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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G01B 9/02

A1

(11) International Publication Number: WO 95/33970

(43) International Publication Date: 14 December 1995 (14.12.95)

(21) International Application Number: PCT/US95/06071

(22) International Filing Date: 16 May 1995 (16.05.95)

(30) Priority Data:
08/252,940 2 June 1994 (02.06.94) US

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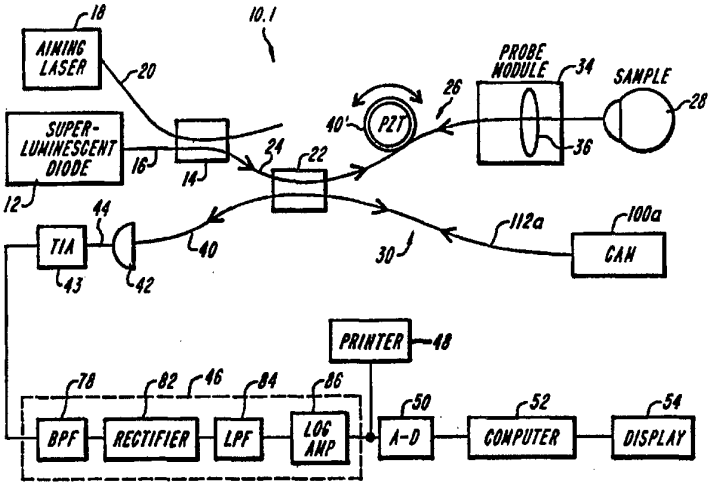
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(81) Designated States: CA, JP, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: ROTATING CAM FOR OPTICAL SYSTEMS



(57) Abstract

A cam (100a) includes a cam disk (101a) having a center (108a) about which the cam disk rotates, an outline and peripheral scattering face (104a) for receiving radiation (117a) from a source and scattering the radiation as scattered radiation (124a). The cam (100a) includes a motor (150a) for rotating the cam disk, wherein the scattered radiation undergoes periodic delay variations determined by the outline of the cam disk. A measuring apparatus (10.1) which utilizes the cam (100a) includes a source (12) for outputting radiation with a short coherence length; a splitter (22) for splitting the radiation into reference radiation and measuring radiation; a radiation directing unit (34) which receives and directs the measuring radiation toward an object (28) and also collects a portion of the measuring radiation scattered off of the object. The cam (100a) receives the reference radiation and scatters a portion of the reference radiation as scattered reference radiation. The measuring apparatus (10.1) includes a detecting unit (42) which detects intensity resulting from part of the measuring radiation which coherently interferes with the scattered reference radiation to provide information about the object.

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ROTATING CAM FOR OPTICAL SYSTEMS

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to an apparatus and method for introducing path length variations and periodic frequency shifts in electromagnetic radiation scattered therefrom and in particular to an apparatus and method for periodically introducing optical path length variations and Doppler shifts in a beam of optical radiation and also to an optical measuring system for high precision measurements which utilizes the apparatus in one of two of its optical paths. This latter apparatus and method involves optically performing precision measurements such as distance and thickness measurements, on biological and other samples.

2. Description of Related Art

Translational scanning systems are often used to introduce optical path length variations and frequency shifts by utilizing a scattering or reflecting surface attached to a translation stage. Such scanning systems are used, for example, in autocorrelators, wavemeters, interferometers, and optical coherence domain reflectometers.

One example of a system which utilizes a translation stage for introducing a fixed (or a known variable) Doppler shift in incident radiation are the optical measuring systems discussed in U.S. Patent Application Ser. No. 08/033,194, the parent application to this application. These optical

measuring systems are used for performing high resolution measurements and in particular for optically performing such measurements, which improved technique does not require contact with the body being measured, which maintains substantially constant high resolution over a scanning depth of interest, regardless of available apertures size and which is relatively compact and inexpensive to manufacture. Such systems are also capable of providing differentiation between sample layers, identification of layer material or of selected properties thereof, and can provide one, two and three-dimensional images of a scanned body. The systems also provide measurements at rapid enough rates for use in biological and other applications where the sample being measured changes over relatively short time intervals. In fact, they can even provide information concerning the birefringence property and spectral properties of the sample.

These optical measuring systems include two optical arms, a measuring arm and a reference arm. The translation stage and reflecting surface are located in the reference arm of the measuring systems.

The translation stage, typically driven by some type of actuator motor, would be coupled to the actuator via some type of gear mechanism. The translation stage would move the scattering surface toward and away from the direction of the incident radiation. Radiation having a wavelength λ and traveling from a location towards which the reflecting surface travels at a speed of V, undergoes a positive Doppler

shift of $2V/\lambda$. When the reflecting surface travels in the same direction as the radiation travels, the radiation undergoes a negative Doppler shift of $2V/\lambda$.

In one approach, the reflecting surface is scanned in one direction at a velocity V, and then rapidly returned to its initial position, the scan having a generally ramp or sawtooth profile. In this case, there is always a "fly back" time during which the radiation undergoes a large non-constant Doppler shift. The time during which this flyback occurs is dead time during which the Doppler shifted radiation is of no use which corresponds to a relatively low (e.g., 70-80%) duty cycle.

Another downfall of translation stages is that the rate at which the scattering surface is scanned back and forth is limited by the above discussed deceleration-stop-acceleration process. In both of the above situation, the faster the scanning rate, a greater portion of the scan is required to decelerate, stop and accelerate in the opposite direction. Hence, as the scanning rate is increased, the duty cycle decreases.

In addition to the above, it is often necessary to increase the velocity V of the translation stage in order to effect a particular Doppler shift, path length variation and measurement rate. If the stroke length (i.e., the length the reflecting surface must travel from the time it is at rest until it is again at rest) remains the same when the velocity increases, the scanning rate necessarily increases.

Consequently, the duty cycle decreases for the same reasons as discussed. If, on the other hand, upon increasing the velocity V, the stroke length is proportionally increased so that the scanning rate remains the same, the length of the translation stage/reflecting surface can quickly become too large. Also, in either of the above cases, as velocity V increases, the reflecting surface is subjected to more and more wobble. This wobble translates into variations in the Doppler shift which the incident radiation undergoes which must be filtered out or compensated for by, e.g., focussing the radiation to a smaller beam when incident on the reflecting surface, or utilizing a specific reflecting mechanism such as a corner cube.

SUMMARY OF THE INVENTION

One object of the invention, therefore, is to provide a scanning cam with nearly a 100% duty cycle.

Another object of the invention is to provide a scanning cam which can scan through cycles at very high rates while avoiding excessive wobble.

Another object of the invention is to provide a scanning cam for use in autocorrelators, wavemeters, interferometers, and optical coherence domain reflectometers.

Another object of the invention is to provide an optical measuring device which incorporates the optical cam in its reference arm.

One advantage of the invention is that the scanning cam has only one moving part.

Another advantage of the invention is that it can scan at high rates while avoiding excessive wobble.

Another advantage of the invention is that its peripheral face when viewed in a fixed direction can operate to provide high scanning rate linear translations.

Another advantage of the invention is that it can be inexpensively made using injection molding, surface duplication or diamond milling techniques which are easily adaptable to mass production techniques.

One feature of the invention is that it has a cam disk with a peripheral face which receives the optical radiation.

Another feature of the invention is that it has a cam disk with a peripheral face.

Another feature of the invention is that the peripheral face has a high reflecting surface.

Another feature of the invention is that it utilizes a motor for rotating the cam disk.

Another feature of the invention is that the peripheral face can be helical.

Another feature of the invention is that the cam disk can be weighted to balance at a center about which the disk rotates.

Another feature of the invention is that the peripheral face can be polished to achieve desired optical properties.

Another feature of the invention is that the peripheral face can have a thin strip mirrored surface affixed thereto.

Another feature of the invention is that the peripheral face can be made using diamond machining techniques.

The above and other objects, advantages and features are accomplished by the provision of a cam, including: a cam disk having a center about which the cam disk rotates, an outline and a peripheral scattering face for receiving radiation from a source and scattering the radiation as scattered radiation; and a motor mechanically coupled to the cam disk such that the motor rotates the cam disk about the center, wherein the scattered radiation undergoes periodic delay variations, and each of the delay variations is determined by the outline of the cam disk.

The above and other objects, advantages and features are accomplished by the provision of a measuring apparatus, including: a source for outputting radiation with a short coherence length; a splitter for splitting the radiation into reference radiation and measuring radiation; radiation directing means for receiving the measuring radiation and directing the measuring radiation toward an object and for collecting a portion of the measuring radiation scattered off of the object; a cam for receiving the reference radiation and scattering a portion of the reference radiation as scattered reference radiation; and detecting means for detecting intensity resulting from a part of the portion of measuring radiation which coherently interfere with the

scattered reference radiation, wherein the intensity provides information with respect to the object.

The above and other objects, advantages and features are further accomplished by the provision of a method of measuring properties of an object, comprising the steps of: outputting radiation with a short coherence length; splitting the radiation into reference radiation and measuring radiation; directing the measuring radiation toward the object and collecting a portion of the measuring radiation scattered off of the object; directing the reference radiation toward a cam and scattering a portion of the reference radiation off of a peripheral surface of the cam as scattered reference radiation; and detecting intensity resulting from a part of the portion of measuring radiation which coherently interferes with the scattered reference radiation, wherein the intensity contains information relating to the properties of the object.

The above and other objects, advantages and features of the present invention will become more apparent from the following description of embodiments thereof taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A shows an optical cam according to one embodiment of the invention. Figure 1B shows a top and tilted view of the cam with a motor and axle which fits into the center of the cam disk. Figure 1C shows Rz(t), as shown

in Figure 1A, as a linear function of time t which repeats every cycle T resulting in a sawtooth type function, Figure 1D shows a cam disk with radius R(0)=30mm and $R(2\pi)$=33mm.

Figure 2A is a schematic block diagram of a first fiber optic embodiment of the invention using an embodiment of the cam. Figure 2B is a schematic block diagram of a second fiber optic embodiment of the invention using an embodiment of the cam.

Figure 3 is a schematic block diagram of a bulk optic embodiment of the invention illustrating the use of two separate wavelengths to enhance resolution.

Figure 4 is a diagram of the envelope of a scan output which might be obtained utilizing the embodiments of Figures 1-3.

Figure 5A is an enlarged diagram of a portion of a detector output from a system such as that shown in Figure 3, illustrating the modulation frequency on which such envelope is superimposed.

Figure 5B is a diagram of the waveform of Figure 5A after demodulation.

Figure 6 is a schematic block diagram of a third fiber optic embodiment of the invention utilizing polarized light to detect birefringence.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1A shows an optical cam 100a according to one embodiment of the invention. In particular, Figure 1A shows cam 100a with cam disk 101a. Cam disk 101a has a peripheral scattering face 104a and a center 108a about which cam 100a rotates at an instantaneous frequency F(t) cycles/second, where t represents an instant in time. Cam disk 101a is preferably weighted such that its moment of inertia is balanced about center 108a.

Cam 100a receives optical radiation from a fiber 112a as follows. Optical radiation 109a is output from tip 111a of fiber 112a and is collimated by a collimating lens 116a (which can be regular or cylindrical lens) into collimated optical radiation 117a. This could be done with a single lens for some applications. Optical radiation 117a is then focussed by a focusing lens 120a as a spot 124a (or ellipse if focussing lens 120a is a cylindrical lens) onto peripheral face 104a. Although Figure 1A shows cam 100a receiving optical radiation from fiber 112a, cam 100a can receive any type of radiation from any type of radiation directing guide or free space radiation directed toward cam 100a. It should be noted that since cam disk 101a is not perfectly circular, radiation 117a should be directed to peripheral face 104a slightly off axis (off the z direction) in order to increase coupling of reflected radiation back into fiber 112a. Also, radiation 117a can be directed toward face 104a so far off the z axis (dashed lines in Figure 1A) that a reflector 123' must be used to redirect radiation scattered off face 104a

back to face 104a and then back towards fiber 112a. In this double pass embodiment, the radiation undergoes twice the Doppler shift of a single pass which could be useful in some applications.

Figure 1B shows a tope and tilted view of cam 100a with a motor 150a and axle 152a which fits into center 108a of cam disk 101a. Motor 150a can be either synchronous or asynchronous. Figure 1B also shows a timing mark 160a and an optoelectronic sensor 164a. Sensor 162a outputs a once in a revolution signal for each revolution of cam disk 101a at output 166a to whatever optical system cam 100a is being used. Timing mark 160a can be a metal tab and optoelectronic sensor 164a can be an LED photodiode combination known in the art.

Referring back to Figure 1A, distance d is defined to be the distance from focusing lens 120a to spot 124a and distance D is the distance from focusing lens 120a to center 108a. The distance from center 108a to peripheral face 104a is defined as radius R. Radius R varies from a smallest value R(0) to a largest value R(2π) where peripheral face 104a has a step transition 130a as indicated in Figure 1A. Angle α is defined to be the angle between the smallest radius R(0) to any radius R on cam 100a. Hence, R is a function of angle α and hence will be referred to as R(α), where $R(0) <= R(\alpha) < R(2\pi)$. It should be noted, however, that R(α) is not limited to be function where $R(0) < R(\alpha) < R(2\pi)$. Hence, in general, R($\alpha$) can vary in any arbitrary manner,

i.e., can both increase and decrease multiple times as α varies from 0 to 2π, e.g., $R(\alpha)$ can have multiple local maxima and minima as α varies from 0 to 2π. Moreover, the outline or shape of peripheral face 104a is determined by the function $R(\alpha)$. Also, α generally relates to the rotation rate F(t) as

$$\alpha(t) = 2\pi \int_0^t F(t)\, d(t)$$

Distance D remains fixed (in one embodiment of the invention) and the rotation of cam 100a about center 108a is translated into transverse motion, and in particular, into a variation of distance d. Hence, distance d varies with time t and will be referred to as d(t). Defining the radius Rz to be the distance from center 108a to spot 124a along the z direction makes Rz a function of time and hence will be referred to as Rz(t). The derivative of Rz(t) is defined as instantaneous velocity V, i.e., V(t)=d(Rz)/dt and the size of step transition 130a is $R(2\pi)-R(0)$. Finally, the distance D=Rz(t) + d(t) for all time t and Rz(t) as well as V(t) repeat every cycle T = 1/F, i.e, Rz(t)=Rz(t+nT) and V(t)=V(t+nT), where n is any integer.

It is possible to design an outline of cam disk 101a which yields dRz/dt equal to a constant (It will be discussed below, for the case of F(t) equal to a constant, this makes $R(\alpha)$ a helix.). It is also possible to design cam disk 101a such that $R(\alpha)$ varies monotonically as α varies from 0 to 2π.

In such a case, the sign of d(Rz)/dt would not change. It is also possible to design an outline which, together with F(t) could ensure that velocity V(t) itself varies monotonically, which could be useful if cam 100a were required to produce a frequency sweep or even "chirped" radiation due to Doppler induced frequency shifts as will be discussed in more detail below. Such chirped radiation can be either up or down, linear or non-linear or any other frequency variation as a function of time. In each case, the shape R() and the rotation rate F(t) of cam disk 101a determine dRz/dt and hence the resulting Doppler induced frequency variation as discussed above.

In the case in which the optical radiation 117a is focused onto peripheral face 104a, the confocal parameter of the focal spot should be approximately equal to the step size as a compromise between sensitivity to angular misalignment and loss due to focal error. A second and possibly the preferred approach is to select focusing lens 120a which has a focal length f approximately equal to D and lens 120a is a cylindrical lens. In this case, the wavefronts of optical radiation output from lens 120a approximately conform to the face 104a of cam 101a. This conformity may further reduce effects of wobble of cam 101a and improve coupling of scattered radiation back into fiber 112a. This improved coupling should result even in the presence of local surface imperfections on face 104a provided cylindrical lens 120a has a focal length approximately equal to distance D.

In one embodiment of the invention, V(t) is made to be a constant V_o. In this case, Rz(t) is a linear function of time t equal to $R(0)=V_0t$ which repeats every cycle T resulting in a sawtooth type function of Rz versus time as shown in Figure 1C. Note that the duty cycle is nearly 100%. That is, there is almost no translational fly back time as required for any traditional linear scanners, and instead cam disk 101a provides a linear change in Rz for the entire cycle T.

One way to make Rz(t) a linear function is time over period T is to fix the rotation rate F(t) to be a constant F_0 with respect to time. In that case, since

$$\alpha(t)=2\pi\int_0^t F(t)\,d(t)$$

$\alpha(t) = 2\pi F_0 t$,

$Rz(t) = R(0) + F_0T(R(2\pi)-R(0))$,

which means the instantaneous velocity V_0 can be written,

$V_0 = dRzz/dt$

$= F_0(R(2\pi)-R(0))$.

Note that the duty cycle is nearly 100%. That is, there is no translational fly back time as required for any traditional linear scanners, and instead the cam disk 101a provides a linear change in Rz for the entire cycle T. In this situation, peripheral face 104a will have a shape $R(\alpha) = R(0) + \alpha[(R(2\pi)-R(0))/2\pi]$ for $0 \langle= \alpha \langle= 2\pi$ which corresponds to a helix. For example, referring to Figure 1D,

cam disk 101a has radius R(0)=30mm, R(2π)=33mm which makes R(α) = 30mm + α[3mm/2π] and hence makes the outline of peripheral face 104a (i.e., the shape of cam disk 101a) a helix.

Cam disk 101a can be made out of any rigid material and preferably a material which leads itself to techniques such as injection molding, surface duplication or diamond milling. In addition, a mirror strip can be adhesively attached to face 104a. If cam disk 101a is made out of a single material having a single density and if cam disk 101a has a smoothly varying shape or outline, disk 101a will have a center of gravity and is such cases, center 108a about which cam disk 101a rotates, should be located at that center of gravity. However, for any shape or outline having a step transition 130a (e.g., the helical outline discussed above) cam disk 101a will not have such a center of gravity. In such a case, cam disk 101a can be modified so that its center of gravity corresponds approximately to center 108a. One way is to add counter weights to and/or lighten the weight (e.g., drill or remove portions) of disk 101a. Cam disk 101a can also be manufactured to have a varying density and its density must vary in such a manner that a resulting center of gravity can serve as center 108a.

Cam 100a can be used in any one of the systems disclosed in U.S. Patent Application Ser. No. 08/033,194 as will be discussed below. In particular, the above discussed helical outline R(α) is particularly useful in any of the systems

disclosed in that application since such an outline provides a fixed Doppler shift over nearly an entire period T for a fixed frequency rate F. The manner in which those systems can be modified to incorporate cam 100a will be discussed below.

Optical Measuring System Incorporating the Cam

Figure 2A shows one fiber optic optical coherence domain reflectometer (OCDR) 10.1 in which cam 100a can be used. In particular, the output from a short coherence length optical source 12 is coupled as one input to an optical coupler 14. Such coupling may be through a fiber optic path 16. Source 12 may, for example, be a light emitting diode (LED) or super luminescent diode (SLD) of suitable wavelength, and preferably has a coherence length of less than 10 micrometers and a single spacial mode. Source 12 might also be a pulsed laser source or an incandescent source; but for most applications an LED or SLD would be preferable, a pulsed laser having higher power, and an incandescent source with a single spatial mode having good resolution but very low power. As will be discussed later, it is desirable that the coherence length of source 12 be minimized to enhance the resolution of the system.

The other input to coupler 14 is from a laser 18 generating an optically visible output which is applied to the coupler through a fiber optic path 20. As will be discussed in greater detail later, laser 18 is utilized only to provide a source of visible light for proper alignment

with a sample when the light from source 12 is in the infrared region or is otherwise not visible. Further, unless otherwise indicated, all optical fibers utilized for the various embodiments will be assumed to be single mode fibers. These fibers may be polarization maintaining or not, but are preferably polarization maintaining to insure good polarization mode matching.

The output from coupler 14 is applied as the input to coupler 22 through fiber optic path 24. The light or optical energy received at coupler 22 is split between a first fiber optic path 26 leading to sample 28 being characterized and a second fiber optic path 30 leading to cam 100a. Fiber optic path 26 is terminated in probe module 34 which includes a lens 36 for focusing the radiation applied to the module on sample 28 and for receiving radiation scattered from object or sample 28 and transmitting the reflections back to the fiber. Path 30 includes fiber 112a, collimating lens 116a and focusing lens 120a as discussed above with reference to Figure 1A. The optical fibers of path 26 may be wrapped around a piezoelectric crystal 40 which vibrates (i.e. expands and contracts) in response to an applied electrical signal to cause slight expansion and contraction of the optical fiber and to thus modulate the optical signal passing through the fiber. The total length of path 26 between coupler 22 and a selected depth point in sample 28 and the total length of path 30 between coupler 22 and peripheral scattering face 104a should be substantially equal for each

depth point of the sample during a scan of selected depth range. In addition, to prevent group velocity dispersion which would decrease spatial resolution, the lengths of the optical fibers in paths 26 and 30 should also be substantially equal. Alternatively, the group velocity dispersions may be equalized by placing optical materials of known group velocity dispersion and thickness in the light paths to compensate for any inequality. For example, where the fiber in the reference path may need to be shorter than that in the sample probe, a length of high dispersion material may be included in the reference path. It is also important that the termination of the optical fibers utilized in the system be angle polished and/or anti-reflection coated to minimize reflections. For the embodiment shown in Figure 2A, velocity V (which relates to rotation rate F as discussed above) is preferably greater than 1cm/sec. The length or extent or movement is at least slightly greater than the desired scan depth range in sample 28.

Radiation received by probe 34 from sample 28 are applied through path 26 to coupler 22 and scattered radiation from cam 100a through lenses 120a and 116a and path 30 to the coupler. Note that one or both of the lenses 116a and 120a can be eliminated depending on the amount of scattered radiation fiber 112a needed to couple back to coupler 22. The scattered radiation received from the sample and the reference are combined in coupler 22, resulting in interference fringes for length matched reflections (i.e.,

reflections for which the difference in reflection path lengths is less than the source coherence length) and the resulting combined output is coupled onto fiber optic path 40. The optical signal on fiber path 40 is applied to a photodetector 42 which converts the optical combined signal on path 40 to a corresponding current-varying electrical signal. The current-varying electrical signal on output line 44 from photodetector 42 is preferably converted to a voltage varying signal by a transimpedance amplifier (TIA) 43 or other suitable means, the TIA output being applied as an input to a demodulator 46.

Various forms of demodulation may be utilized in practicing the teachings of this invention. In its simplest form, demodulator 46 may consist of a bandpass filter 78 centered around the modulation frequency of the combined output signal and an envelope detector. The filter assures that only the signal of interest is looked at and removes noise from the output. This enhances the signal-to-noise ratio of the system and thus system sensitivity. The filtered signal is then applied to the envelope detector.

The envelope detector in demodulator 46 may consist of a rectifier 82 and a subsequent low pass filter 84. The rectifier output would be proportional to the square root of the sample reflectivity. The second filter removes any high frequency components from what is basically a base band signal. The demodulator preferably also includes a logarithmic amplifier 86, strong reflections from boundaries

would either be off scale or weaker reflections would not be visible. Alternatively, logarithmic limiting detectors such as Analog Devices 606 may be used.

The exemplary demodulator described above is one type of heterodyne demodulator. However, a variety of other demodulation techniques know in the art may also be utilized to perform the demodulator function.

The demodulated output from demodulator 46 is the envelope of the interferometric signal of interest. A suitable printer 48 may be utilized to obtain a visual record of this analog signal which may be utilized by a doctor, engineer or other person for various purposes. For preferred embodiments, the analog output from demodulator 46 is applied, either in addition to or instead of to printer 48, through an analog-to-digital converter 50 to a suitable computer 52 which is programmed to perform desired analyses thereon. computer 52 may, for example, control the display of the demodulated signal on a suitable display device 54, such as a cathode ray tube monitor, or may control a suitable printer to generate a digital record. In addition, computer 52 may detect various point of interest in the demodulated envelope signal and may perform measurements or make other useful determinations based on such detectors. Computer 52 may be a suitably programmed standard processor or a special purpose processor may be provided for performing some or all of the required functions.

The embodiment shown in Figure 2A would be utilized where cam disk 101a rotates at a frequency F which translates into a uniform but intermediate velocity V(t). For purposes of this discussion, and intermediate velocity V(t) is considered one at which the Doppler frequency shift causes by the rotation frequency F of cam disk 101a is not negligible, but is low enough to fall within the predominant low frequency noise for the system. The noise spectrum includes noises arising from fluctuations in light source 12, mechanical components and electrical circuits, and are larger at lower frequencies, typically below 10 kHz.

The Doppler shift frequency f_D results from the rotation F of cam disks 101a and is given by the equation:

$$f_D = \frac{2V(t)}{\lambda}$$

where V(t) is the instantaneous velocity as discussed above at a given time t and λ is the wavelength of source 12 at which the peak intensity is output. Where this Doppler shift is less than 10 kHz, additional modulation is needed to shift the modulation frequency above the predominant noise spectrum. In Figure 2A this is achieved by introducing sinusoidal phase modulation by use of piezoelectric transducer 40. While in Figure 2A the additional modulation is introduced by the use of the oscillator or transducer in path 26, such modulation could also be provided in path 30. Further, in addition to piezoelectric crystal 40, the small

movement required for this supplemental modulation may be achieved using electromagnetic, electrostatic, or other elements known in the art for providing small generally sinewave movements. Alternatively, this supplemental modulation can be achieved by passing light in the reference arm and/or sample arm through acousto-optic modulators.

The supplemental modulation from transducer 40 or other suitable means which modulate the optical path length at a frequency F_M and the oscillation amplitude of this modulator is adjusted so that the peak-to-peak oscillating movement or optical delay change is approximately one-half of the wavelength λ of source 12. The combined effect of the supplemental modulation and the Doppler shift frequency causes the output envelope to be on modulating frequencies of f_D, $f_M + f_D$, $f_M - f_D$ and at higher harmonics. f_M is normally chosen to be higher than the predominant noise spectrum.

Demodulation of the output from photodetector 42 is normally at $f_M + f_D$ and/or $f_M - f_D$. For purposes of illustration, it will be assumed that demodulation is at $f_M + f_D$. The center frequency for bandpass filter 78 is thus set for the frequency $(f_M + f_D)$. The bandwidth for filter 78 should be approximately two to three times the full-width-half-maximum (FWHM) bandwidth of the received signal to avoid signal broadening and distortion. This bandwidth is given by the quotation

$$\Delta f_{FWHM} = \frac{4(\ell n 2)V}{\pi \Delta \ell_{FWHM}} \sim \frac{V}{\pi \Delta \ell_{FWHM}}$$

where V is the instantaneous velocity discussed above, $\Delta \ell_{FWHM}$ is the coherence length of source 12 $\Delta \ell_{FWHM}$ is given by the equation

$$\Delta \ell_{FWHM} = (\ell n 2)\frac{2}{\pi}\frac{\lambda^2}{\Delta \lambda_{FWHM}}$$

where λ_{FWHM} is the full-width half-power spectral width or wavelength bandwidth of the optical radiation or light from source 12 and might typically be in a range from 20 to 30 nm. The bandwidth of low pass filter 84 would typically be roughly identical to that of bandpass filter 78.

If the velocity V is large enough, the resulting Doppler shift frequency is higher than the predominant noise spectrum, then supplemental modulation by a device such as phase modulator 40 is not required. For an 830 nm wavelength output from source 12, which might be a typical source wavelength, this occurs for a velocity V about approximately 4 mm/sec which for a helical peripheral with R(0) = 30mm, and $R(2\pi)$ = 33mm, means

$$V_o = F_o[R(2\pi) - R(0)] \qquad (6)$$

and solving for F_o yields Fo = 4/3 Hz. In such a system, the detection electronics would be the same as those discussed above in conjunction with Figure 2A, except that the center frequency for bandpass filter 78 would be set to Doppler

shift frequency F_D. Recall that as the scanning speed increases (i.e. as the velocity of reference mirror 32 increases, (see application Serial No. 08/033,194, incorporated herein in its entirety by reference), the bandwidth of the signal Δf_{FWHM} also increases, resulting in corresponding increases in the bandwidth of filters 78 and 84. This leads to a loss of detection sensitivity, an inevitable result of high speed scan.

There may be situations where cam 100a has an outline $R(\alpha)$ and instantaneous frequency F(t) yields an instantaneous velocity V(t) which is not constant, e.g., sinusoidal, the Doppler shift frequency f_D is no longer constant, and the demodulator 46 much be adapted for this carrier frequency variations. There are at least two methods for accomplishing this objective. In both cases, as illustrated for system 10.2 in Figure 2B, an output line 87a is provided from cam 100a. The voltage on line 87a will vary as a function of F(t). Moveover, since the outline $R(\alpha)$ of cam disk 101a is known apriori, line 87 outputs a signal from which V(t) and $R_Z(t)$ can be determined using digital or analog electronics 210a. Electronics 210a has two outputs, line 87 which corresponds to velocity V(t) and line 89 which corresponds to position $R_Z(t)$. If electronics 210a provides a digital output, then line 87 may be connected to computer 52 without going through A/D converter 50'. Also, if the signal output from TIA 43 is digitally sampled, then all subsequent processing can be done digitally in software. The

signal on line 87 is required when velocity V(t) is not constant so that intensity and other inputs received at computer 52 may be correlated with $R_Z(t)$. This correlation is not required with a linear scan where position can be determined from the time an input is received.

In the simpler technique, the acceptance band for bandpass filter 78 and low pass filter 84 are increased to accommodate the variations in the Doppler shift frequency f_D. These variations occur because f_D varies directly with variations in V as discussed above. This increased demodulator acceptance bandwidth will lead to increased acceptance of noise and thus results in lower detection sensitivity. However, this technique is simple and can be used in cases where the requirement for detection sensitivity is not critical. Further, this increase in acceptance bandwidth may be relatively small when the signal bandwidth Δf_{FWHM} is already large relative to f_D, this occurring when the coherent length is very small.

Figure 2B illustrates the second technique wherein the demodulation frequency is dynamically tuned to the instantaneous Doppler shift frequency using a superheterodyne system. Electronics 210a provides a velocity dependent voltage on line 89 which is modified by a gain circuit 91 and a bias circuit 93 before being applied to a voltage controlled oscillator 95. The output from oscillator 95 is multiplied in a multiplier 97 with the output from detector 42 via amplifier 43. The gain and bias of the signal applied

to VCO 95 are adjusted so that the modulating frequency at the output from multiplier 97 is substantially constant at a desired center frequency which is selected as the center frequency for bandpass filter 78. As with the embodiment of Figure 2A, the bandwidth of filter 78 is set at two or three times the peak signal bandwidth and, except for the need for the output on line 87, the remainder of the detection and processing would be substantially identical to that previously described in conjunction with Figure 2A.

Figure 3 shows a system 10.3 which is similar to that of Figure 2A, except that bulk optics are utilized rather than fiber optics and ability to observe spatial properties is enhanced by providing two light sources 12A and 12B whic are at different wavelengths. While the multiple wavelength option is being shown for purposes of illustration in conjunction with a bulk optics embodiment, it is to be understood that multiple wavelengths could also be, and may preferably be, used with the fiber optic embodiments. Sources 12A and 12B could be the same type of light sources designed to operate at different wavelengths or could be different types of light sources. The outputs from sources 12A and 12B are merged in a coupler 60, the optical output from which is applied to a coupler 62. The other input to coupler 62 is the output from a laser 18, for example, a helium neon laser, which again is used only for alignment purposes. Coupler 60 and 62 could, for example, be dichotic

beam splitters, polarization beam splitters and normal beam splitters.

The output from coupler 62 is applied to beam splitters 64 and 66. Beam splitter 64 applies a portion of its input through lenses 116a and 120a to peripheral scattering surface 104a and also passes optical radiation to beam splitter 66 which applies this radiation through lens 36 to sample 28. Reflections from peripheral scattering surface 104a are applied through lenses 120a and 116a, beam splitter 64 and mirror 68 to interferometric coupler 70. Peripheral scattering surface 104a and lenses 116a and 120a may be part of a translation stage which is moved by a mechanism such as transnational mechanism 39a. Reflections from sample 28 are applied through lens 36 and beam splitter 66 to the interferometric coupler 70.

The output from coupler 70 may be applied to a CCD camera 72 used for alignment purposes and is also applied through a lens 74 to a photodetector 42. The output from the detector 42 is applied through two separate paths. Each path contains a demodulator 46A, 46B containing a bandpass filter 78B having a center frequency which corresponds to the Doppler shift frequency f_D for the given source 12 since f_D varies inversely as a function of the source wavelength, each demodulator only demodulates signals corresponding to the appropriate source wavelength permitting outputs resulting from the two source wavelengths to be separated. After being applied through corresponding A-D converters 50A and 50B, the

two outputs are applied to computer 52 where they may be appropriately processed.

Alternatively, a detector 42 may be provided corresponding to each source wavelength where each photodetector is preceded by an optical wavelength filter that only transmits the appropriate wavelength with an appropriate pass band. A beam splitter would be provided ahead of the optical wavelength filters, with a demodulator at the detector output.

While in Figure 3, and in the discussion above, only two separate radiation wavelengths λ have been shown, this is not a limitation on the invention, and a great number of light sources and detectors (and/or demodulator circuits) may be provided for appropriate applications.

For purposes of describing the operation of the system 10.1 or 10.3, it will be assumed that the sample 28 is the eye of a human or animal patient. When such measurements are to be made, there are three alignments which are critical. First, the beam must be aligned with the sample so that it enters the sample at a desired angle. This angle is normally an angle perpendicular to the angle of the eye layers. Second, the beam must be laterally positioned on the sample area of interest. This is a control of the lateral position of the beam. Finally, the beam must be focused at the level of interest in the eye. A number of techniques may be utilized for performing each of these alignment functions.

In particular, a number of different techniques may be utilized to obtain a desired incidence angle. since reflections will generally be substantially maximized when the beam is normal to the layer or surfaces being reflected off of, one simple way to achieve alignment is to adjust the position or angle of the probe of beam splitter 66, or lens 36 and/or of the sample (i.e., the patient's eye) and, with the reference arm blocked, detect reflections from the sample. The alignment at which the power of the detected reflections is maximum would thus be the desired alignment angle. It would normally be possible to locate the desired angle relatively quickly using this technique.

A second technique for achieving angular alignment is similar to the first except that the reference arm is not blocked and, with normal readings being taken from the system, alignment is manually adjusted until an alignment which maximizes the output is obtained.

A third method is to look at the direction in which the cam is reflected in order to detect beam alignment. Since it is hard to do this directly, particularly when a fiber is utilized, such determination is generally made by providing a beam splitter which directs a portion of the beam reflected form the sample to a device such as CCE camera 72 (Figure 3) which can measure beam position. This device is initially calibrated with the system so that the spot on which the beam impinges on the camera when the beam is properly aligned with a sample is determined. Then, in operation, the sample and

probe can be adjusted until an angle of alignment is achieved where the beam impinges on the CCD camera 72 at the previously determined point.

Lateral position alignment is at this time best performed manually. to perform this operation, laser 18 is turned on. Source 12 may either be on or off for this operation. Laser 18 provides a narrow beam visual indication of the lateral position on the eye where the beam is striking and the position of either the probe beam or the patient may then be manually adjusted until the beam is striking the desired position. If light from source 12 is in a visible band, laser 18 may not be required and light from source 12 may be used for alignment.

The focusing cone angle to be utilized for performing readings is determined by balancing the desirability of having as large a numerical aperture (cone angle) as possible against being able to achieve a desired longitudinal range or depth of field in which back scattered or reflected light is efficiently coupled back to the fiber (or to the other optical path 26 where a fiber is not employed). A large numerical aperture makes angular alignment for normal incidence o the sample surface less critical and for measurement of back scattering where the returned radiation is spread over wide solid angles, a wider cone angle increases the coupling into the fiber. However, the large cone angle increases the longitudinal range. Thus, the numerical aperture or f number should be selected to

correspond to a depth of field that is equal to the longitudinal extent of the area in the eye or other sample on which measurements are to be taken. For purposes of this discussion, depth of field is defined as the longitudinal distance from the focal plane at which the back coupling efficiency into the fiber is reduced by one-half.

As for the other alignments, the sample and/or probe are moved relative to each other until the system is focused to a desired point within the sample, i.e., within the eye. Since even with the laser it may be difficult to visually determine the focal point, a preferable way to perform focusing may be to operate the system with, for example, an output being obtained on display 54 (Figure 2A). As will be discussed later, certain high amplitude points in such output are indicative of a particular layer or transition in the eye and focus can be adjusted until the transition occurs at a desired point in the scan.

Once alignment has been achieved, the system may be utilized to take desired measurements. To perform such measurements, aiming laser 18 is turned off and source 12 is turned on. Cam 100a and in particular motor 150a is also turned on, if not already on, to cause desired rotation of cam disk 101a.

As previously indicated, source 12 should have a low coherence length which implies being spectrally wide. Thus, for light sources of the type previously mentioned having a coherence length of approximately 10 micrometers, spatial

separation, and thus resolution, to 10 micrometers can be obtained. This is a far higher resolution than is available than many other currently available devices.

Path lengths 26 and 30 are initially equal with the beam focused at a desired initial scan depth in sample 28. As peripheral scattering surface 104a moves away from lens 120a, the point in the sample 28 at which the path lengths are equal is scanned to successively greater depths within the sample. At each point in the scan, reflections occur and light scattering occurs which are a function of the refractive index variation for the material through which the light is passing and of such index boundaries. Interference fringes occur for depth points in the sample (L_s) and the path length to the current mirror location (L_m) differ by less than the coherence length ($\Delta\ell_{FWHM}$) of the light source (i.e., $|L_s - L_m| < \Delta\ell_{FWHM}$). Therefore, the coherence length of the light source determines available system resolution. This is the reason for keeping coherence length as low as possible.

The interferometric output from coupler 22 or 70 is thus indicative of reflections or scattering obtained at a particular depth within the sample. The successive interferometric outputs obtained during a scan form an envelope signal such as that shown in Figure 4, which normally has peaks at optical junctions within the samples where reflections are normally maximum and may have some

lesser peaks in a predetermined pattern, depending on the scattering characteristics of the medium at the scan depth.

When cam disk 101a rotates to yield a velocity V, a Doppler shift frequency having a frequency $f_D = 2V/\lambda$, where V is the velocity at which the mirror is moved and λ is the wavelength of source 12, is superimposed on the envelope signal as shown for a small portion of an intensity output in Figure 5A. Figure 5B shows this same output portion after demodulation.

From the equation indicated above, it is seen that the Doppler shift frequency is dependent on the wavelength of source 12. Thus, for the embodiment shown in Figure 3, where two separate optical energy sources 12A and 12B are provided, the interferometric output from coupler 70 will contain two separate envelopes which are a function of the difference in absorption and reflection at the different wavelengths, and each interference output will be modulated at a different Doppler shift frequency. Thus, as previously indicated, the bandpass filter 78A and 78B in each demodulator 46A may be selected to have a center frequency and bandwidth for a different one of the Doppler shift frequencies, or optical filtering with multiple detectors may be utilized, to permit detection and separation of these two signals.

The ability to perform the interferometric detection at two or more different wavelengths offers unique advantages. These advantages arise from the fact that the absorption, reflection and other optical characteristics of various

sample materials vary with wavelength. Thus, taking measurements at two or more wavelengths permits the spectral characterization of optical properties of the sample such as the wavelength dependent absorption and scattering thereof. In particular, the log rate of attenuation of back scatter is different for different materials and, for a given material, may vary with wavelength. By observing the back scatter pattern at different wavelengths from a substance, and possibly by observing the average rate of back scatter or reflection attenuation from layers of the sample, information concerning the material of the layer or various properties of such material may be obtained. The measurement of various spectral properties may be of interest in themselves and may also be used to distinguish between two sample layers, for example, two tissue layers that it is normally difficult to distinguish with single wavelength measurements because of their similar optical properties. In particular, by taking ratios at each of the wavelengths, spurious effects such as misalignment are compensated for permitting boundaries to be more easily and accurately identified. Basically, such boundaries are identified by looking at ratios rather than absolute values.

Figure 6, illustrates an alternative embodiment of the invention, system 10.4, utilizing polarized light to detect birefringence. For this embodiment of the invention, light from light source 12 is polarized in a polarizer 90 sandwiches between a pair of lenses 92 before being applied

to a polarization maintaining (high birefringence) fiber 94. For purposes of illustration, polarizer 90 is shown as vertically polarizing light from source 12, vertical polarization being one of the modes of fiber 94. Fiber 94 is connected to a polarization maintaining coupler 96 which outputs the vertically polarized light on polarization maintaining fibers 98 and 100. Fiber 98 terminates in a focusing lens 102, the optical output from which is applied through a quarter wave retardation plate 104 to sample 28. Plate 104 is preferably a zero order or low order plate which is placed and oriented in a manner so that circularly polarized light is incident on sample 28. in the absence of sample birefringence, plate 104 converts reflected light passing therethrough to fiber 98 into horizontal polarization. In the presence of sample birefringence which causes light to travel at different speeds through the layer depending on polarization, the light reflected from sample layers which are in, or deeper than, the birefringent sample structures will in general return to the fiber in elliptical polarization states.

In the reference arm, the vertically polarized light in fiber 100 is focused by lens 102 and a quarter-wavelength retardation plate 110 to peripheral scattering surface 104a of optical cam 100a. Plate 110, which is also preferably zero order or low order, is oriented in such a manner that light applied to the mirror is elliptically polarized and some of the radiation scattered from peripheral scattering

surface 104a are in linear polarization state with equal horizontal and vertical components. The sample and reference reflections are recombined with approximately interferometric fringes in coupler 96 and applied to a polarization maintaining fiber 112. Fiber 112 terminates in a lens 114 leading to a polarizing beam splitter 116, with horizontally polarized light from the beam splitter being applied to detector 43C and vertically polarized light from the beam splitter being applied to detector 42D. Lens 114 and polarizing beam splitter 116 may be replaced by a fiber polarizing beam splitter.

The interferometric signals detected by the two detectors, which signals are both at the same Doppler shift frequency, are separately processed in demodulator 46 and A/D converters 50 (the separate demodulator and A/D converters being shown for simplicity as single units in Figure 6) to produce two interferometric signals, a horizontal amplitude component I1 and a vertical amplitude component I2. These signals are applied to computer 52 and can be used therein to determine the round trip birefringent retardation ϕ in the sample light path

$$\phi = \arctan (I_2/I_1)$$

and to determine the amplitude $|I_1|$ for the sample reflection.

$$|I_t| = |I_1|^2 + |I_2|^2$$

Thus, by measuring the relative amplitude and phase of the two detector outputs, information on the relative phase

retardation along the sample principal axes are obtained as a function of sample depth. Birefringence is observed in structures in the eye such as the nerve fiber layer of the retina, as well as in other highly ordered biological tissues, crystals and other structures. Changes in eye nerve fiber layer thickness of 10-20 micrometers may be significant interval changes in glaucoma, and may presage the development of optic nerve head cupping and other visual field loss. Prior art techniques for measuring retinal thickness have only had a resolution on the order of 40 micrometers. However, the apparatus shown in Figure 6 can detect the thickness of the birefringent retinal nerve fiber layer with a resolution of 10 microns. Back scattering from inside the retinal nerve fiver layer (RFNL) can be identified because the refringent retardation of back scattering from inside the RNFL increases, as for other birefringent surfaces, wit depth. The range of depth over which the birefringent retardation is changing is the thickness of the RNFL and the rate of change of birefringent retardation (total retardation divided by the thickness of the RNFL) can provide a measure of the nerve axon density inside the RNFL. The back scattering and reflections from layers deeper than the RNFL will acquire a constant amount of birefringent retardation.

The ability to make such nerve fiber layer measurements provides a marked advantage in the early detection of glaucoma and in the objective assessment of progression of glaucomatous damage. Thus, weak back scattering signals for

retinal substructures could be measured and could yield direct measurements of not only the overall retinal thickness, but the thickness of component sublayers as well.

Back scattered light can also be detected from the first few millimeters of turbid tissue samples such as arterial plaque and normal arterial wall. A fiber optic probe of the type shown in Figure 2A or Figure 6 could be delivered by use of an endoscope to a desired site to provide high resolution images for use in laser angioplasty and lithotripsy. This would enhance the usability of such procedures by reducing the dangers of unintentional vessel damage and rupture. This is because not only can this technique provide finer resolution than is obtainable with prior ultrasonic techniques, but it also provides the ability to distinguish between arterial plaque an normal artery wall in a number of ways, including elastic lamina of arteries are highly birefringent, which plaques are not. Plaques also have other different spectral characteristics. Such differentiation is not easily obtained with ultrasonic techniques.

While for the preferred embodiments, rotation and/or translation of cam 101a effects alteration of the reference path length for scanning the sample, what is required for sampling is that there be relative change between the sample and reference path lengths. While generally this can most easily be accomplished by rotating cam disk 101a, this is not a limitation on the invention, and in appropriate

applications, either one or both the sample and cam may be moved, an cam disk 101a can be rotated and/or translated.

IN the discussion above, the beam has been projected along a single axis. However, by using a probe beam steering mechanism in the sample are, the probe and/or beam may after alignment be laterally scanned on a sample area of interest to provide two-dimensional or three-dimensional information or imaging. For example, with a display 54 (Figure 2A), a tomographic image of a sample can be obtained in much the same way that such images are obtained with ultrasonic scanners.

Further, while specific fiber optic and bulk optic implementations have bee shown, it is apparent that this invention could also be practiced utilizing other optical implementations and that other modifications in the specific equipment shown for performing the functions might be possible, depending on the application. Thus, while the invention has been particularly shown and described above with reference to preferred embodiments, the foregoing and other changes in form and detail may be made therein by one skilled in the art without departing from the spirit and scope of the invention.

WHAT IS CLAIMED IS

1. A cam, comprising:

a cam disk having a center about which said cam disk rotates, an outline and peripheral scattering face for receiving radiation from a source and scattering said radiation as scattered radiation; and

a motor mechanically coupled to said cam disk such that said motor rotates said cam disk about said center, wherein said scattered radiation undergoes periodic delay variations, and each of said delay variations is determined by the outline of said cam disk.

2. The cam as claimed in claim 1, wherein said peripheral scattering face is a peripheral optical scattering surface and said radiation is optical radiation scattered from said scattering surface.

3. The cam as claimed in claim 1, wherein said peripheral scattering face is a peripheral optical reflecting surface and said radiation is optical radiation reflected from said peripheral reflecting surface.

4. The cam as claimed i claim 1, wherein said outline is approximately a helix.

5. The cam as claimed in claim 1, wherein said cam disk has radii of curvature $R(\alpha)$ defining said outline, which

vary from a smallest radius R(O) to a largest radius R(2π) and R(α) is the radius of said cam disk at an angle α with respect to said smallest radius R(o).

6. The cam as claimed in claim 1. wherein said cam disk has radii of curvature R(α) defining said outline, which vary monotonically from a smallest radius R(o) to a largest radius r(2π) as a function of an angle α with respect to the smallest radius.

7. The cam as claimed in claim 1, wherein said cam disk has a moment of inertia approximately about said center.

8. The cam as claimed in claim 7, wherein said radii R(α) vary linearly with variations in α.

9. The cam as claimed in claim 1, wherein said peripheral scattering face is coated with a reflective material.

10. The cam as claimed in claim 1, wherein said peripheral scattering face has a mirrored finish.

11. The cam as claimed in claim 1, wherein said peripheral scattering face has a reflective adhesive strip attached thereto.

12. The cam as claimed in claim 1, further comprising an optoelectronic detector for detecting rotation rate of said cam disk.

13. The cam as claimed in claim 1, further comprising a sensor for periodically detecting a portion of said scattered radiation and outputting a resulting timing signal.

14. A measuring apparatus, comprising:

a source for outputting radiation with a short coherence length;

a splitter for splitting said radiation into reference radiation and measuring radiation;

radiation directing means for receiving said measuring radiation and directing said measuring radiation toward an object and for collecting a portion of said measuring radiation scattered off of said object;

a cam for receiving said reference radiation and scattering a portion of said reference radiation as scattered reference radiation; and

detecting means for detecting intensity resulting from a part of said portion of said measuring radiation which coherently interferes with said scattered reference radiation, wherein said intensity provides information with respect to said object.

15. The measuring apparatus as claimed in claim 14, wherein said cam comprises:

a cam disk having a center about which said cam disk rotates with a rotation frequency, an outline and a peripheral scattering face for receiving said reference radiation and scattering said reference radiation as said scattered reference radiation; and

a motor mechanically coupled to said cam disk such that said motor rotates said cam disk about said center, wherein said scattered reference radiation undergoes periodic delay variations, wherein each of said periodic delay variations is determined by the outline of said cam disk and said rotation frequency.

16. A method of measuring properties of an object, comprising the steps of:

outputting radiation with a short coherence length;

splitting said radiation into reference radiation and measuring radiation;

directing said measuring radiation toward the object and collecting a portion of said measuring radiation scattered off of the object;

directing said reference radiation toward a cam and scattering a portion of said reference radiation off of a peripheral surface of the cam as scattered reference radiation; and

detecting intensity resulting from a part of said portion of the measuring radiation which coherently interferes with said scattered reference radiation, wherein said intensity contains information relating to the properties of the object.

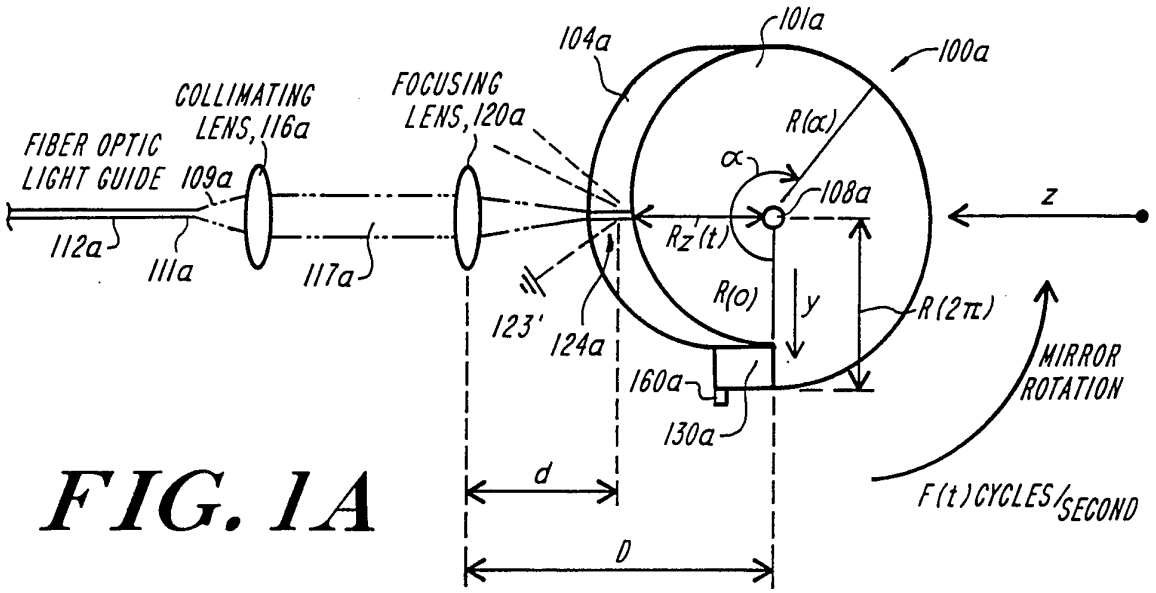

104a
101a
100a
COLLIMATING LENS, 116a
FOCUSING LENS, 120a
FIBER OPTIC LIGHT GUIDE
109a
R(α)
α
108a
z
112a
111a
117a
$R_Z'(t)$
R(0)
y
R(2π)
123'
124a
160a
130a
MIRROR ROTATION
d
D
F(t) CYCLES/SECOND

FIG. 1A

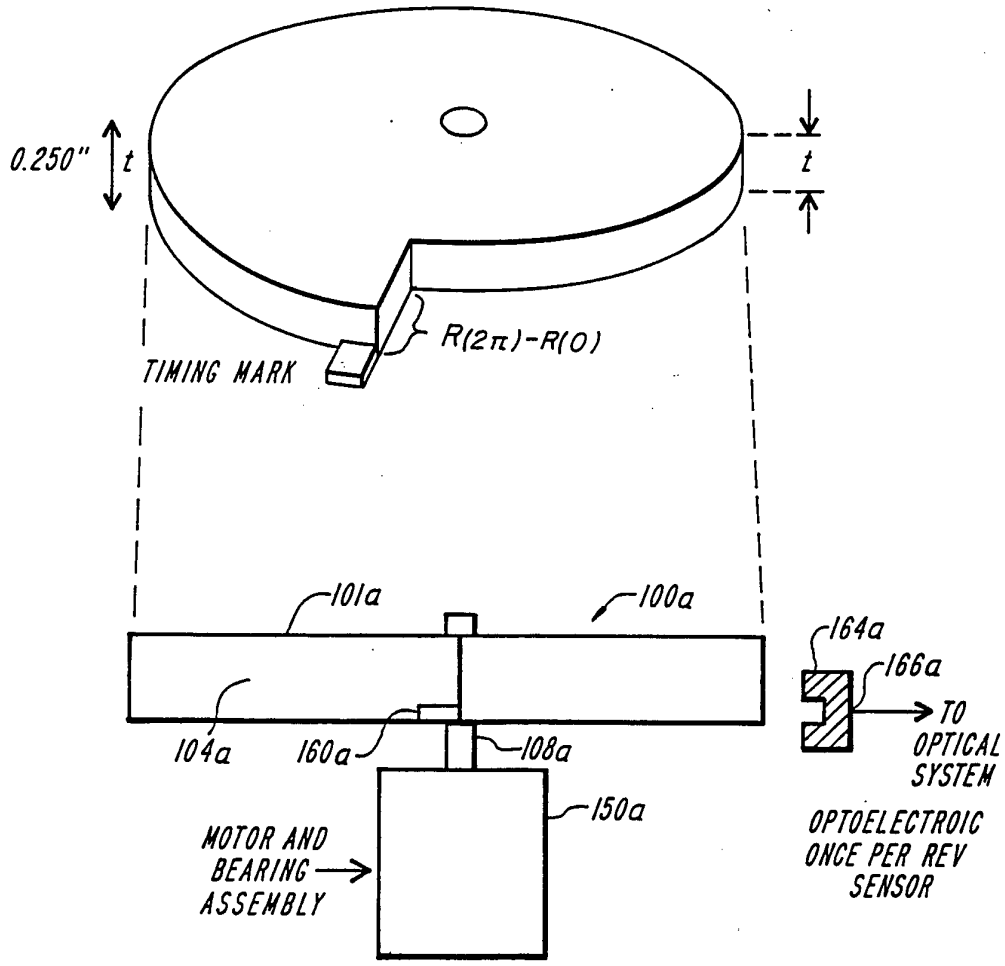

0.250"
t
t
R(2π)-R(0)
TIMING MARK
101a
100a
164a
166a
TO OPTICAL SYSTEM
104a
160a
108a
150a
MOTOR AND BEARING ASSEMBLY
OPTOELECTROIC ONCE PER REV SENSOR

FIG. 1B

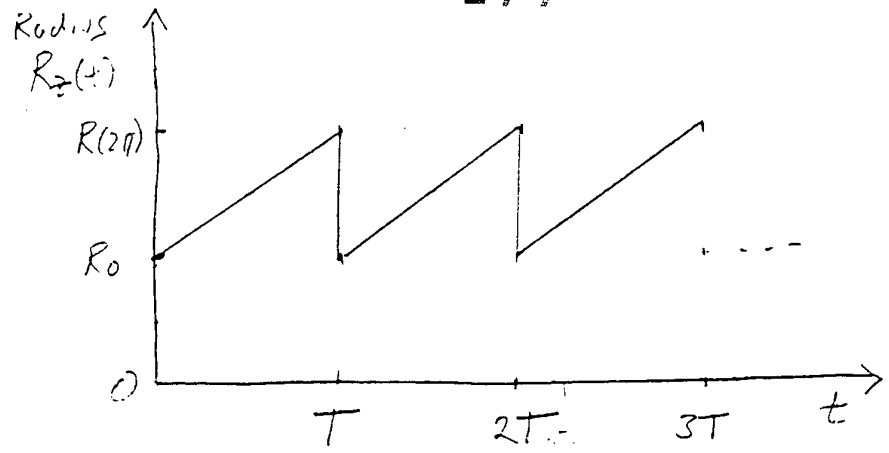


Figure 1C

Helical Cam Scanning Mirror
The radius is a linear function of angle.
Surface should be of optical quality.
Height transition at step can be minimized to maximize duty cycle.

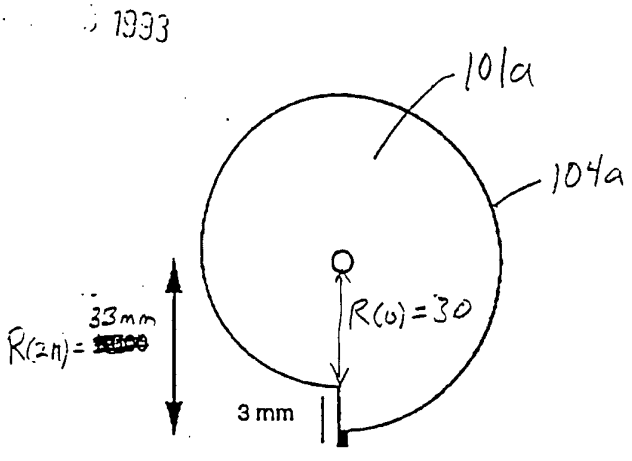


Figure 1D

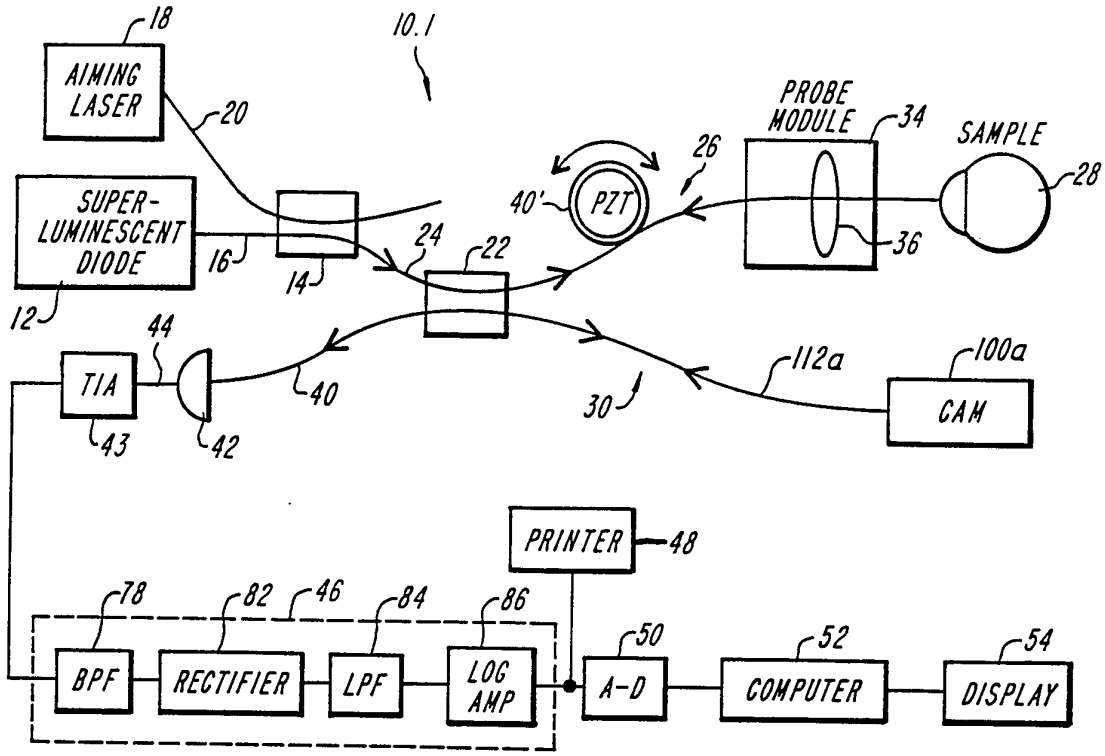


FIG. 2A

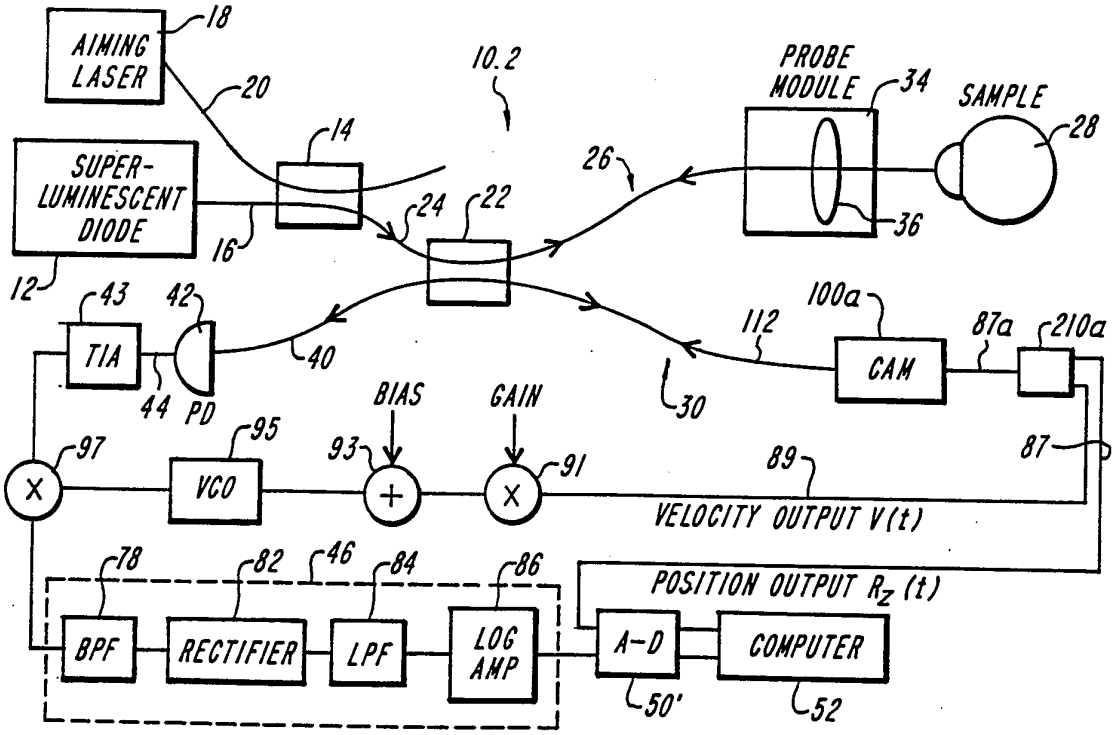


FIG. 2B

RECTIFIED SHEET (RULE 91)

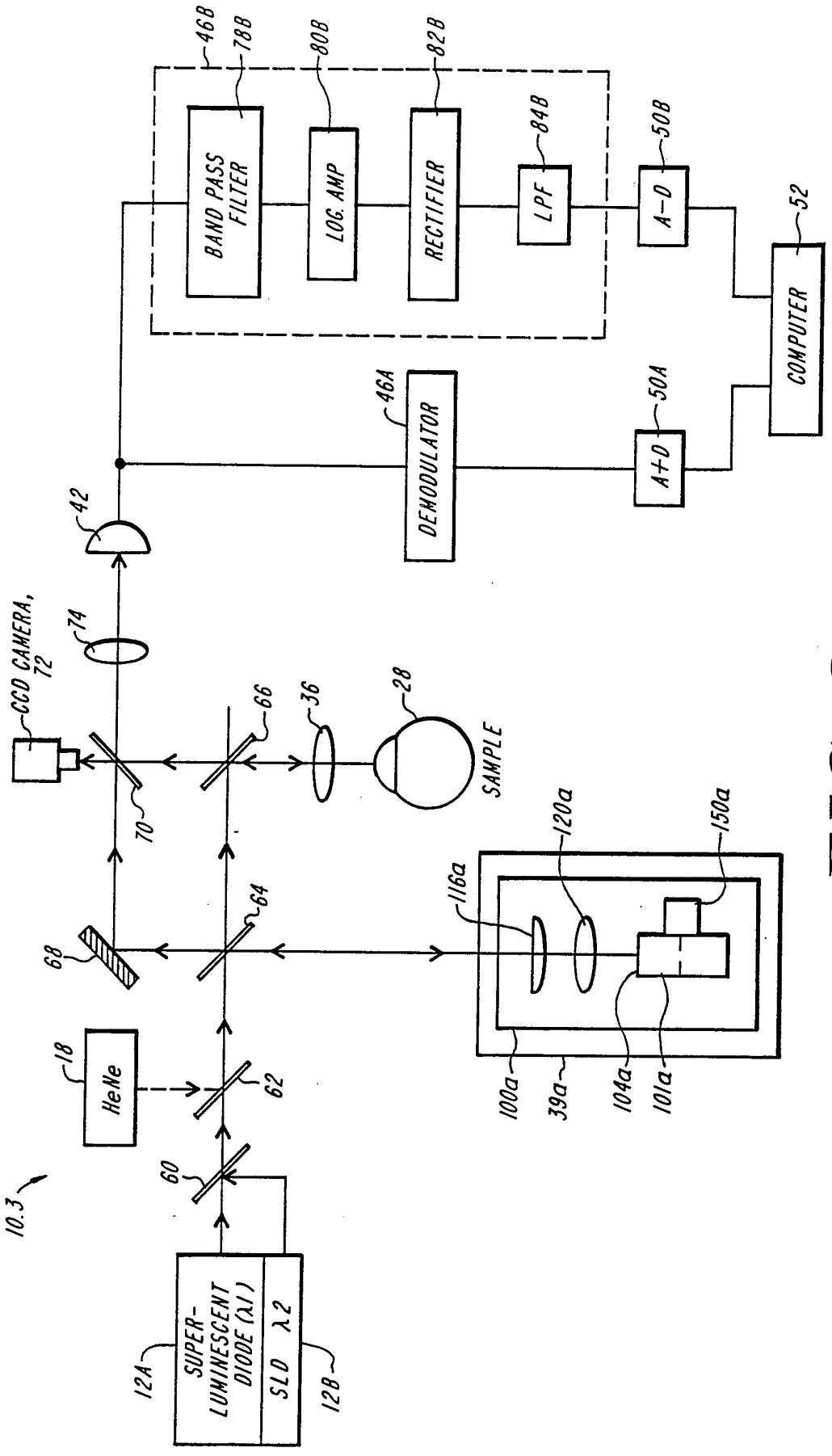

46B
78B
80B
82B
BAND PASS FILTER
LOG. AMP
RECTIFIER
84B
LPF
50B
A-D
52
COMPUTER
46A
DEMODULATOR
50A
A+D
42
74
CCD CAMERA, 72
66
36
28
SAMPLE
70
120a
150a
116a
64
68
18
HeNe
62
60
10.3
100a
39a
104a
101a
12A
SUPER-LUMINESCENT DIODE (λ1)
SLD λ2
12B

FIG. 3

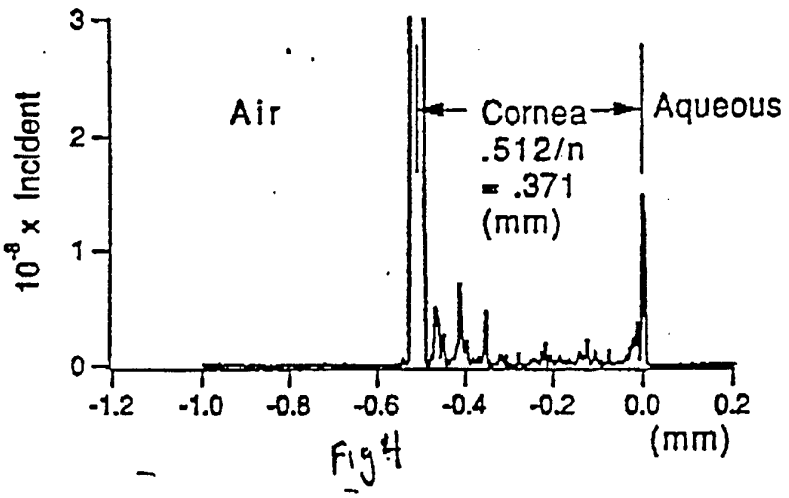

3
2
1
0
10^{-8} x Incident
Air
Cornea
.512/n
= .371
(mm)
Aqueous
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
(mm)

Fig 4

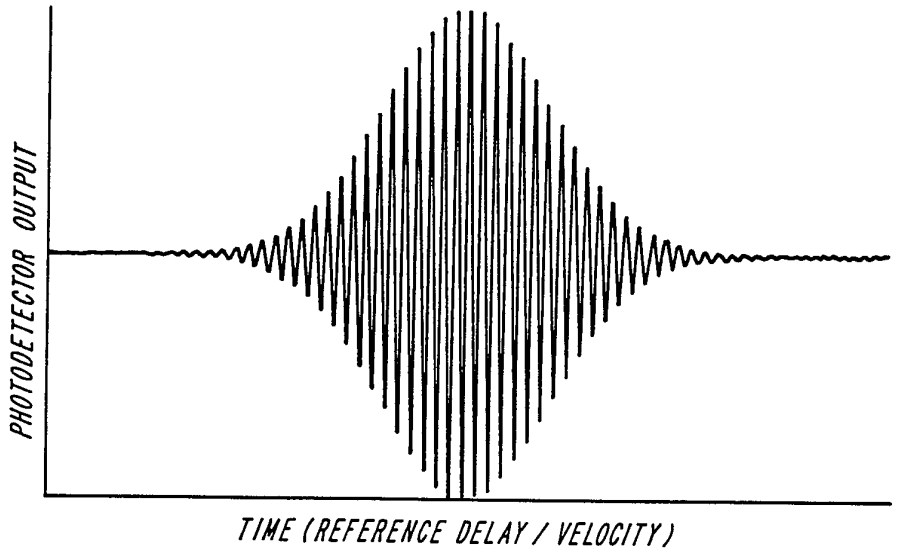

PHOTODETECTOR OUTPUT
TIME (REFERENCE DELAY / VELOCITY)

FIG. 5A

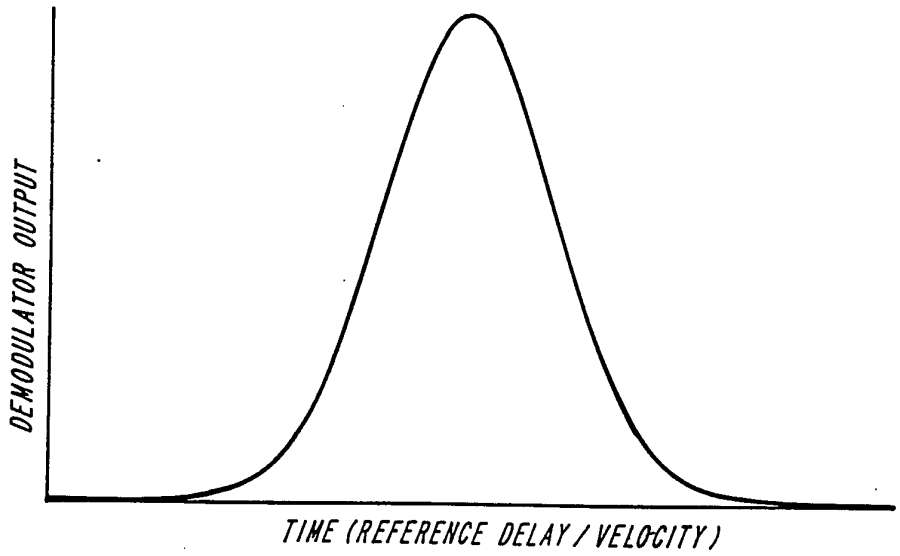

DEMODULATOR OUTPUT
TIME (REFERENCE DELAY / VELOCITY)

FIG. 5B

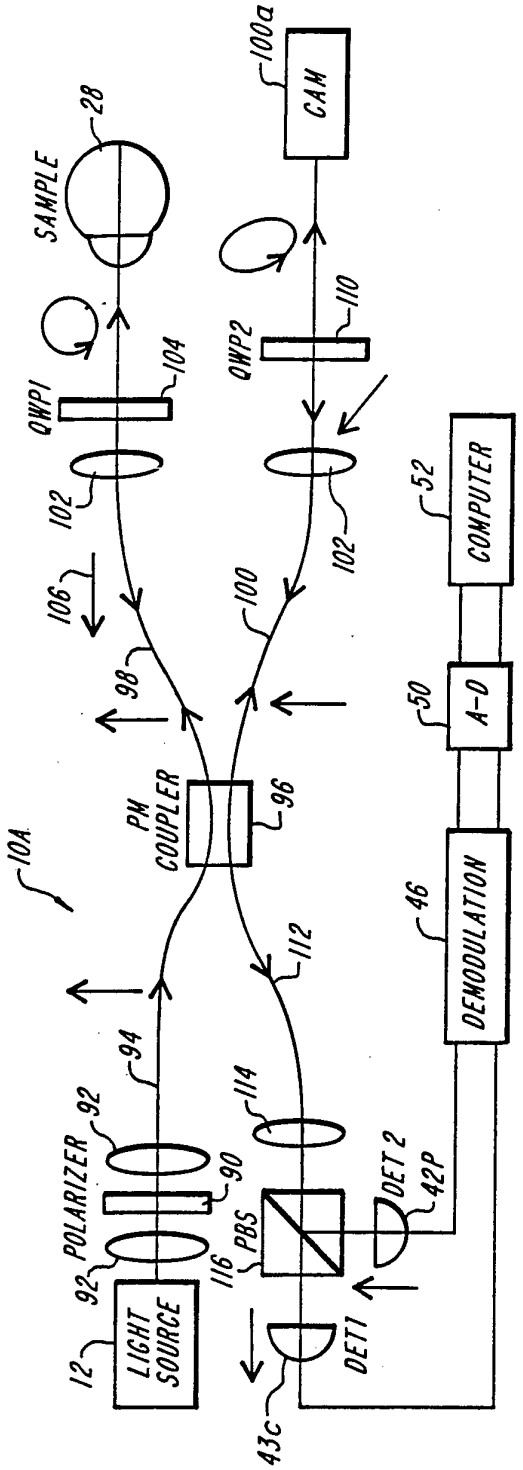

100a
CAM
28
SAMPLE
110
QWP2
104
QWP1
102
102
106
100
98
52
COMPUTER
50
A-D
PM
COUPLER
96
10A
46
DEMODULATION
112
94
114
92
POLARIZER
90
DET 2
42P
92
PBS
116
12
LIGHT
SOURCE
DET1
43c

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US95/06071

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G01B 9/02
US CL :356/345

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/345, 357, 358, 360

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y , P	US, A, 5,387,969 (MARANTETTE) 07 FEBRUARY 1995, FIGURES 3, AND 3A.	13
Y	JP, A, 60-129,614 (TASAKA) 07 OCTOBER 1985, FIGURES 1-5.	1-16
Y	APPLIED OPTICS, VOLUMN 26, NO. 9, ISSUED 01 MAY 1987, TAKADA ET AL, 'NEW MEASUREMENT SYSTEM FOR FAULT LOCATION IN OPTICAL WAVEGUIDE DEVICES BASED ON AN INTERFEROMETRIC TECHNIQUE, PAGES 1603-1606.	14-16

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
02 AUGUST 1995	09AUG 1995
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer SAMUEL A. TURNER Telephone No. (703) 308-4803

Form PCT/ISA/210 (second sheet)(July 1992)*