said first optical detector and the output of said second optical detector.

21. An apparatus in accordance with claim 19, wherein said electrical differencing circuit generates a focus error signal related to the difference between the distance from said first focal plane to said pinhole and the distance from said second focal plane to said pinhole.

22. An apparatus in accordance with claim 19, further comprising a second optical lens disposed in the path of said read light beam after said second focal plane and before said polarizing beam splitter.

23. An apparatus in accordance with claim 19, wherein said pinholes has a diameter that allows for the passage of about 90% of the intensity of said read light beam when said pinhole is positioned at a point of focus.

24. A method for generating a focus error signal from a read light beam returning from an optical storage media comprising the steps of:

foocussing said read light beam;
providing a birefringent plate through which said read light beam passes to create a first focal plane of a first polarization and a second focal of a second polarization;

providing a pinhole in the path of said read light beam after said birefringent plate and in close proximity to said first and second focal planes;

providing a polarizing beam splitter disposed in said path of said read light beam after said second focal plane, said polarizing beam splitter creating a first polarization beam and a said second polarization beam from said read beam;

providing a first optical detector in the path of said first polarization beam;

providing a second optical detector in the path of said second polarization beam; and

generating a focus error signal related to the difference between an output from said first optical detector and an output from said second optical detector.

25. A method in accordance with claim 24, wherein the step of generating a focus error signal further comprises generating a focus error signal related to the difference between the distance from said first focal plane to said pinhole and the distance from said second focal plane to said pinhole.

26. A method in accordance with claim 24, further comprising the step of providing an optical lens through which said read light beam passes after said second focal plane and before said polarization beam splitter.

27. A method in accordance with claim 24, further comprising the steps of:

positioning said pinhole after said first focal plane; and

positioning said pinhole before said second focal plane.

28. A method in accordance with claim 24, further comprising the step of providing said pinhole with a diameter that allows for passage of about 90% of the intensity of said read light beam when said pinhole is positioned at a first point of focus within said first focal plane.
29. A method in accordance with claim 24, further comprising the step of providing said pinhole with a diameter that allows for passage of about 90% of the intensity of said read light beam when said pinhole is positioned at a second point of focus within said second focal plane.

30. A system for optical delivery and detection comprising:
   a laser source that emits a first light beam;
   an optical head that receives said first light beam;
   an optical lens within said optical head that focuses said first light beam on a location within a storage media;
   a data detector that receives said first light beam returning from said storage media and provides data signals;
   a tracking error detector that receives said first light beam returning from said storage media and provides a tracking error signal to said optical head; and
   a focus error signal generator that receives said first light beam returning from said optical storage media and provides a focus error signal to said optical head, said focus error signal generator including:
   a first optical lens disposed in the path of said first light beam;
   a birefringent plate disposed in the path of said first light beam after said first optical lens, said birefringent plate creating a first focal plane of a first polarization and a second focal plane of a second polarization from said first light beam;
   a pinhole disposed in the path of said first light beam after said birefringent plate and in close proximity to said first and second focal planes;
   a polarizing beam splitter disposed in the path of said first light beam after said second focal plane, said polarizing beam splitter creating a second light beam of first polarization and a third light beam of second polarization from said first light beam;
   a first optical detector disposed in the path of said second light beam;
   a second optical detector disposed in the path of said third light beam; and
   an electrical differencing circuit having a first input coupled to said first optical detector, a second input coupled to said second optical detector and an output.

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31. A system in accordance with claim 30, wherein said storage media has layer separation ($\Delta z$), said layer separation having a corresponding spacing ($\Delta z'$) as measured by an optical focus displacement and wherein said pinhole is placed $(1/4) \Delta z'$ from said first focal plane and said pinhole is placed $-(1/4) \Delta z'$ from said second focal plane.

32. An apparatus for generating a focus error signal from a read light beam returning from an optical storage media comprising:

a birefringent lens disposed in the path of said read light beam, said birefringent optical lens creating a first focal plane of a first polarization and a second focal plane of a second polarization;

a pinhole disposed in the path of said read light beam after said first optical lens and in close proximity to said first and second focal planes;

a polarizing beam splitter disposed in the path of said read light beam after said second focal plane, said polarizing beam splitter creating a first polarization beam and a second polarization beam from said read light beam;

a first optical detector disposed in the path of said first polarization beam;

a second optical detector disposed in the path of said second polarization beam; and

an electrical differencing circuit having a first input coupled to said first optical detector, a second input coupled to said second optical detector and an output.

33. An apparatus in accordance with claim 32, wherein said electrical differencing circuit generates a focus error signal related to the difference between the output of said first optical detector and the output of said second optical detector.

34. An apparatus in accordance with claim 32, wherein said electrical differencing circuit generates a focus error signal related to the difference between the distance from said first focal plane to said pinhole and the distance from said second focal plane to said pinhole.

35. An apparatus in accordance with claim 32, further comprising:
a first optical lens disposed in the path of said read light beam after said birefringent lens and before said pinhole;

36. An apparatus in accordance with claim 32, further comprising a second optical lens disposed in the path of said read light beam after said second focal plane and before said polarizing beam splitter.

37. An apparatus in accordance with claim 32, wherein said pinhole has a diameter that allows for the passage of about 90% of the intensity of said read light beam when said pinhole is positioned at a point of focus within a focal plane.

38. An apparatus for generating a focus error signal from a read light beam returning from an optical storage media:

means for focussing said read light beam at a first point of focus within a first focal plane of a first polarization and a second point of focus within a second focal plane of a second polarization;

means for confocal light beam filtration disposed in the path of said read light beam in close proximity to said first point of focus and said second point of focus;

means for polarization beam splitting said read light beam into a first polarization beam and a second polarization beam;

means for first optical detection in the path of said first polarization beam;

means for second optical detection in the path of said second polarization beam; and

means for generating a focus error signal related to the difference between an output from said means for first optical detection and an output from said means for second optical detection.

39. A method for generating a focus error signal from a read light beam returning from an optical storage media comprising the steps of:

focussing said read light beam at a first point of focus within a first focal plane and a second point of focus within a second focal plane;
providing a pinhole in the path of said read light beam in close proximity to said first and second point of focus;

providing a polarizing beam splitter disposed in said path of said read light beam after said second focal plane, said polarizing beam splitter creating a first polarization beam and a second polarization beam from said read light beam;

providing a first optical detector in the path of said first polarization beam;

providing a second optical detector in the path of said second polarization beam; and

generating a focus error signal related to the difference between an output from said first optical detector and an output from said second optical detector.

40. A method in accordance with claim 39, wherein the step of generating a focus error signal further comprises generating a focus error signal related to the difference between the distance from said first point of focus to said pinhole and the distance from said second point of focus to said pinhole.

41. A method in accordance with claim 39, further comprising the step of providing a birefringent lens through which said read light beam passes to create said first point of focus within said first focal plane and said second point of focus within said second focal plane.

42. A method in accordance with claim 39, further comprising the step of providing an optical lens through which said read light beam passes after said second point of focus and before said polarization beam splitter.

43. A method in accordance with claim 39, further comprising the steps of:

positioning said pinhole after said first focal plane; and

positioning said pinhole before said second focal plane.

44. A method in accordance with claim 39, further comprising the steps of:
providing said pinhole with a diameter that allows for passage of about 90\% of the intensity of said read light beam when said pinhole is positioned at said first point of focus.

45. A method in accordance with claim 39, further comprising the step of providing said pinhole with a diameter that allows for passage of about 90\% of the intensity of said read light beam when said pinhole is positioned at said second point of focus.

46. A system for optical delivery and detection comprising:

a laser source that emits a first light beam;
an optical head that receives said first light beam;
an optical lens within said optical head that focuses said first light beam on a location within a storage media;
a data detector that receives said first light beam returning from said storage media and provides data signals;
a tracking error detector that receives said first light beam returning from said storage media and provides a tracking error signal to said optical head; and
a focus error signal generator that receives said first light beam returning from said optical storage media and provides a focus error signal to said optical head, said focus error signal generator including:
a birefringent lens disposed in the path said first light beam, said birefringent optical lens creating a first focal plane of a first polarization and a second focal plane of a second polarization;
a pinhole disposed in the path of said first light beam after said first optical lens and in close proximity to said first and second focal planes;
a polarizing beam splitter disposed in the path of said first light beam after said pinhole, said polarizing beam splitter creating a second light beam of first polarization and a third light beam of second polarization beam from said first light beam;
a first optical detector disposed in the path of said second light beam;
a second optical detector disposed in the path of said third light beam; and
an electrical differencing circuit having a first input coupled to said first optical detector, a second input coupled to said second optical detector and an output.

47. A system in accordance with claim 46, wherein said storage media has layer separation ($\Delta z$), said layer separation having a corresponding spacing ($\Delta z'$) as measured by an optical focus displacement and wherein said pinhole is placed $(1/4) \Delta z'$ from said first focal plane and said pinhole is placed $-(1/4) \Delta z'$ from said second focal plane.

48. An apparatus for generating a focus error signal from a read light beam returning from an optical storage media comprising:
   a first optical lens disposed in the path of said read light beam, said first optical lens creating a point of focus within a focal plane;
   a first polarizer of a first polarization having a first pinhole formed therein, said first polarizer and said first pinhole disposed in the path of said read light beam after said first optical lens;
   a second polarizer of a second polarization having a second pinhole formed therein, said second polarizer and said second pinhole disposed in the path of said read light beam after said first polarizer;
   a polarizing beam splitter disposed in the path of said read beam of light after said second polarizer, said polarizing beam splitter creating a first polarization beam and a second polarization beam from said read light beam;
   a first optical detector disposed in the path of said first polarization beam;
   a second optical detector disposed in the path of said second polarization beam; and
   an electrical differencing circuit having a first input coupled to said first optical detector, a second input coupled to said second optical detector and an output.

49. An apparatus in accordance with claim 48, wherein said electrical differencing circuit generates a focus error signal related to the difference between the output of said first optical detector and the output of said second optical detector.
50. An apparatus in accordance with claim 48, wherein said electrical differencing circuit generates a focus error signal related to the difference between the distance from said focal plane to said first pinhole and the distance from said focal plane to said second pinhole.

51. An apparatus in accordance with claim 48, further comprising a second optical lens disposed in the path of said read light beam after said second polarizer and before said polarizing beam splitter.

52. An apparatus in accordance with claim 48, wherein said first and second pinholes have diameters that allow for the passage of about 90% of the intensity of said read light beam when a pinhole is positioned at the point of focus.

53. An apparatus for generating a focus error signal from a read light beam returning from an optical storage media:
   means for focussing said read light beam at a point of focus within a focal plane;
   means for first polarization disposed in the path of said read light beam in close proximity to said point of focus, said means for first polarization including a means for first confocal light beam filtration disposed in said path of said read light beam;
   means for second polarization disposed in said path of said read light beam after said means for first polarization and in close proximity to said point of focus, said means for second polarization including a means for second confocal light beam filtration disposed in said path of said read light beam;
   means for polarization beam splitting said read light beam into a first polarization beam and a second polarization beam;
   means for first optical detection in the path of said first polarization beam;
   means for second optical detection in the path of said second polarization beam; and
means for generating a focus error signal related to the difference between an output from said means for first optical detection and an output from said means for second optical detection.

54. A method for generating a focus error signal from a read light beam returning from an optical storage media comprising the steps of:

focussing said read light beam at a point of focus within afocal plane;
providing a first polarizer of a first polarization having a first pinhole formed therein, said first polarizer and said first pinhole disposed in the path of said read light beam;
providing a second polarizer of a second polarization having a second pinhole formed therein, said second polarizer and said second pinhole disposed in said path of said read light beam after said first polarizer;
providing a polarizing beam splitter disposed in said path of said read light beam after said second polarizer, said polarizing beam splitter creating a first polarization beam and a second polarization beam from said read light beam;
providing a first optical detector in the path of said first polarization beam;
providing a second optical detector in the path of said second polarization beam; and

generating a focus error signal related to the difference between an output from said first optical detector and an output from said second optical detector.

55. A method in accordance with claim 54, wherein the step of generating a focus error signal further comprises:

generating a focus error signal related to the difference between the distance from said point of focus to said first pinhole and the distance from said point of focus to said second pinhole.

56. A method in accordance with claim 54, further comprising the step of providing a first optical lens through which said read light beam passes to create the focussing mechanism for said point of focus within said focal plane.
57. A method in accordance with claim 54, further comprising the step of providing a second optical lens through which said read light beam passes after said second polarizer and before said polarizing beam splitter.

58. A method in accordance with claim 54, further comprising the steps of:
positioning said first polarizer before said focal plane; and
positioning said second polarizer after said focal plane.

59. A method in accordance with claim 54 further comprising the steps of:
providing said first pinhole with a diameter that allows for passage of about 90% of the intensity of said read light beam when said first pinhole is positioned at said point of focus; and
providing said second pinhole with a diameter that allows for passage of about 90% of the intensity of said read light beam when said second pinhole is positioned at said point of focus.

60. A system for optical delivery and detection comprising:
a laser source that emits a first light beam;
an optical head that receives said first light beam;
an optical lens within said optical head that focuses said first light beam on a location within a storage media;
a data detector that receives said first light beam returning from said storage media and provides data signals;
a tracking error detector that receives said first light beam returning from said storage media and provides a tracking error signal to said optical head; and
a focus error signal generator that receives said first light beam returning from said optical storage media and provides a focus error signal to said optical head, said focus error signal generator including:
a first optical lens disposed in the path of said first light beam, said first optical lens creating a point of focus within a focal plane;
a first polarizer of a first polarization having a first pinhole formed therein, said first polarizer and said first pinhole disposed in the path of said first light beam after said first optical lens;
a second polarizer of a second polarization having a second pinhole
formed therein, said second polarizer and second pinhole disposed in the path of said
first light beam after said first polarizer;

a polarizing beam splitter disposed in the path of said first beam of light
after said second polarizer, said polarizing beam splitter creating a second light beam of
said first polarization and a third light beam of said second polarization;

a first optical detector disposed in the path of said second light beam;
a second optical detector disposed in the path of said third light beam; and
an electrical differencing circuit having a first input coupled to said first
optical detector, a second input coupled to said second optical detector and an output.

61. A system in accordance with claim 60, wherein said storage media has
layer separation (Δz), said layer separation having a corresponding spacing (Δz') as
measured by an optical focus displacement and wherein said first pinhole is placed (1/4)
Δz' from said focal plane and said second pinhole is placed -(1/4) Δz' from said focal
plane.
FIG. 7C

FIG. 8

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**INTERNATIONAL SEARCH REPORT**

International application No.  
PCT/US00/00581

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC(7)  : G11B 7/09, 7/12  
US CL  : 369/44.23, 44.14, 112, 118  
According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**  
Minimum documentation searched (classification system followed by classification symbols)  
U.S. : 369/44.23, 44.14, 112, 118  
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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</thead>
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<tr>
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<td>US 5,590,110 A (SATO) 31 December 1996, Fig. 7.</td>
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Further documents are listed in the continuation of Box C.  
See patent family annex.

Date of the actual completion of the international search  
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06 APR 2000

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