LOW-BIREFRINGENCE OPTICAL FIBER FOR USE IN AN OPTICAL DATA STORAGE SYSTEM

Related Applications

The present invention is related to and claims priority from U.S. Provisional Applications 60/079,903 entitled "Optical Drive Utilizing Low Birefringence Fiber," filed 30 March 1998 and 60/088,192 entitled "Laser Phase Noise Minimization In Optical Drive," filed 5 June 1998, which are incorporated herein by reference.

Background Of The Invention

1. Field of the Invention

The present invention relates generally to optical fiber for use in data storage systems. More particularly, the present invention relates to low-birefringence optical fibers in optical data storage systems.

2. Background Art

In a magneto-optical storage system, using a magneto-optical (MO) recording material deposited on a rotating disk, information may be recorded on the disk as spatial variations of magnetic domains. During readout, a magnetic domain pattern modulates an optical polarization, and a detection system converts a resulting signal from optical to electronic format.

In one type of a magneto-optical storage system, a magneto-optical head assembly is located on a linear actuator that moves the head along a radial direction of the disk to position the optical head assembly over data tracks during recording and readout. A magnetic coil is placed on a separate assembly on the head assembly to create a magnetic field that has a magnetic component in a direction perpendicular to the disk surface. A vertical magnetization of polarity, opposite to that of the surrounding magnetic material of the disk medium, is recorded as a mark indicating zero or a one by first focusing a beam of laser light to form an optical spot on the disk. The optical spot functions to heat the magneto-optical material to a temperature near or above a Curie point (a temperature at which the magnetization may be readily altered with an applied magnetic field). A current passed through the magnetic coil orients the spontaneous vertical magnetization either up or down. This orientation process occurs in the region of the optical spot where the temperature is suitably high. The orientation of the magnetization mark is preserved after the laser beam is removed. The mark is erased or overwritten if it is locally reheated to the Curie point by the laser beam during a time the magnetic coil creates a magnetic field in the opposite direction.

Information is read back from a particular mark of interest on the disk by taking advantage of the magnetic Kerr effect so as to detect a Kerr rotation of the optical polarization that is imposed on a reflected beam by the magnetization at the mark of interest. The magnitude of the Kerr rotation is determined by the material's properties (embodied in the Kerr coefficient). The sense of the rotation is measured by established differential detection schemes and, depending on the direction of the spontaneous magnetization at the mark of interest, is oriented clockwise or counter-clockwise.

Conventional magneto-optical heads, while presently providing access to magneto-optical disks with areal densities on the order of 1 Gigabit/in^2, tend to be based on relatively large optical assemblies which make the physical size and mass of the head rather bulky (typically 3-15mm in a dimension). Consequently, the speed at which prior art magneto-optical heads are mechanically moved to access new data tracks on a magneto-optical storage disk is slow. Additionally, the physical size of the prior art magneto-optical heads limits the spacing between magneto-optical disks. Because the volume available in standard height disk drives is limited, magneto-optical disk drives have, thus, not been available as high capacity commercial products. For example, a commercial magneto-optical storage device presently available provides access to only one side of a 130 mm double sided 2.6 ISO gigabyte magneto-optical disk, a 40 ms disk access time, and a data transfer rate of 4.6 MB/Sec.

N. Yamada (US Patent No. 5,255,260) discloses a low-profile flying optical head for accessing an upper and lower surface of a plurality of optical disks. The flying optical head disclosed by Yamada describes an actuating arm that has a static (fixed relative to the arm) mirror or prism mounted thereon, for delivering light to and receiving light from a phase-change optical disk. While the static optics described by Yamada provides access to both surfaces of a plurality of phase-change optical disks contained within a fixed volume, Yamada is limited by the size and mass of the optics. Consequently, the performance and the number of optical disks that can be manufactured to function within a given volume is also limited. Utilization of optical fibers to deliver light to a storage location within an optical disk drive allows a low profile optical path which can increase the number of disks that can be vertically positioned within a given form factor.

Prior art magneto-optical flying heads that employ a polarization-maintaining fiber and Fabry-Perot (FP) laser to deliver polarized light from a source to a storage location are subject to significant mode partition noise that limits the available signal-to-noise ratio. Mode partition noise (MPN), in the form of broadband polarization fluctuations, is an intrinsic

property of the FP laser that is manifest when a highly birefringent element is placed its optical path. Polarization-maintaining optical (PM) fiber is, by design, very birefringent; therefore, MPN is very difficult to eliminate when PM fiber is utilized with a FP laser.

What is needed, therefore, is an optical data storage system that utilizes optical fiber to convey light between a laser source and a storage location of an optical drive optical data storage system with sufficient signal-to-noise (SNR) and that allows an increase in the number of disks that can be placed within a given volume, as compared to the prior art. The improved optical head should preferably provide a high numerical aperture, a reduced head size and mass. Additionally, the optical head should improve upon prior art access to disk surfaces, disk drive access times, data transfer rates, optically induced noise, and ease of alignment and manufacture.

Summary of the Invention

The present invention provides improvements over prior art optical disk drives. The improvements allow an increase in the number of storage disks that can be placed within any given volume. The improvements include the use of low-birefringence optical fibers to transfer information to and from optical storage media. The improvements further include a high resonance frequency tracking servo device on a reduced profile head which, in conjunction with the optical fibers provides improved access to storage media, improved disk drive access times, and improved data transfer rates.

The optical disk of the present invention also utilizes various aspects of Winchester magnetic disk technology, for example, flying head technology. In the present invention, a laser optics assembly directs light from an optical light source to an optical switch, which directs the light to one of a plurality of optical fibers coupled to one or more rotary arms, each of which support a flying optical head. Light is delivered through the optical fiber to a respective optical head for the purpose of reading and writing of data at a respective storage media with a focused optical spot. A reflected light signal from the storage media couples back through the optical head and optical fiber for subsequent processing. In one embodiment, the optical source of light comprises a Fabry Perot laser.

The optical path of the light delivered by the optical fiber is altered by a steerable micro-machined mirror. Track following and seeks to adjacent tracks are performed by rotating a central mirror portion of the mirror about an axis of rotation. A reflected light from the steerable micro-machined mirror is directed through an embedded micro-objective lens such as a GRIN (Gradient index) lens or a molded lens. A focused optical spot is scanned

back and forth in a direction which is approximately parallel to the radial direction of the storage media. In another embodiment, track following and seeks to adjacent tracks may be performed with more than one storage media surface at a time by operating a set of steerable micro-machined mirrors independently from each other.

In the present invention, a further improvement includes information transfer to and from magneto-optical storage disks using low-birefringence optical fibers. Due to inevitable stresses that are applied to the optical fibers, the SNR ratio of polarization information from the storage media may be degraded when conveyed by the optical fibers. The present invention provides an apparatus and method for increasing the SNR. In one embodiment, in-plane bend induced birefringence in low birefringence optical fibers is compensated for to increase the SNR. In another embodiment, out-of-plane bend induced birefringence is compensated for to increase the SNR. In another embodiment, both in-plane bend induced and out-of-plane bend induced birefringence are compensated for to increase the SNR. Out-of-plane bend induced birefringence may be compensated for by providing an optical polarization rotation element, which may comprise a ½ wave plate or a combination of a fixed ¼ plate and a rotatable ¼ wave plate. In-plane bending may be compensated by providing optical phase retardation of the reflected light. Phase retardation may be provided by an optical phase retardation element comprising, a combination of a liquid crystal retarder and a fixed ½ wave plate, a combination of a fixed ¼ wave plate and a rotatable ½ wave plate, or a fixed ¼ wave plate and rotatable leaky beam splitter. In yet another embodiment, the SNR may be increased by providing an optical source of light comprising a modulated Fabry Perot laser.

Brief Description of the Drawings

Figure 1a illustrates one embodiment of magneto-optical storage and retrieval system with in-plane bending and out-of-plane bending of a low birefringence optical fiber;

Figure 1b illustrates a magneto-optical storage and retrieval system with out-of-plane bending of a low birefringence optical fiber;

Figure 2a illustrates a laser-optics assembly of the present invention;

Figure 2b illustrates one embodiment of an optical phase retarder;

Figure 2c illustrates another embodiment of an optical phase retarder;

Figure 2d illustrates another embodiment of an optical phase retarder;

Figure 2e illustrates an embodiment of an optical polarization rotator;

Figure 2f illustrates an embodiment in which a Fabry Perot laser is pulsed;

Figure 3 illustrates an optics module comprising an optical switch;

Figures 4a-g illustrate a flying head of the present invention in various views; and

Figures 5a-b illustrate two embodiments of a magneto-optical disk drive.

Detailed Description Of The Invention

Referring in detail now to the drawings wherein similar parts of the invention are identified by like reference numerals, there is seen in Figure la a magneto-optical storage and retrieval system **100**, generally illustrated in a perspective view. In a preferred embodiment, the magneto-optical (MO) data storage and retrieval system **100** includes a set of Winchester-type flying heads **106** that are adapted for use with a set of double-sided first surface MO disks **107** (one flying head for each MO disk surface). The set of flying heads **106** (hereinafter referred to as flying MO heads) are coupled to a rotary actuator magnet and coil assembly **120** by a respective suspension **130** and actuator arm **105** so as to be positioned over the surfaces of the set of MO disks **107**. In operation, the set of MO disks **107** are rotated by a spindle motor so as to generate aerodynamic lift forces between the set of flying MO heads **106** and the set of MO disks **107** and so as to maintain the set of flying MO heads **106** in a flying condition approximately 15 micro-inches above the upper and lower surfaces of the set of MO disks **107**. The lift forces are opposed by equal and opposite spring forces applied by the set of suspensions **130**. During non-operation, the set of flying MO heads **106** are maintained statically in a storage condition away from the surfaces of the set of MO disks **107**. System **100** further includes an optics module **103** and a set of low birefringence optical fibers **102** coupled thereto.

Figure 2b illustrates a laser-optics assembly **101** used as part of the laser optics module **103**. In the present invention, the optics module **103** of Figs la and b comprises laser-optics assembly **101**, which includes a Fabry Perot (FP) laser source **231** of a variety that is well known in the art. In an exemplary embodiment, the laser source **231** operates at a wavelength of approximately 660 nm within a red region of the visible light spectrum; however, it is understood that laser sources operating at other wavelengths are also within the scope of the present invention. Fabry-Perot laser diodes are characterized by high-frequency fluctuations in their spectral output, which is also referred to in the art as mode partition noise (MPN). In the prior art, when linearly polarized light is launched into a highly birefringent element, for example, a single-mode polarization-maintaining (PM) optical fiber, mode partition noise (MPN) is converted into polarization noise, which acts to reduce available signal-to noise ratio

(SNR). In MO recording, since polarization information from the MO disk **107** is desired to be read, it is important that polarization noise be kept to a minimum, which, however, is difficult to achieve when using the FP laser source and single-mode polarization-maintaining optical fiber of the prior art. The laser-optics assembly **101** further includes: collimating optics **234**, a leaky beam splitter **232**, and a coupling lens **233**. The laser-optics assembly **101** directs a P polarized laser beam **291** from the laser source **231** through the leaky beam splitter **232** and coupling lens **233** towards the optical switch **104**. The laser-optics assembly **101** also receives S and P polarization components of a reflected laser beam **292** from the surface of a particular MO disk **107**. The reflected laser beam **292** is directed by the coupling lens **233** and is routed by the leaky beam splitter **232** towards a differential detector comprising: a polarizing beam splitter **239**, a mirror **235**, and a set of photo-diodes **236**. After conversion by the set of photo-diodes **236**, the differential signal is processed by the differential amplifier **237** and is output as signal **294**. The differential detector measures the optical power of the orthogonal S and P polarization components of the reflected laser beam **292**, with a differential signal being preferably a sensitive measure of polarization rotation induced by a Kerr effect at the surface of the particular MO disk **107**. As will be discussed below, in particular embodiments of the present invention, the laser-optics assembly **101** may further include a variety of optical components at locations indicated at AA and BB to provide optical phase retardation and/or optical polarization rotation of the laser beams **291** and **292**.

Figure 3 illustrates the optics module **103** comprising an optical switch **104**. The optical switch **104** is disposed between the set of optical fibers **102** and the laser optics-assembly **101** and is shown in a representative optical path that includes one of the set of optical fibers **102**, one of the set of flying MO heads **106**, and one of the set of MO disks **107**. The optical switch **104** provides sufficient degrees of selectivity so as to direct the outgoing laser beam **291** towards a respective proximal end of a particular optical fiber **102**. The outgoing laser beam **291** exits a distal end of the optical fiber **102** and is directed through the flying MO head **106** onto a surface recording layer **349** of a respective MO disk **107**.

During writing of information, the outgoing laser beam **291** lowers a coercivity of the surface recording layer **349** by heating a selected spot of interest **340** to approximately the Curie point of the MO recording layer **349**., The optical intensity of outgoing laser beam **291** is held constant, while a time varying vertical bias magnetic field is used to define a pattern of "up" or "down" magnetic domains perpendicular to the MO disk **107**. This technique is known as magnetic field modulation (MFM). Alternatively, outgoing laser beam **291** may be

modulated in synchronization with the time varying vertical bias magnetic field at the spot of interest **340** in order to better control domain wall locations and reduce domain edge jitter. Subsequently, as the selected spot of interest **340** cools at the surface layer **349**, information is encoded at the surface of the respective spinning disk **107**.

During readout of information, the outgoing laser beam **291** (at a lower power compared to writing) is selectively routed to the MO disk **107** such that upon its reflection from the spot of interest **340** the Kerr effect causes a polarization state of the reflected laser beam **292** to be rotated either clockwise or counter clockwise (as indicated with arrow **363**). The aforementioned optical path is bi-directional in nature. Accordingly, the reflected laser beam **292** is received through the flying MO head **106** and enters the distal end of the optical fiber **102**. The reflected laser beam **292** is directed by the optical fiber **102** towards the optical switch **104** and is selectively routed by the optical switch **104** towards the laser-optics assembly **101** for subsequent optical-to-electrical signal conversion.

Referring back to Fig. 1a, in the preferred embodiment, the set of optical fibers **102** of the present invention comprises single-mode low-birefringence optical fibers. The present invention identifies that by using an optical fiber that is designed to have low birefringence, a fiber that is known in the optical fiber arts as low-birefringence or lo-bi optical fiber, mode partition noise may be reduced to achieve an acceptable SNR. The low birefringence of lo-bi optical fiber contrasts with the inherent high birefringence of single-mode polarization-maintaining optical fibers, also known as PM optical fiber. Lo-bi fiber can be provided as "spun fiber," which is spun from a slightly birefringent fiber preform during a fiber drawing process. Geometrical twisting is frozen into the spun fibers when cooled. If the fibers are spun sufficiently, the effects of bend induced linear birefringence due to the non circular cross section or the anisotropic thermal stress can be overwhelmed by the effective circular birefringence introduced by the spinning. Most optical fibers exhibit linear birefringence caused by geometry and internal stresses. Spun fibers are the exceptions. It is understood that the present invention need not be limited to lo-bi fibers that are spun, as lo-bi optical fibers manufactured using other means are also known in the art. In an exemplary embodiment of the present invention, the set of lo-bi optical fibers **102** comprises: a phase retardation of 1-2 degrees per meter, an operating wavelength of approximately 660 nm, a cutoff wavelength of 580-600 nm, a cladding diameter of approximately 80 um, a dual acrylate jacket with a diameter of 160-190 um, an operational temperature range of 0-70 degrees A, a mode field diameter of approximately 4.0 um, and a mode field ellipticity of less than 5%.

As illustrated in Fig. la, the set of lo-bi optical fibers **102** are coupled at the distal ends to respective ones of the set of flying MO heads **106**, are routed along respective ones of the set of actuator arms **105** and set of suspensions **130**, are routed around the optics module **103**, and are coupled at the proximal ends to the optics module **103**. Because of limitations imposed by a limited volume present in the system **100**, the set of optical fibers **102** may require routing in other than a co-linear and/or a co-planar manner, which in turn may stress the optical fibers **102** and thus induce birefringence in the optical fibers **102**. In the present invention, the optical fibers **102** exit the optic module **103** at illustrated point A and are grouped together and wound around the optics module **103**. The extra windings provide extra fiber length to facilitate assembly and rework if necessary. The fibers are preferably routed in such a way that a majority of static bending occurs in a single plane (referred to hereafter as in-plane bending). An example of in-plane bending of the optical fibers **102** is illustrated at point C. In the present invention, at some point the fibers **102** fan out to their respective heads, for example starting at illustrated point B; thus, there may also be some out-of-plane bending between the optical fibers **102**, which may alter the local orientation of the birefringence, but if the bend radius is kept sufficiently large, then the magnitude of the out-of-plane birefringence may be relatively small. Bend induced birefringence can be characterized by (1) a magnitude that is proportional to $(R_{fiber}/R_{bend})^2$ where R_{fiber} is the fiber cladding radius and R_{bend} is the bend radius, and (2) an orientation such that one axis is in the plane of bending and the other axis is perpendicular to the plane. Those skilled in the art will recognize that if not for the bending of the set of optical fibers **102**, the outgoing and the reflected laser beams **291** and **292** would in theory experience the set of optical fibers **102** with low-birefringence, similar to a set of free space optical paths. The polarization rotation information conveyed by the set of optical fibers **102** may be degraded by the aforementioned bend induced birefringence in the set of lo-bi optical fibers **102**. Accordingly, the present invention provides a method and apparatus for compensation thereof, including optical elements in the optical paths of the laser beams **291** and/or **292** to provide optical phase retardation and/or optical polarization rotation.

The present invention identifies that phase shifts are introduced between the outgoing laser beam **291** and reflected laser beam **292** by the bend induced birefringence of the set of optical fibers **102** and that the phase shifts may be compensated for by placing optical phase retardation elements in the optical path of the reflected beam **292** and that, furthermore, for detection of a Kerr rotation of the reflected laser beam **292** with a maximum SNR, the phase shift between the P polarized outgoing laser beam **291** and the reflected P and S polarized

reflected laser beam **292** should be maintained 0 degrees modulo π. In the preferred embodiment, optical phase retardation is utilized to optimize the Kerr signal from the MO disk **107** by bringing the reflected laser beam **292** in the absence of the Kerr signal and the orthogonally polarized Kerr components in phase and, thus, to also minimize the mode partition noise induced by the set of optical fibers **102** by operating at the bottom of a noise fringe. Optical phase retardation can be provided by an optical phase retardation element which resolves a light wave into two orthogonal linear polarization components and produces a phase shift between them. Ideally, optical elements that provide optical retardation will not polarize, nor will they induce an intensity change in a light beam passing therethrough; they will simply change beam's polarization state. Elements that provide optical phase retardation can be of a fixed or variable variety and are typically available as birefringent, uniaxial materials having two different refractive indices. Such materials may comprise, for example, a uniaxial crystal, a quartz crystal, a mica, nematic liquid crystal, an electro-optic material, a polymer, to name a few.

The present invention identifies that to achieve these conditions, the bend induced axes of the set of optical fibers **102** should be aligned with the axes of the leaky beam splitter **232** such that the P polarization of the outgoing laser beam **291** will be rotated into the same plane and perpendicular to the in-plane bend induced axes of the set of optical fibers **102**.

As discussed above, the set of optical fibers **102** may experience bending, for example, a combination of in-plane bending and/or out-of-plane bending. In another embodiment illustrated in Figure 1b, it is possible that the optical fibers **102** be routed such that minimal out-of-plane bending of the set of optical fibers **102** occurs, for example, if the optical fibers **102** are routed to exit the optics module **103** and are maintained along parallel planes having a between plane spacing equivalent to a spacing between the respective heads **106** to which they are routed (rather than fanning out at point B). In this embodiment, even with no out-of-plane bending, in-plane bending of the fibers may still occur, such as during normal routing of the set of optical fibers **102** from the optics module **103** to the heads **106**.

In one embodiment where minimal out-of-plane bending of the optical fibers **102** occurs, optical phase retardation may be provided by an optical phase retarder **255** comprising a variable liquid crystal retarder, such as an LVR 100 VIS manufactured by Meadowlark Optics, Frederick, CO 805030. In this embodiment, the optical phase retarder **255** is used in combination with a first ½ wave plate **253**, both of which are disposed at point BB in the optical path between the leaky beam splitter **232** and the polarizing beam splitter **239**

(illustrated in Figures 2a and 2b). Preferably the optical axes of the optical phase retarder **255** are aligned at zero degrees relative to the optical axes of the leaky beam splitter **232**, and the optical axes of the first ½ wave plate **253** are aligned at 22.5 degrees relative to the axes of the leaky beam splitter **232**. In an exemplary use of the variable liquid crystal retarder, an peak to peak input voltage of 1.53 volts is applied, which has been shown to produce adequate compensation for in-plane induced stresses; slight variations of in-plane bending between the set of optical fibers **102** may require slightly different voltages. The particular voltage to be applied when a particular optical fiber **102** is utilized may be predetermined during a calibration phase. The voltage may be changed during the intervals between switching of the optical switch **104**.

In another embodiment where minimal out of plane bending of the optical fibers **102** occurs, optical phase retardation may be provided by a combination of a ¼ wave plate **254** of a variety well known in the art and a dynamically rotating ½ wave plate **257**, both of which are disposed between the leaky beam splitter **232** and the polarizing beam splitter **239** (illustrated in Figures 2a and 2c). In this embodiment, the optical axes of the ¼ wave plate **254** are aligned at forty five degrees relative to the optical axes of the leaky beam splitter **232**, and the optical axes of the dynamically rotating ½ wave plate **257** rotate relative to the axes of the leaky beam splitter **232**. The dynamically rotating ½ wave plate **257** may comprise a ½ wave plate coupled to an electromechanical or electro-micro-machined actuator to enable a desired rotation of the ½ wave plate. The particular rotation to be applied to the ½ wave plate **257** when a particular optical fiber **102** is utilized may be predetermined during a calibration phase. The rotation may be applied during the intervals between switching of the optical switch **104**.

In still another embodiment, optical phase retardation is provided by a ¼ wave plate **254**, which is disposed between the leaky beam splitter **232** and the polarizing beam splitter **239**, with the optical axes of the ¼ wave plate **254** preferably aligned at forty five degrees relative to the optical axes of the leaky beam splitter **239** (illustrated in Figures 2a and 2c). In this version, the polarizing beam splitter **239** is provided as a dynamically rotating polarization beam splitter. The dynamically rotating polarizing beam splitter may comprise a polarizing beam splitter coupled to an electromechanical or electro-micro-machined actuator that enables a desired rotation of the polarizing beam splitter. The particular rotation to be applied when a particular optical fiber **102** is utilized may be predetermined during a calibration phase and may be applied during the intervals between switching of the optical switch **104**.

In the aforementioned embodiments, while static in-plane bend induced stress in low-birefringence optical fibers is compensated for, dynamic in-plane bend induced stress can be neglected as it is typically quite small, although it could in principle be compensated for as well with sufficiently fast compensation.

As discussed above, the bend induced axes of the set of optical fibers **102** are preferably aligned with the axes of the leaky beam splitter **232** such that P polarization of the outgoing laser beam **291** will be aligned with one of the bend induced axes of the set of optical fibers **102.** This condition may be achieved by manually aligning the axes of the optical fibers **102** to each other and to those of the leaky beam splitter **232.** In the event the axes of the optical fibers **102** and the leaky beam splitter **232** are not aligned, an optical polarization rotator **256** may be disposed at point AA between the coupling lens **233** and the leaky beam splitter **232** Figure 2a. The optical polarization rotator **256** may comprise a second ½ wave plate of a variety well known in the art. In this embodiment, the optical axes of the optical fibers **102** are all pre-aligned to each other and the ½ wave plate is disposed to provide optical rotation of the p-polarization of the outgoing laser beam **291** into the plane of the bend induced axes of the set of lo-bi optical fibers **102.**

In the aforementioned embodiment of Fig. la, the set of optical fibers **102** are each routed around the optics module **103** to respective flying optical heads **106.** Routing of the optical fibers **102** to the spaced apart heads **106** causes each optical fiber to traverse a slightly different path and, thus, experience different out-of-plane bending relative to exit point A. The out-of-plane bends cause each lo-bi optical fiber **102** to comprise bend induced axes that vary slightly in orientation relative to one another and/or with the leaky beam splitter **232.** The variations between the out-of-plane bend induced axes of each optical fiber **102** can be accommodated for by using an optical polarization rotator **256** that is dynamically adjustable to rotate linear polarization of the outgoing laser beam **291,** for example, by a ¼ wave plate retarder of a variety well known in the art coupled at 45 degrees relative to the axes of a second variable liquid crystal retarder (illustrated in Figure 2e). Polarization rotation is achieved by electrically controlling the retardence of the variable liquid crystal. A variable optical polarization rotator as described above is available as an LPR 100 660, which is manufactured by Meadowlark Optics, Frederick, CO., 805030. The optical polarization rotator **256** may also be enabled through mechanical actuation of rotation. The amount of polarization rotation necessary for alignment to the induced axes of each optical fiber **102** can be determined during a calibration step such that, in operation, when switching between optical

fibers **102** occurs, a control voltage corresponding to the particular optical fiber **102** being used is applied to the optical polarization rotator **256** in a feed-forward fashion to provide the required polarization rotation.

Without the aforementioned in-plane bending of the optical fibers **102**, such as in an embodiment where the optical path traversed by the optical fibers **102** is maintained with minimal bending, it is understood that the optical phase retardation would not necessarily be required. Without the aforementioned out-of-plane bending of the optical fibers **102**, such as in an embodiment in which only a single lo-bi fiber **102** is used to convey information to a single MO disk **107**, it is understood that optical polarization rotation would not necessarily be required. In other embodiments, where both in-plane and out-of-plane bending is present, both optical phase retardation and the optical polarization rotation may be required. It should be apparent, therefore, that the present invention should not be limited to the embodiments discussed above but only the scope of the ensuing claims.

In a fourth embodiment illustrated in Figure 2f, it has been identified that spurious reflection from the proximal ends of the set of optical fibers **102** may degrade SNR, whereby the reflected beam **292** may contain a component of a reflection of the beam **291** from the proximal ends, thereby resulting in a reflected beam **293** comprising $E(t) + E(t+\tau)$. In such a case, the present invention may include a FP laser source **231** that is pulsed on and off with a duty cycle of 50% or less and with a modulation frequency of approximately 350 MHz. Pulsing of the laser **231** allows the reflected pulses of the beam **292** to be time separated from the beam **291** thereby reducing interference between the two pulse trains and thus effectively increasing the SNR of the detected Kerr signal. In an exemplary embodiment, with an optical fiber **102** index of refraction of 1.5, the length of each of the optical fibers **102** is selected to be about 71.35 mm. The relationship between the modulation frequency (F) and the length (L) of the optical fibers **102** is embodied in the equation: $F= c(2i+1)/4Ln$ $i = 0,1,2, \ldots$ where c = speed of light, n = refractive index of the fiber. The length of the set of optical fibers **102** is selected to ensure a proper time separation of the pulses trains. It is understood that in other embodiments, the length of the optical fiber **102** can be selected in accordance with other indices of refraction and other pulsing frequencies and, thus, the present invention should be limited only by the scope of the claims. Although the present invention describes use of low birefringence optical fibers, it is understood that pulsing of the laser and selecting an appropriate optical fiber length as described in the fourth embodiment may also be used to

increase SNR in an embodiment utilizing high birefringence optical fibers (i.e., polarization maintaining optical fiber).

Figures 4a-g illustrate a magneto-optical head of the present invention in various views. The set of flying MO heads may be illustrated with reference to a single representative flying MO head **106**. A single representative flying MO head **106** is shown in Figure 4b to be positioned respectively above a surface recording layer **349** of one of the set of spinning MO disks **107**. In a preferred embodiment, the flying MO head **106** includes: a body **444**, an air bearing surface **447**, a steerable micro-machined mirror assembly **400**, an objective optics **446**, and a magnetic coil **460**. In an exemplary embodiment, the magnetic coil **460** is a micro multi-turn coil positioned near the air-bearing surface **447** so as to generate a magnetic field that is: approximately 300 Oersteds of either polarity, reversible in a time of about 4ns, and approximately perpendicular to the plane of the spinning MO disk **107**. The steerable micro-machined mirror assembly **400** is described in commonly assigned U.S. Patent Application 08/844,207, which incorporated herein by reference. Preferably, the magnetic coil should not interfere with the outgoing and reflected laser beams **291** and **292** during passage through the flying MO head **106** to the spinning MO disk **107**, or vice versa. As determined by mechanical dimensions and/or optical properties of the aforementioned elements comprising the flying MO head **106**, the body **444** includes a height of approximately 889 um and a planar footprint area that corresponds to that of 2032 um x 1600 um. The low-birefringence optical fiber **102** is preferably coupled to the flying MO head **106** and is held along an axis of the body **444** by a v-groove **443** or other suitably dimensioned channel. The optical fiber **102** is positioned within the v-groove **443** to preferably direct the outgoing laser beam **291** as an optimally focused spot of interest **340** onto the MO disk **107**. The optical fiber **102** may be subsequently secured in place by using an ultraviolet curing epoxy or a similar adhesive. Use of the optical fiber **102** within a V-groove permits accurate alignment and delivery of the outgoing laser beam **291** relative to the small mirror assembly **400**. The steerable micro-machined mirror assembly **400** and objective optics **446** are preferably compact and low mass so as to fit within a physical volume defined approximately the rectangular outer dimensions of the body **444** and yet sufficiently large to direct a full cross section of the outgoing and reflected laser beams **291** and **292** so that minimal power is lost and significant distortion and aberrations in the outgoing and reflected laser beams **291** and **292** are not introduced. The MO head **106** profile, weight, and design are further simplified through the use of the low-birefringence optical fibers **102** of the present invention, in that, a ¼ wave plate is not required

as an additional optical component for use on the flying MO head **106** as is required when using the polarization-maintaining optical fibers of the prior art.

The steerable micro-machined mirror assembly **400** is preferably aligned in the representative optical path so as to direct the outgoing laser beam **291** through the objective optics **446** towards the MO disk **107** and so as to direct the reflected laser beam **292** from the MO disk **107** back to the laser optics assembly **101**. In one embodiment, the objective optics **446** may be a microlens with a numerical aperture (NA) of approximately .67. Because flying height above the air bearing surface **447** is maintained with a constant value, a focusing servo is not necessarily required.

As used in the magneto-optical storage and retrieval system **100**, fine tracking and short seeks to nearby tracks are performed by rotating a reflective central mirror portion **420** (shown as hidden by dotted lines in Fig. 4a) of the steerable micro-machined mirror assembly **400** about a rotation axis constrained by a set of hinges **410** such that the propagation angle of the outgoing laser beam **291** is changed before transmission to the objective optics **446**. The reflective central mirror portion **420** is rotated about axes formed by the hinges **410** by applying a differential voltage to drive electrodes. The differential voltage creates an electrostatic force that enables the focused spot of interest **340** to be moved in the radial direction **450** on the MO media **107**. In an exemplary embodiment, the central mirror portion **420** rotates approximately +/- 2 degrees, which is equivalent to approximately +/- 4 tracks at the surface of the MO disk **107**. Although, in the exemplary embodiment a movement of +/- 4 tracks is disclosed, depending on the desired performance characteristics of the steerable micro-machined mirror **400** described above, a range of movement greater or fewer than +/- 4 tracks is understood to also be possible. Consequently, movement of the focused spot of interest **340** across the MO disk **107** and detection of the reflected laser beam **292** may be used in storage and retrieval of information, track following, and seeks from one data track to another data track. Coarse tracking may be maintained by adjusting a current to rotary actuator magnet and coil assembly **120** (Fig. 1a). The track following signals used to follow a particular track of the MO disk **107** may be derived using combined coarse and fine tracking servo techniques that are well known in the art. For example, a sampled sector servo format may be used to define tracks. The servo format may include either embossed pits stamped into the MO disk **107** or magnetic domain orientations that are read similar to data marks. If embossed pits are used, an adder output circuit may be used to supplement the differential amplifier **237** (Fig. 2). Those skilled in the art will recognize that conventional prior art

multiple magnetic disk Winchester magnetic disk drives use a set of respective suspensions and actuator arms that move in tandem as one integral unit. Therefore, because each flying head of such an integral unit is fixed relative to another flying head, during track following of a particular magnetic disk surface, simultaneous track following of another magnetic disk surface is not possible. In contrast, irrespective of the movement of the set of actuator arms **105** and set of suspensions **130**, a set of steerable micro-machined mirror assemblies **400** may be used to operate independently and thus permit track following and seeks so as to read and/or write information using more than one MO disk surface at any given time. Independent track following and seeks using the set of concurrently operating steerable micro-machined assemblies **400** would preferably require a set of separate respective read channel and fine track electronics and mirror driving electronics. Because the aforementioned embodiment would also preferably require use of separate laser-optics assemblies **101**, an optical switch **104** for switching between each of the separate optical paths would not necessarily be required.

Figure 5a illustrates a magneto-optical data storage and retrieval system as part of a magneto-optical disk drive. In a preferred embodiment, the magneto-optical system **100** comprises a compact high-speed and high-capacity MO disk drive **500** that includes an industry standard 5.25 inch half-height form factor (1.625 inch), at least six double-sided MO disks **107**, and at least twelve flying MO heads **106**. As discussed above, the flying MO heads **106** may be manufactured to include optical fibers **102** as part of a very small mass and low profile high NA optical system so as to enable utilization of multiple MO disks **107** at a very close spacing within the MO disk drive **500** and; therefore, to comprise a higher areal and volumetric and storage capacity than is permitted in an equivalent volume of the prior art. In the preferred embodiment, a spacing between each of the MO disks **107** is less than or equal to .182 inches. The present invention identifies that a polarization state may be conveyed by low birefringence optical fibers **102** with reduced noise over that when conveyed by polarization-maintaining optical fiber.

In an alternative embodiment shown in Figure 5b, the half-height form factor MO disk drive **500** may include a removable MO disk cartridge portion **510** and two fixed internal MO disks **107**. By providing the removable MO disk cartridge portion **510**, the fixed internal and removable combination permits external information to be efficiently delivered to the MO disk drive **500** for subsequent transfer to the internal MO disks **107**. The copied information may, subsequently, be recorded back onto the removable MO disk cartridge portion **510** for

distribution to other computer systems. In addition, the removable MO disk cartridge portion **510** allows for very convenient and high speed back-up storage of the internal MO spinning disks **107**. The fixed internal and removable combination also permits storage of data files on the removable MO disk cartridge portion **510** and system files and software applications on the internal MO spinning disks **107**. In another alternative embodiment (not shown) an MO disk drive **500** may include: any number (including zero) of internal MO disks **107** and/or any number of MO disks **107** within any number of removable MO disk cartridge portions.

The present invention does not necessarily require use of rotary actuator arms, for example, linear actuator arms may be used. The low profile optical paths disclosed by the present invention may be used to convey information to and from a storage location without requiring objective optics (e.g., using a tapered optical fiber or an optical fiber with a lens formed on an end); and/or reflective substrates (e.g., using a curved optical fiber to convey information along surfaces of the magneto-optical head **106**).

It is understood that the present invention can find utility in a variety of environments, such as other types of optical drives, communications systems, and the like. Therefore, although the present invention has been described herein with reference to particular embodiments thereof, a latitude of modification, various changes and substitutions are intended in the foregoing disclosure, and it will be appreciated that in some instances some features of the invention will be employed without a corresponding use of other features without departure from the scope of the invention as set forth.

We Claim:

1. At least one optical fiber, said at least one optical fiber exhibiting a low-birefringence when in an unstressed condition, wherein said optical fiber is disposed to convey a beam of light along an optical path between a source and a storage location.

2. The at least one optical fiber of claim 1, wherein said storage location comprises at least one magneto-optical disk.

3. The at least one optical fiber of claim 2, wherein each of said at least one optical fiber is coupled to a flying optical head.

4. The at least one optical fiber of claim 2, wherein said beam of light is directed between said storage location and said at least one optical fiber by a steerable mirror.

5. The at least one optical fiber of claim 4, wherein said steerable mirror comprises a micro-machined mirror.

6. The at least one optical fiber of claim 1, wherein an optical phase retarder is disposed in said optical path to compensate for a stressed condition of said optical fiber.

7. The at least one optical fiber of claim 1, wherein an optical polarization rotator is disposed in said optical path to compensate for a stressed condition of said optical fiber.

8. The at least one optical fiber of claim 3, wherein said stressed condition results from an in-plane bend of said at least one optical fiber.

9. The at least one optical fiber of claim 3, wherein said stressed condition results from an out-of-plane bend of said at least one optical fiber.

10. The at least one optical fiber of claim 1, wherein an optical phase retarder and an optical polarization rotator are disposed in said optical path to compensate said optical path for a stressed fiber condition.

11. The at least one optical fiber of claim 10, wherein said stressed condition results from a combination of an out-of-plane bend and an in-plane bend of said at least one optical fiber.

12. The at least one optical fiber of claim 1, wherein said beam of light is modulated at a particular frequency.

13. The at least one optical fiber of claim 12, wherein said at least one optical fiber comprises a length, said length comprising a function of said frequency.

14. A system for directing a beam of light along an optical path between a source and a storage location, wherein said optical path comprises a low-birefringence optical fiber.

15. The system of claim 14, wherein said storage location comprises a magneto-optical storage location.

16. The system of claim 14, wherein said system comprises a magneto-optical disk drive.

17. The system of claim 16, wherein an optical phase retarder is disposed in said optical path between said source and said storage location.

18. The system of claim 17, wherein said optical phase retarder comprises an liquid crystal.

19. The system of claim 16, wherein a optical polarization rotator is disposed in said optical path between said source and said storage location.

20. The system of claim 19, wherein said optical polarization rotator comprises a ½ wave plate.

21. The system of claim 19, wherein said optical polarization rotator comprises a rotating ½ wave plate.

22. The system of claim 19, wherein said optical polarization rotator comprises a ¼ wave plate and a liquid crystal cell.

23. The system of claim 14, wherein said beam of light is a modulated at a particular frequency.

24. The system of claim 23, wherein said optical fiber comprises a length, said length comprising a function of said particular frequency.

25. The system of claim 14, wherein said beam of light is provided by a Fabry-Perot laser.

26. The system of claim 17, wherein said optical phase retarder comprises a rotating ½ wave plate in combination with a static ¼ wave plate.

27. A method of directing a beam of light along an optical path between a source and a storage location of an optical drive, comprising the steps of:

directing said beam of light through a low-birefringence optical fiber.

28. The method of claim 27, further comprising the step of:

directing said light through an optical polarization rotator disposed in said optical path.

29. The method of claim 27, further comprising the step of:

directing said light through an optical phase retarder disposed in said optical path.

30. The method of claim 27, further comprising the steps of:

pulsing said beam of light at a particular frequency; and

providing a length of said optical fiber as a function of said frequency.

31. A system for directing a beam of light along an optical path between a source and a storage location, comprising: means for compensating an optical path for bend induced birefringence of a low-birefringence optical fiber.

