

FOCUS SENSING APPARATUS AND METHOD

5 The present invention relates generally to radiation beam geometry evaluation, and finds application in optical recording and playback systems. In particular, the present invention is applicable to arrangements used to monitor the focus position of a light beam with respect to an optical disk.

10 Optical recording and playback systems, such as those utilizing optical memory disks, compact disks, or video disks, require precise focusing of an illuminating optical beam through an objective lens onto the surface of an optical disk. The incident illuminating beam is generally
15 reflected back through the objective lens, and is then used to read information stored on the disk. Subsequent to passing back through the objective lens, a portion of the reflected beam is typically directed to an apparatus designed to gauge the focus of the illuminating beam on
20 the disk. Information extracted from the reflected beam by this apparatus may then be used to adjust the focus of the illuminating beam by altering the position of a movable objective lens relative to the disk.

25 A number of techniques for detecting the focus of an illuminating optical beam are known. For example, U.S. Pat. No. 4,423,495, U.S. Pat. No. 4,425,636 and U.S. Pat. No. 4,453,239 employ what has been termed the "critical angle prism" method of determining beam focus. In this
30 method an illuminating beam reflected from a storage disk is made incident upon a detection prism surface which is set very close to a critical angle with respect to the reflected illuminating beam. When the focus of the illuminating beam on the surface of the disk deviates from a desired state, the variation in the amount of optical
35 energy reflected by the detection prism surface may be used to derive a focus error signal used to adjust the focus of the illuminating beam.

The critical angle prism method generally requires that the orientation of the detection prism surface relative to the reflected illuminating beam be precisely adjusted. This requirement arises as a result of discontinuities in the reflectivity characteristic of the detection prism in the neighborhood of the critical angle and makes focus error detection systems based on this method extremely sensitive. However, the critical angle technique has several disadvantages. First, the focus error signal it produces depends on the light reflection at the interface between the detection prism surface and air; thus, changes in altitude, which change the index of refraction of the air, can cause false focus readings (offsets) to occur. Also, the critical angle technique is inherently unsuitable for use in differential focus sensing systems.

Differential systems are increasingly important because they allow cancellation of certain types of noise that can occur in optical disk drives. The critical angle method is unsuited to differential operation for two reasons. First, the transmitted beam produced by the sensing prism is compressed along one axis, making it unsymmetrical with the reflected beam. Symmetry of the two beams is preferred in a differential system to optimize the noise-cancellation properties in varied environments. Second, at the point on the reflectivity curve of a critical angle prism where the intensities of the two beams are balanced, the slope is far too low to produce a useful differential focus error signal.

A focus detecting apparatus which requires somewhat less precise adjustment of the optical surface on which the reflected illuminating beam is incident, when compared to the critical angle technique, is disclosed in U.S. Patent No. 4,862,442. In particular, the optical surface described therein comprises a dielectric multilayer coating having a reflectivity which varies continuously with respect to the angle of incidence of the reflected

illuminating beam. It follows that rotational maladjustment of the surface comprising the multilayer coating will have smaller effect on the value of the focus error signal, but that also the technique will have reduced angular sensitivity. Also, inaccuracies in the focus error signal produced by multilayer dielectric systems may develop in response to relatively slight changes in the wavelength of the reflected illuminating beam. Such sensitivity to wavelength changes is undesirable since the focus error signal is designed to relate solely to the focus of the illuminating beam.

In addition, certain systems using a dielectric multilayer reflecting surface provide focus error signals having only a limited degree of sensitivity. For example, Figure 2 of US Pat. No. 4,862,442 shows a particular reflectivity characteristic for a layered dielectric reflecting surface, with the slope of the reflectivity characteristic being proportional to the sensitivity of the focus error signal. The disclosed reflected intensity ranges in value from approximately 0.75 to 0.05 over angles of incidence extending from 42 to 48 degrees. This reflectivity change of approximately 10% per degree produces a focus error signal of relatively low sensitivity.

Accordingly, a need in the art exists for an optical arrangement characterized by a reflectivity profile which allows generation of a highly sensitive focus error signal relatively immune to changes in altitude and to chromatic aberration, and which is capable of use in differential systems.

The invention provides a focus sensing apparatus for determining the focus of an illuminating beam, said apparatus comprising: a source of radiation energy; means for focusing radiation from the radiation energy source upon an object; means for separating at least a portion of radiation reflected by said object into transmitted and reflected beams, said separating means including a separation layer which varies in reflectivity

in response to the angle of incidence of said reflected radiation, said separation layer having a thickness which is larger than one half of the wavelength of said reflected radiation incident thereon; and photodetector means for detecting the intensities of said transmitted and reflected beams which intensities vary with the angle of incidence and thus with the degree of focus of the illuminating beam.

The invention also provides a focus sensing apparatus for determining the focus of an illuminating beam, said apparatus comprising: a light source for generating a light beam; an objective lens for focusing said light beam upon an object; a beam separation module for separating at least a portion of light reflected by said object into transmitted and reflected beams when said portion of said reflected light impinges on said beam separation module at an angle of incidence having an angular value within a selected continuous range of angular values between a critical angle of a first angular value and a next adjacent angle of minimum reflectance having a second angular value wherein said second angular value is less than said first angular value, said separation module including a separation layer which varies in reflectivity in response to the angle of incidence of said reflected light; beamsplitting means for directing at least a portion of said reflected light to said beam separation module; and a photodetector arrangement for detecting the intensities of said transmitted and reflected beams which intensities vary with the angle of incidence and thus with the degree of focus of the illuminating beam.

Further, the invention provides a focus sensor for determining the focus of an illuminating beam, said sensor comprising: a light source; means for focusing light from the light source as said illuminating beam upon an object; means for separating at least a portion of light reflected by the object into a transmitted beam of a first intensity distribution and a reflected beam of a second

intensity distribution, said separating means being configured such that said transmitted and reflected beams are each of an intensity which varies with the angle of incidence of the light from the object onto the separating means, and are of a substantially similar intensity distribution when the light is in focus on the object, and such that the spatial variation in the intensity of the transmitted beam is mirrored by a substantially equal and opposite spatial variation in the intensity of the reflected beam when the focus of the light deviates from the object, said means for separating having a thickness which is larger than one half of the wavelength of said reflected radiation incident thereon; and means for providing an indication of the spatial intensity variation varies with the angle of incidence and thus with the degree of focus of the illuminating beam.

Further, the invention provides a focus sensor for determining the focus of an illuminating beam, said sensor comprising: a light source for producing an optical beam; an objective lens arrangement for focusing the beam as said illuminating beam upon an object, said arrangement including a polarization beamsplitter and an objective lens; a beam separation module for separating at least a portion of light reflected by the object into a transmitted beam of a first intensity distribution and a reflected beam as a second intensity distribution which both vary with the angle of incidence at which said reflected light impinges on said beam separation module, the angle of incidence having an angular value within a selected continuous range of angular values between a critical angle of a first angular value and a next adjacent angle of minimum reflectance of a second angular value, wherein said second angular value is less than said first angular value, said separating means being configured such that said transmitted and reflected beams are of a substantially similar intensity distribution when the illuminating beam is in focus on the object, and such

that the variation in the intensity distribution of the transmitted beam is mirrored by a substantially equal and opposite variation in the intensity distribution of the reflected beam when the focus of the beam deviates from the object; and first and second photodetectors in optical alignment with said transmitted and reflected beams, respectively, for providing first and second signals indicative of the variation in the intensity distribution of the transmitted and reflected beams which intensity distribution varies with the angle of incidence and thus with the degree of focus of the illuminating beam.

Further, the invention provides a focus sensing apparatus for determining the focus of an illuminating beam by detecting characteristics of transmitted and reflected beams, said apparatus comprising: a radiation source; an optical member for focusing radiation from the radiation source upon an object; a frustrated total reflection prism for receiving radiation reflected from the object and for providing a reflected radiation beam and a transmitted radiation beam, said transmitted radiation beam being produced by frustrated total reflection of a portion of said radiation reflected from said object when said reflected radiation impinges on said separation layer at an angle of incidence with an angular value within a selected continuous range of angular values between a critical angle of a first angular value and a next adjacent angle of minimum reflectance of a second angular value, wherein said second angular value is less than said first angular value; and means for detecting a characteristic of one of the reflected and transmitted beams, which varies with the angle of incidence and hence with the degree of focus of the illuminating beam.

Further, the invention provides a method of sensing focus between a radiation source and an object by detecting characteristics of transmitted and reflected means, said method comprising the steps of: positioning a frustrated total reflection prism at a location so as to

receive radiation reflected from the object and to provide therefrom a reflected radiation beam and a transmitted radiation beam, said prism including a separation layer having a thickness which is larger than one half of the wavelength of said reflected radiation incident thereon, wherein said transmitted radiation beam is produced by frustrated total reflection of a portion of said radiation reflected from said object; and detecting characteristics of one of the reflected and transmitted beams, which vary with the angle of incidence of the radiation from the object onto the separation layer of the prism and hence with the degree of focus of the radiation on the object.

The preferred apparatus includes a beam separation module which provides a pair of well-balanced beams, either of which may be used to produce a focus error signal, and which also may be used together to produce a differential focus error signal. Moreover, certain physical parameters of the beam separation module may be varied to adjust the dynamic range of the apparatus and its sensitivity to changes in the focus of an illuminating beam.

Thus the preferred apparatus comprises: a substantially monochromatic light source, and an optical focusing arrangement including an objective lens, a beam separation module, and a photodetective element. In one preferred embodiment of the present invention, the light source generates a substantially linearly polarized beam which is collimated by a collimating lens. The collimated beam is directed by an optical beamsplitting arrangement to an objective lens, which then converges the beam onto the surface of the optical disk. The disk reflects the beam focused thereon back through the objective lens to the beamsplitting arrangement. A portion of the optical energy incident on the beamsplitting arrangement is then redirected to form a servo beam, with the beam separation module being positioned to intercept the servo beam. The beam separation module is operative to separate the servo

beam into transmitted and reflected beams of preferably similar shape and intensity. Electrical signals produced by photodetective elements in response to variations in the intensity profiles of the transmitted and reflected beams may then be used to differentially generate a focus error signal.

In a particular preferred embodiment of the present invention the beam separation module is a "frustrated total reflection" (FTR) prism which includes a separation layer which is sandwiched between a pair of glass members. The index of refraction of the separation layer is selected to be less than that of the surrounding glass, with the chosen indices of refraction defining the appropriate angle at which the FTR prism should be positioned relative to the servo beam. In addition, the thickness of the separation layer may be adjusted in accordance with the desired sensitivity of the differential focus error signal.

These and other objects and features of the present invention will become more fully apparent from the following description and appended claims taken in conjunction with the accompanying drawings.

Brief Description of the Drawings

Figure 1 is a block diagrammatic representation of a preferred embodiment of the beam focus sensing apparatus of the present invention.

Figure 2 is a magnified top cross-sectional view of a differential version of the inventive beam separation module (FTR prism).

Figure 3 is an illustrative front view of the first and second quad detectors included within the inventive focus sensing apparatus.

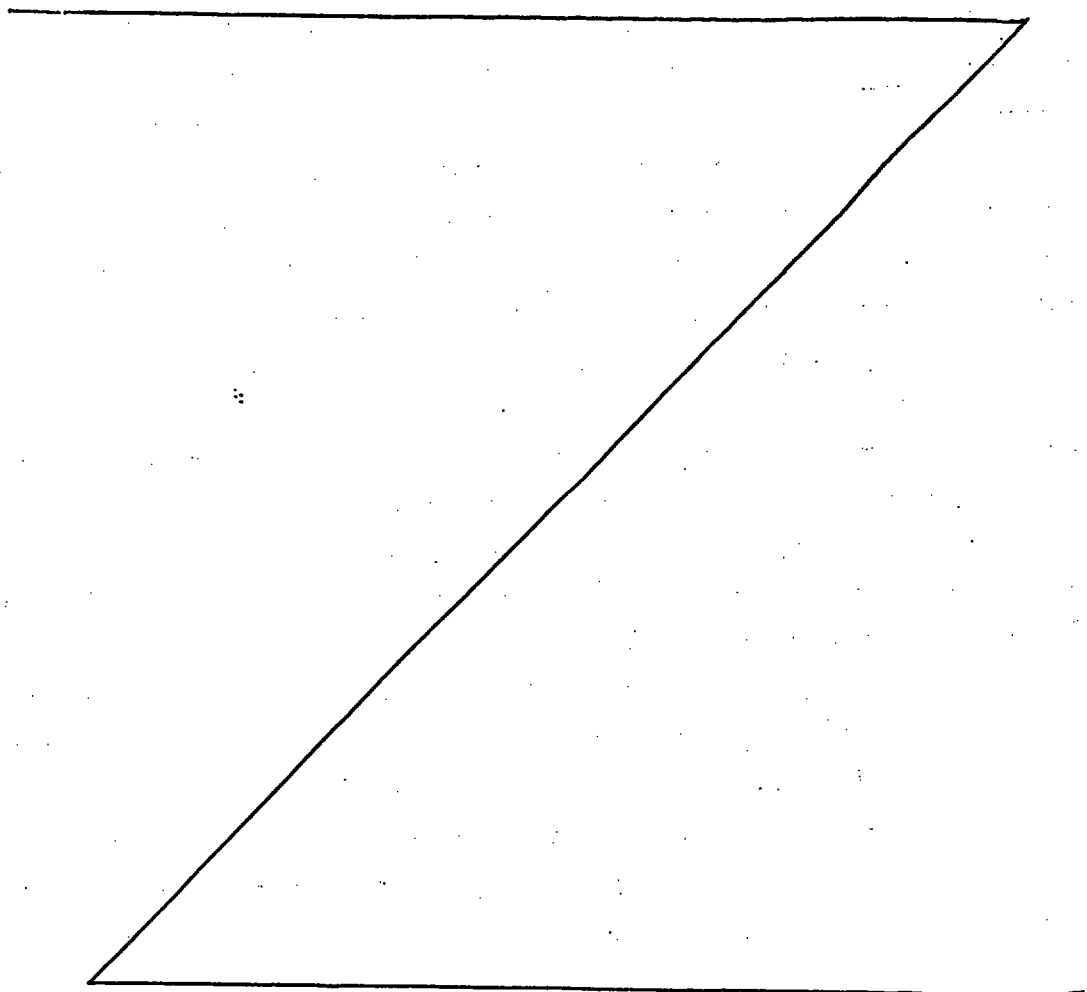
Figure 4 is a graph showing the reflectivity of the FTR prism as a function of the angle of incidence of the servo beam.

Figure 5 is a graph of the value of a differential focus error signal generated by a preferred embodiment of

the apparatus of the present invention as a function of the position of the objective lens relative to an optical disk.

Detailed Description of the Preferred Embodiments

Figure 1 is a block diagrammatic representation of the preferred embodiment of the beam focus sensing apparatus 10 of the present invention. The apparatus 10 includes an optical arrangement 12 for providing a servo beam S indicative of the focus of an illuminating beam I upon an optical disk 14. The servo beam S comprises a portion of the illuminating beam I reflected by the disk 14. Techniques for generating such a servo beam are well known to those skilled in the art. For example, an optical system such as the optical arrangement 12 for generating



the servo beam S is described in U.S. Pat. No. 4,862,442, which is herein incorporated by reference. A brief summary of the operation of the optical arrangement 12 is set forth below.

5 As shown in Figure 1, the optical arrangement 12 includes a laser source 16 which generates a linearly polarized beam B. The beam B is collimated by a collimating lens 18, and the collimated beam is directed by an optical beamsplitting arrangement 20 to an objective
10 lens 24. The collimated beam is then converged by the objective lens 24 onto the surface of the optical disk 14. The optical disk may, for example, comprise a compact disk, video disk, or optical memory disk. The disk 14 reflects the illuminating beam focused thereon back through the
15 objective lens 24 to beamsplitting arrangement 20. Those skilled in the art will appreciate that the beamsplitting arrangement 20 may include a first beamsplitter (not shown) to redirect a first portion of the reflected illuminating beam in order to form the servo beam S. The beamsplitting
20 arrangement 20 will also generally include a second beamsplitter (not shown) to redirect a second portion of the reflected illuminating beam to create a data beam. Such a data beam carries information stored on the optical disk 14. The servo beam S is intercepted by the FTR prism
25 30, the design and construction of which is discussed more fully hereinafter.

 As is also described more fully below, the servo beam S is divided into a transmitted beam T and a reflected beam R by the FTR prism 30. In the embodiment of Figure 1 the
30 transmitted and reflected beams T,R are of substantially equal cross section and intensity. The transmitted beam T is incident on a first quad detector 32, while the reflected beam R is incident on a second quad detector 34. Electrical signals produced by the quad detectors 32, 34 in
35 response to the intensity distributions of the transmitted and reflected beams T, R are utilized by a control unit 37 to generate a differential focus error signal (DFES)

indicative of the focus of the illuminating beam I on the disk 14. One preferred embodiment of a control unit 37 and associated method for generating the DFES is discussed hereinafter. The focus error signal may, for example, be used to control a mechanical arrangement (not shown) disposed to adjust the focus of the illuminating beam I by altering the displacement of the objective lens 24 relative to the disk 14.

Figure 2 shows a magnified top cross-sectional view of the FTR prism 30. The prism 30 includes first and second optical members 35, 36 which sandwich a separation layer 38. The optical members 35, 36 may be realized from glass having an index of refraction larger than that of the separation layer 38. For example, in one preferred embodiment the optical members 35, 36 may be manufactured from glass having an index of refraction of 1.55, while the separation layer 38 is composed of a solid such as either magnesium fluoride (MgF_2) or fused silica (SiO_2) having indices of refraction of 1.38 and 1.48, respectively. The separation layer 38 need not consist of a solid, and may be realized from a liquid or air provided that the optical members 35, 36 are of a larger index of refraction.

A brief description of the physics of the interaction of the light in beam S with layer 38 is as follows. If layer 38 and optical member 35 are not present, the well-known phenomenon of total internal reflection takes place at the hypotenuse face of optical member 36, sending all of beam S in the direction of beam R. However, some light energy exists behind the hypotenuse face of optical member 36 in the form of "evanescent waves", which do not propagate. When optical member 35 is brought close enough to optical member 36, this energy is coupled without loss into member 35 and propagates in the direction of beam T. This phenomenon is known as frustrated total reflection (FTR). In this condition, if the FTR prism is disposed with respect to beam S such that the incidence angle A of beam S at separation layer 38 is close to the region of

frustrated total reflection, the transmission and reflection curves will have very steep slopes (angular sensitivities). This allows the fabrication of a very sensitive focus sensing system. Further, the transmission and reflection curves for such a system based on the FTR principle will be relatively insensitive to the wavelength of the light in beam S, as compared to the curves of a multilayer structure.

The prism 30 may be fabricated by first depositing the separation layer on either of the optical members via conventional thin film techniques. The complementary optical member may then be affixed to the exposed surface of the separation layer with an optical glue. Although the indices of refraction of the first and second optical members 35, 36 will generally be chosen to be identical, differing indices of refraction may also be selected. In the preferred embodiment, the first and second optical members have identical indices of refraction in such a geometry that the transmitted and reflected beams T and R are of substantially equal cross-section.

As shown in the illustrative front view of Figure 3, the first quad detector 32 includes first, second, third and fourth photodetective elements 40, 42, 44, 46, respectively, which produce electrical signals hereinafter referred to as T1, T2, T3, and T4 in response to the intensity of the transmitted beam T impinging thereon. Similarly, the second quad detector 34 includes fifth, sixth, seventh and eighth photodetective elements 50, 52, 54, 56, respectively, which provide electrical signals hereinafter referred to as R1, R2, R3 and R4 in response to incidence of the reflected beam R. The photodetective elements may be realized by PIN diodes, wherein the level of the electrical output from each diode is proportional to the optical energy received thereby.

When the objective lens 24 (Figure 1) is situated relative to the disk 14 such that the illuminating beam I is properly focused, the rays included within the servo

beam are well collimated (i.e. substantially parallel) and are therefore incident on the separation layer 38 at a substantially identical angle A shown in Fig. 2. Contrary to this, when the objective lens 24 does not focus the illuminating beam in the plane occupied by the surface of the disk 14 the rays comprising the servo beam S will be either mutually convergent or divergent. It follows that all rays within the servo beam S will impinge on the separation layer 38 at the substantially same angle when the illuminating beam I is suitably focused, while rays of a different range of angles of incidence will address the separation layer 38 when the beam I is out of focus.

The prism 30 is designed such that the reflectivity and transmissivity of the separation layer 38 is extremely sensitive to the angle at which optical energy is incident on the separation layer 38. Thus, the spatial distribution in the intensity of the transmitted and reflected beams T, R will vary as the focus position of the illuminating beam I varies relative to the surface of the disk 14. That is, an illuminating beam I which is properly focused gives rise to a well collimated servo beam S such that all the rays thereof experience the same degree of reflection by the separation layer 38. Accordingly, the transmitted and reflected beams T, R will be of substantially uniform intensity when the illuminating beam I is appropriately focused. Conversely, a convergent or divergent servo beam S will engender transmitted and reflected beams T, R of nonuniform spatial intensity distributions since the rays within the servo beam S will be subject to a variety of degrees of reflection by the separation layer 38. By detecting these spatial variations in the intensity of the transmitted and reflected beams the photodetectors 32, 34 produce electrical signals which may be utilized to produce a DFES indicative of the focus position of the illuminating beam I.

The manner in which a DFES may be synthesized in response to the degree of collimation of the servo beam S

may be further understood with reference to Fig. 4. Figure 4 is a graph showing the reflectivity (intensity of beam R / intensity of beam S) of the FTR prism 30 as a function of the angle of incidence of rays within the servo beam S relative to the separation layer 38. Specifically, the graph of Figure 4 depicts the reflectivities R_s and R_p of the prism 30 in response to illumination by both s-polarized and p-polarized optical energy of wavelength 0.78 microns. The reflectivity profiles of Figure 4 pertain to a FTR prism 30 having a separation layer with a thickness of 4.5 microns and an index of refraction of 1.38, with the separation layer being sandwiched by glass members having an index of refraction of 1.55. As shown in Figure 4, the prism 30 is preferably positioned relative to the servo beam S at an angle of incidence A_1 such that the prism 30 is operative about a working point P. That is, at the working point P the prism 30 is positioned such that an illuminating beam I properly focused on the disk 14 engenders a well collimated servo beam S having rays which impinge on the separation layer 38 at the angle A_1 . Since the reflectivity of the prism 30 is approximately 0.5 at the operating point P, the transmitted and reflected beams produced by the module 30 are of substantially identical average intensity.

When the separation between the objective lens 24 and the disk 14 varies such that the servo beam S decollimates in either a convergent or divergent manner, a first portion thereof will impinge on the separation layer 38 at an angle of incidence larger than the angle A_1 . For example, at an angle of incidence of A_2 (Fig. 4) a corresponding portion of the servo beam will experience a reflectivity of approximately 0.7. Since the first servo beam portion is subject to a reflectivity of only 0.5 when the servo beam S is well collimated, the regions of the detectors 32, 34 which receive the parts of the reflected and transmitted beams R, T derived from the first servo beam portion will collect more and less optical energy, respectively, than

when the illumination beam I is properly focused. Similarly, the areas of the detectors 32, 34 in optical alignment with parts of the transmitted and reflected beams T, R arising from a second portion of the servo beam S incident on the separation layer 38 at an angle of incidence A_3 (smaller than the angle A_1) will be illuminated by more and less optical energy, respectively, than in a condition of proper focus. The DFES is produced in response to electrical signals engendered by the photodetectors 32, 34 indicative of this spatial nonuniformity in the intensity distribution of the transmitted and reflected beams T, R. Moreover, since in the preferred embodiments described herein the module 30 is optically nonabsorbing, variation in the intensity of the transmitted beam T arising from a change in the angle of incidence of a portion of the servo beam S is mirrored by an equal, oppositely directed variation in the magnitude of the part of the reflected beam R engendered by the identical servo beam portion.

Non-differential error signals may be generated independently from either the transmitted or reflected beam, using the equations:

$$FES(\text{transmitted}) = (T_1 + T_2) - (T_3 + T_4) \quad [1]$$

$$FES(\text{reflected}) = (R_1 + R_2) - (R_3 + R_4) \quad [2]$$

In the differential system, the differential focus error signal (DFES) is generated by the control unit 37 in accordance with the following expression:

$$DFES = (R_1 + R_2 + T_3 + T_4) - (T_1 + T_2 + R_3 + R_4) \quad [3]$$

The control unit 37 includes circuitry suitable for carrying out the arithmetic operations of equation [3] and for generating a DFES based on these operations. Preamplifiers (not shown) are included to amplify the electrical signals from the photodetectors 32, 34 prior to

processing by the control unit 37.

Utilizing the dual quad photodetector arrangement described herein leads to the synthesis of differential focus error signals having a reduced sensitivity to certain beam imperfections not induced by inaccuracies in the focus position of the illuminating beam relative to the disk 14.

Since a localized decrease in the intensity of the servo beam S unrelated to the focus position of the illuminating beam affects the detectors 32 and 34 in a substantially similar manner, such a decrease does not affect the value of the DFES due to the corresponding cancellation which occurs in equation [3].

As mentioned in the Background of the Invention, prior focusing systems were generally ill-equipped to implement the differential focus sensing scheme described by equation [3]. In particular, a feature of the present invention lies in the ability of the FTR prism 30 to provide transmitted and reflected beams of substantially similar cross section and intensity such that both may effectively contribute to the synthesis of a DFES.

In addition to providing a DFES for maintaining the focus of the illuminating beam I in the direction normal to the surface of the disk 14, the electrical outputs from the photodetectors 32, 34 may also be used by the control unit 37 to generate a tracking error signal (TES). The TES is indicative of the radial position of the illuminating beam I relative to the conventional spiral or concentric guiding tracks (not shown) imprinted on the surface of the disk 14. The TES enables the beam I to follow the guiding tracks despite eccentricities therein by controlling a mechanical arrangement (not shown) operative to adjust the radial position of the objective lens 24 relative to the disk 14. The TES is calculated by the control unit 37 on the basis of electrical outputs from the photodetectors 32, 34 in accordance with the following equation:

$$TES = (T1 + T3 + R3 + R1) - (T2 + T4 + R2 + R4) \quad [4]$$

Again, the manner in which a tracking error signal may be derived from the relationship existing between spatial intensity changes of the servo beam and the tracking position of the illuminating beam is disclosed in, for example, U.S. Pat. No. 4,707,648.

In perhaps the majority of systems operative to control the focus of an illuminating beam relative to an optical disk it will be desired to generate both tracking and focus error signals in response to the electrical outputs of the photodetective elements. Since generation of both the focus and tracking error signals is known to generally require at least one quad photodetector, the embodiments of the present invention disclosed herein have been described with reference to quad photodetectors. However, it is also known that a focus error signal may be derived on the basis of electrical signals produced by photodetectors having only two independent photosensitive regions (bicell detectors). Accordingly, in applications requiring only the generation of a focus error signal a single photodetective element could be substituted for the first and second elements 40, 42 of the photodetector 32, and a single photodetective element could replace the third and fourth elements 44, 46. Similarly, a single photodetective element could be used in lieu of the fifth and sixth elements 50, 52 of the photodetector 34, and a single element could be substituted for the seventh and eighth elements 54, 56.

The slope of the reflectivity profile of Figure 4 about the working point P is proportional to the sensitivity of the DFES generated by the apparatus 10. Specifically, the sensitivity of the apparatus 10 to changes in the focus of the illuminating beam I is augmented by increases in the slope of the reflectivity profile. Accordingly, it is an object of the present invention to provide a prism 30 characterized by a reflectivity profile which is as steep as practically

possible.

The shape of the reflectivity profile of Figure 4 about the working point P may be altered by adjusting the thickness of the separation layer 38. For example, increasing the thickness of the separation layer 38 translates the angle of minimum reflectivity A_m towards the critical angle A_c (see Fig. 4) without affecting the value of the latter. It follows that increasing the separation layer thickness serves to increase the slope of the reflectivity profile in the vicinity of the working point P. Similarly, reducing the thickness of the separation layer 38 enlarges the angular displacement between the critical angle A_c and the angle of minimum reflectivity A_m . The shape of the reflectivity profile of the prism 30 may be varied in order to adjust the sensitivity of the DFES. A reasonable slope can be obtained, for example, by use of a separation layer having a thickness that is greater than one half of the wavelength of the illuminating beam I.

The value of the critical angle A_c may be adjusted by varying the index of refraction of the separation layer 38 relative to that of the glass members 35, 36. Thus, adjustment of the separation layer thickness in conjunction with manipulation of the indices of refraction of the separation layer and surrounding glass members allows the prism 30 to be fabricated in accordance with a desired reflectivity profile.

Figure 5 is a graph of the value of a normalized DFES (NDFES) generated by the apparatus 10 as a function of the deviation from the desired displacement of the objective lens 24 relative to the disk 14. NDFES is mathematically represented as follows:

$$\text{NDFES} = \frac{\text{DFES}}{(T_1+T_2+T_3+T_4+R_1+R_2+R_3+R_4)} \quad [5]$$

Again, the data in Figure 5 was obtained by utilizing a prism 30 having a separation layer of index of refraction 1.38 and thickness 4.5 microns sandwiched between glass

members of index of refraction 1.55, with the prism 30 being illuminated by a servo beam of wavelength 0.78 microns. As is shown in Figure 5, the value of the DFES is preferably zero when the desired displacement exists between the objective lens 24 and the disk 14. The sign (+ or -) of the DFES is thus indicative of whether the displacement between the objective lens and disk surface exceeds or is less than that required for proper focusing. As mentioned above, the DFES may be used to control a mechanical arrangement (not shown) disposed to adjust the separation between the objective lens 24 and the disk 14. It may be appreciated that the slope of the NDFES is approximately 0.16 micron^{-1} at the working point defined by 0 (zero) disk displacement.

Although the servo beam S has been represented herein to be substantially collimated when incident on the separation layer 38, the present invention is not limited to configurations giving rise to collimated servo beams. When a convergent or divergent servo beam is utilized, inaccuracies in the focus position of the illuminating beam will alter the degree of convergence or divergence thereof. Those skilled in the art will appreciate that the focus sensing apparatus of the present invention may be utilized to generate a DFES in response to such changes in convergence or divergence.

The inventive focus sensing apparatus has thus been shown to overcome the disadvantages inherent in other focus detection systems by providing reflected and transmitted beams of substantially similar shape and intensity from which a high precision, altitude insensitive focus error signal may be differentially derived. The focus sensing technique disclosed herein nonetheless retains features present in certain related focus detection systems such as low sensitivity to mechanical vibration, decreased sensitivity to disk tilt, and increased thermal stability.

Although the invention has been described herein as used in particular applications associated with focus

sensing, the invention applies to the more general field of beam geometry evaluation. It is not intended that the scope of the invention be limited to the specific embodiments described herein, since the invention finds application in the evaluation of radiation beam geometry generally, regardless of what defines this beam geometry.

While the above detailed description has shown, described and pointed out the fundamental novel features of the invention as applied to various embodiments, it will be understood that various omissions and substitutions and changes in the form and details of the device illustrated may be made by those skilled in the art, without departing from the spirit of the invention.

CLAIMS

1. A focus sensing apparatus for determining the focus of an illuminating beam, said apparatus comprising: a source of radiation energy; means for focusing radiation from the radiation energy source upon an object; means for separating at least a portion of radiation reflected by said object into transmitted and reflected beams, said separating means including a separation layer which varies in reflectivity in response to the angle of incidence of said reflected radiation, said separation layer having a thickness which is larger than one half of the wavelength of said reflected radiation incident thereon; and photodetector means for detecting the intensities of said transmitted and reflected beams which intensities vary with the angle of incidence and thus with the degree of focus of the illuminating beam.

2. The focus sensing apparatus of Claim 1 wherein said beam separation means includes first and second optical members, said optical members being arranged so as to sandwich said separation layer.

3. The focus sensing apparatus of Claim 2 wherein said first and second optical members are of a first index of refraction, and wherein said separation layer is of a second index of refraction less than said first index of refraction.

4. The focus sensing apparatus of Claim 2 wherein said first and second optical members are of first and third



indices of refraction, and wherein said separation layer is of a second index of refraction less than said first and third indices of refraction.

5 5. The focus sensing apparatus of Claim 1, further comprising means for detecting variation in the intensity distributions of the transmitted and reflected beams, and thereby providing an indication as to the extent to which the radiation from the radiation energy source is not
10 focused on the object.

6. The focus sensing apparatus of Claim 1, wherein the beam separation means comprises a frustrated total reflection prism.

7. The focus sensing apparatus of Claim 1, wherein said
15 photodetector arrangement includes a first photodetector in optical alignment with said transmitted beam, and a second photodetector in optical alignment with said reflected beam.

8. The focus sensing apparatus of Claim 7, further including a control unit, in electrical communication with
20 said first and second photodetectors, for generating a differential focus error signal.

9. The focus sensing apparatus of Claim 1, wherein the radiation energy comprises light energy.

10. A focus sensing apparatus for determining the focus of
25 an illuminating beam, said apparatus comprising: a light source for generating a light beam; an objective lens for focusing said light beam upon an object; a beam separation module for separating at least a portion of light reflected



by said object into transmitted and reflected beams when said portion of said reflected light impinges on said beam separation module at an angle of incidence having an angular value within a selected continuous range of angular values between a critical angle of a first angular value and a next adjacent angle of minimum reflectance having a second angular value wherein said second angular value is less than said first angular value, said separation module including a separation layer which varies in reflectivity in response to the angle of incidence of said reflected light; beamsplitting means for directing at least a portion of said reflected light to said beam separation module; and a photodetector arrangement for detecting the intensities of said transmitted and reflected beams which intensities vary with the angle of incidence and thus with the degree of focus of the illuminating beam.

11. The focus sensing apparatus of Claim 10, wherein said beam separation module includes first and second optical members, said optical members being arranged so as to sandwich said separation layer.

12. The focus sensing apparatus of Claim 11, wherein said first and second optical members are of a first index of refraction, and wherein said separation layer is of a second index of refraction less than said first index of refraction.

13. The focus sensing apparatus of Claim 12, wherein said light beam includes optical energy of a first wavelength and



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said separation layer is of a thickness greater than one half of said first wavelength.

14. The focus sensing apparatus of Claim 10, wherein the beam separation module comprises a frustrated total reflection prism.

15. A focus sensor for determining the focus of an illuminating beam, said sensor comprising: a light source; means for focusing light from the light source as said illuminating beam upon an object; means for separating at least a portion of light reflected by the object into a transmitted beam of a first intensity distribution and a reflected beam of a second intensity distribution, said separating means being configured such that said transmitted and reflected beams are each of an intensity which varies with the angle of incidence of the light from the object onto the separating means, and are of a substantially similar intensity distribution when the light is in focus on the object, and such that the spatial variation in the intensity of the transmitted beam is mirrored by a substantially equal and opposite spatial variation in the intensity of the reflected beam when the focus of the light deviates from the object, said means for separating having a thickness which is larger than one half of the wavelength of said reflected radiation incident thereon; and means for providing an indication of the spatial intensity variation which spatial intensity variation varies with the angle of incidence and thus with the degree of focus of the



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illuminating beam.

16. A focus sensor as defined in Claim 15, wherein the separating means includes a separation layer which acts on the reflected light to produce the transmitted and reflected beams, and which varies in reflectivity in response to the angle of incidence of the reflected light.

17. A focus sensor as defined in Claim 16, wherein the separating means comprises: a first optical member of a first selected index of refraction; a second optical member of a second selected index of refraction; and a separation layer positioned between the first and second optical members, wherein said separation layer is of an index of refraction that is less than the first and second selected indices of refraction.

18. A focus sensor as defined in Claim 17, wherein the first and second selected indices of refraction are substantially the same.

19. A focus sensor for determining the focus of an illuminating beam, said sensor comprising: a light source for producing an optical beam; an objective lens arrangement for focusing the beam as said illuminating beam upon an object, said arrangement including a polarization beamsplitter and an objective lens; a beam separation module for separating at least a portion of light reflected by the object into a transmitted beam of a first intensity distribution and a reflected beam as a second intensity distribution which both vary with the angle of incidence at



which said reflected light impinges on said beam separation module, the angle of incidence having an angular value within a selected continuous range of angular values between
5 a critical angle of a first angular value and a next adjacent angle of minimum reflectance of a second angular value, wherein said second angular value is less than said first angular value, said separating means being configured such that said transmitted and reflected beams are of a
10 substantially similar intensity distribution when the illuminating beam is in focus on the object, and such that the variation in the intensity distribution of the transmitted beam is mirrored by a substantially equal and opposite variation in the intensity distribution of the
15 reflected beam when the focus of the beam deviates from the object; and first and second photodetectors in optical alignment with said transmitted and reflected beams, respectively, for providing first and second signals indicative of the variation in the intensity distribution of
20 the transmitted and reflected beams which intensity distribution varies with the angle of incidence and thus with the degree of focus of the illuminating beam.

20. A focus sensing apparatus for determining the focus of an illuminating beam by detecting characteristics of
25 transmitted and reflected beams, said apparatus comprising: a radiation source; an optical member for



focusing radiation from the radiation source upon an object; a frustrated total reflection prism for receiving radiation reflected from the object and for providing a reflected radiation beam and a transmitted radiation beam, said transmitted radiation beam being produced by frustrated total reflection of a portion of said radiation reflected from said object when said reflected radiation impinges on said separation layer at an angle of incidence with an angular value within a selected continuous range of angular values between a critical angle of a first angular value and a next adjacent angle of minimum reflectance of a second angular value, wherein said second angular value is less than said first angular value; and means for detecting a characteristic of one of the reflected and transmitted beams, which varies with the angle of incidence and hence with the degree of focus of the illuminating beam.

21. A focus sensing apparatus as defined in Claim 20, further comprising means for detecting a characteristic of the other of the reflected and transmitted beams.

22. A focus sensing apparatus as defined in Claim 21, wherein the means for detecting characteristics of the reflected beam and the means for detecting characteristics of the transmitted beam comprise photodetectors for detecting intensities of said reflected and transmitted beams.

23. A focus sensing apparatus as defined in Claim 20,



further comprising means responsive to the detecting means for providing an indication as to the extent to which the radiation from the radiation source is not focused on the object.

5 24. A focus sensing apparatus as defined in Claim 20, wherein the frustrated total reflection prism comprises first and second optical members and a separation layer sandwiched between said first and second optical layers, and wherein said frustrated total reflection prism is
10 disposed with respect to the radiation reflected from the object such that the angle of incidence of said radiation reflected from said object at said separation layer is close to a region of total frustrated reflection.

15 25. A method of sensing focus between a radiation source and an object by detecting characteristics of transmitted and reflected means, said method comprising the steps of: positioning a frustrated total reflection prism at a location so as to receive radiation reflected from the object and to provide therefrom a reflected radiation beam
20 and a transmitted radiation beam, said prism including a separation layer having a thickness which is larger than one half of the wavelength of said reflected radiation incident thereon, wherein said transmitted radiation beam is produced by frustrated total reflection of a portion of
25 said radiation reflected from said object; and detecting characteristics of one of the reflected and transmitted beams, which vary with the angle of incidence of the



radiation from the object onto the separation layer of the prism and hence with the degree of focus of the radiation on the object.

5 26. A method of sensing focus as defined in Claim 25, further comprising the step of detecting a characteristic of the other of the reflected and transmitted beams.

10 27. A method of sensing focus as defined in Claim 26, wherein the steps of detecting characteristics of the reflected beam and detecting characteristics of the transmitted beam comprise the step of detecting the intensities of said reflected and transmitted beams.

15 28. A method of sensing focus as defined in Claim 25, further comprising the step of providing, in response to the detecting step, an indication as to the extent to which the radiation from the radiation source is not focused on the object.

20 29. A method of sensing focus as defined in Claim 25, wherein the frustrated total reflection prism comprises first and second optical members and a separation layer sandwiched between said first and second optical layers, and wherein said positioning step comprises the step of disposing the frustrated reflection prism with respect to the radiation reflected from the object such that the angle of incidence of said radiation reflected from said
25 object at said separation layer is close to a region of total frustrated reflection.

30. Focus sensing apparatus, substantially as described



herein with reference to the accompanying drawings.

31. A beam evaluation system, substantially as described herein with reference to the accompanying drawings.

5 32. A method of sensing focus, substantially as described herein with reference to the accompanying drawings.

33. A method of evaluating beam geometry, substantially as described herein with reference to the accompanying drawings.

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