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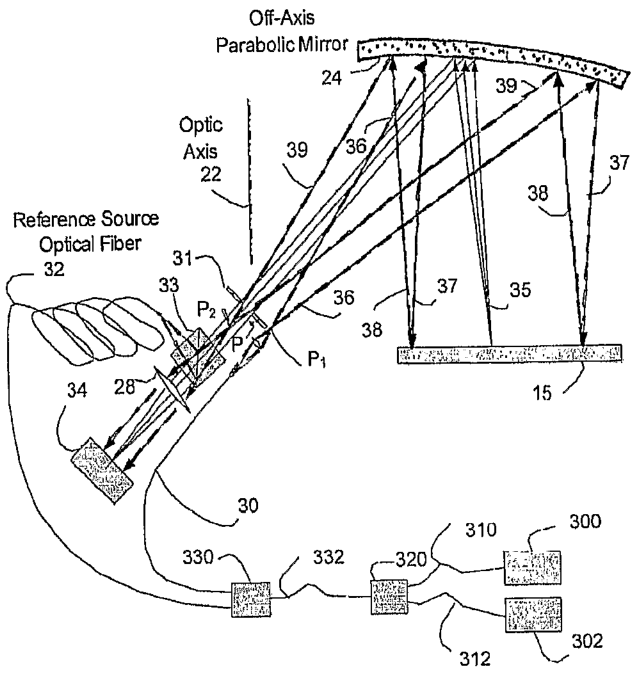
(54) Title: OPTICAL FIBER-DELIVERED REFERENCE BEAM FOR INTERFEROMETRIC IMAGING



(57) Abstract: The present invention includes an interferometric imaging system including a paraboloid mirror defining an axis and an illumination source adapted to radiate light from an illumination point of an illumination optical fiber at an off-axis portion of the paraboloid mirror. The present invention also includes a reference illumination source adapted to illuminate the surface of an image receiver through a reference optical fiber with a reference beam having a selectable, variable, or predetermined phase with respect to the illumination source. The from the reference illumination source and light from the optical system cooperate to form a phase image of object on the image receiver.

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OPTICAL FIBER-DELIVERED REFERENCE BEAM FOR INTERFEROMETRIC IMAGING

TECHNICAL FIELD

[0001] This invention relates generally to the optical field, and more specifically to an improved system optical system for interferometric imaging.

BACKGROUND

[0002] Interferometry has been used for over a century to measure the surface topography of objects, typically optical components, and distances and small changes in such distances. With the advent of lasers having long coherence lengths and high brightness, the field has expanded greatly. Interferometric comparison of objects with a known surface has been difficult to implement for very large objects with surfaces with steps or slopes greater than a half wavelength of light per resolution element of the imaging system, because the phase count is lost, and the height of the object surface is known only modulo $\lambda / 2$, where λ is the wavelength of light used for the interferometer.

[0003] If a series of imaging interferograms are recorded with different wavelengths λ_i, the ambiguity in the phase may be resolved, and the heights on the object surface relative to a particular location on the particle surface may be calculated, as is described in the in various prior art publications assigned to the assignee of the present invention. For example, U. S. Patent 5,907,404, U. S. Patent 5,926,277, U. S. Patent Application 10/893052, U. S. Patent Application 10/349651, U. S. Patent Application 11/181664, and U. S. Patent Application 11/194097, which all describe phase resolution and surface calculations and are incorporated in their entirety by this reference.

[0004] FIGURE 1 is a schematic diagram of a prior art interferometer. The particular interferometer shown in FIGURE 1 is conventionally called a Michelson interferometer, and has been used since the nineteenth century in optical experiments and measurements. A light source 10 produces light that is collimated by passing through a lens system 11 to produce a parallel beam of light 12 that passes to a beamsplitter 13. The beam of light 12 is partially reflected to a reference mirror 14 and partially transmitted to an object 15. Light reflected from the reference mirror 14 partially passes through the beamsplitter to an image receiver 16. Light reflected from the object is partially reflected from the beamsplitter 15 and is passed to the image receiver 16. The image receiver 16 may be film, or may be an electronic photodetector or a CCD or a CMOS array, or any other image receiver known in the art.

[0005] If both the reference mirror 14 and the object 15 are flat mirrors aligned perpendicular to the incoming light from beam 12, and the light path traversed by the light from the light source to the image receiver is identical, the light from both the reference mirror and the object mirror will be in phase, and the image receiver will show a uniformly bright image. Such devices were the bane of undergraduate optics students before the advent of lasers, since the distances had to be equal to within distances measured by the wavelength of the light and the mirrors had to be aligned within microradians. Even with the advent of lasers with very long coherence lengths, such devices are subject to vibration, thermal drift of dimensions, shocks, etc.

[0006] The Michelson interferometer design of FIGURE 1 is useful to explain the many different types of interferometers known in the art. In particular, suppose the reference mirror 14 is moved back and forth in the direction of the arrow in FIGURE 1. As the reference mirror is moved, the phase of the light beam reflected from the reference mirror and measured at the image receiver 16 will change by 180 degrees with respect to the phase of the light reflected from the object 15 for every displacement of one quarter wavelength. The light from the two beams reflected from the object 15 and the reference mirror 14 will interfere constructively and destructively as the mirror moves through one-quarter wavelength intervals. If the intensity of both the reference and object beams are equal, the intensity at the image receiver will be zero when the mirrors are positioned for maximum destructive interference. Very tiny displacements of one of the mirrors 14 or 15 can thus be measured.

[0007] FIGURE 2 is a schematic diagram of a prior art imaging interferometer much like the interferometer of FIGURE 1, except that the light source does not use a lens to collimate the light into a parallel beam 12. Instead, an off-axis paraboloid mirror 24 is used to reflect the light output 26 of an optical fiber 20 into a parallel beam of light 12. Mirror 24 is a section having a reflecting surface that is part of a parabola of revolution about the axis 22. The end of the optical fiber 20 is placed on the axis 22 at or very near the focal point P of the paraboloid mirror, i.e., the point to which a parallel light beam parallel to light beam the axis 22 (which is the optical axis of the paraboloid mirror) coming in to and reflected from the mirror 24 would be focused.

[0008] The optical fiber 20 may incorporate a lens system (not shown) that appears to diverge the beam of light from the focal point P. An optical system (shown symbolically as lens 29) is shown for imaging the surface of the object 15 on to the image receiver 16. The optical system 29 and image receiver 15 can be integrated into a camera, where the image size of the object 15 on the image receiver may be much smaller than the size of the object 15.

[0009] The optical set up shown in FIGURE 2 is shown as a telecentric optical system, where diverging light rays 25 scattered from a point on the surface of the object 15 diverge until they pass through lens 29, then travel parallel to each other through an aperture 27, and are converged again to a point on the surface of the image receiver 16.

[0010] Both prior art versions of the Michelson interferometer incorporate far too many cumbersome and expensive optical elements. Notably, the prior art interferometers must include a reference mirror, a beam splitter, and an optical system or lens for collimating the light into the image receiver. Accordingly, there is a need in the art for interferometric system for investigating, imaging, and measuring the topography of the surfaces of large objects having lighter and/or less expensive optical elements. Moreover, there is a need in the art for an interferometric system having an easily variable ratio of object illumination intensity to reference beam intensity.

SUMMARY

[0011] Accordingly, the present invention includes an interferometric imaging system including a paraboloid mirror defining an axis and an illumination source adapted to radiate light from an illumination point of an illumination optical fiber at an off-axis portion of the paraboloid mirror. The illumination point is disposed remotely from the axis of the paraboloid mirror such that light diverges from the

illumination point and proceeds to the paraboloid mirror such that the paraboloid mirror reflects light from the illumination source into a substantially parallel beam of light for illumination of an object.

[0012] The present invention further includes an image receiver optically coupled to the illumination source and the paraboloid mirror and an optical system adapted to receive light reflected from the surface of the object and to transmit an image of the object on the image receiver. The present invention also includes a reference illumination source adapted to illuminate the surface of the image receiver through a reference optical fiber with a reference beam having a predetermined phase with respect to the illumination source. As described below, light from the reference illumination source and light from the optical system cooperate to form a phase image of object on the image receiver.

[0013] These and further details and advantages of the present invention are detailed below in respect to the preferred embodiments of the present invention described with reference to the following FIGURES.

BRIEF DESCRIPTION OF THE FIGURES

[0014] FIGURES 1 and 2 are schematic drawings of prior art interferometric systems.

[0015] FIGURE 3 is a schematic diagram of an interferometric system in accordance with a preferred embodiment of the present invention.

[0016] FIGURE 4 is a schematic drawing of a variation of the preferred embodiment of the invention.

[0017] FIGURE 5 is a schematic drawing of another variation of the preferred embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0018] The following description of preferred embodiments of the invention is not intended to limit the invention to these embodiments, but rather to enable any person skilled in the art to make and use this invention.

[0019] A preferred embodiment of the present invention includes an interferometric imaging system that obviates the need for any of the cumbersome and expensive optical elements associated with the prior art. In particular, the system of the preferred embodiment includes an interferometric imaging system including a paraboloid mirror defining an axis and an illumination source adapted to radiate light from an illumination point of an illumination optical fiber at an off-axis portion of the paraboloid mirror. The illumination point is disposed remotely from the axis of the paraboloid mirror such that light diverges from the illumination point and proceeds to the paraboloid mirror such that the paraboloid mirror reflects light from the illumination source into a substantially parallel beam of light for illumination of an object.

[0020] The present invention further includes an image receiver optically coupled to the illumination source and the paraboloid mirror and an optical system adapted to receive light reflected from the surface of the object and to transmit an image of the object on the image receiver. The present invention also includes a reference illumination source adapted to illuminate the surface of the image receiver through a reference optical fiber with a reference beam having a predetermined phase with respect to the illumination source. In operation of the system of the preferred embodiment, light from the reference illumination source and light from the optical system cooperate to form a phase image of object on the image receiver.

[0021] As shown in FIGURE 3, in the system of the preferred embodiment the large reference mirror, the large beam splitter, and the lens described in the prior art are no longer needed. Light 36 is radiated from an illumination source including an illumination optical fiber 30 and is shown diverging from an illumination point P_1 disposed remotely from the focus point P of the paraboloid mirror 24 and thus remotely from an optical axis 22 of the paraboloid mirror 24. The light travels to the paraboloid mirror 24 and is reflected as a substantially parallel beam 37 that falls on the surface of an object 15. Since the illumination point P_1 is apart from the focus point P of the paraboloid, a collimated light beam 37 is not parallel to the optical axis 22 of the paraboloid mirror. Object light 38 is shown as a parallel beam reflecting from a surface of the object 15, where the surface is substantially perpendicular to the optical axis 22. Object light 38 reflects again from the paraboloid mirror 24, and is then brought to a focus at a second point P_2 that is also disposed remotely from the focal point P and the optical axis 22 of the paraboloid mirror 24.

[0022] In a first variation of the preferred embodiment, the optical system includes an aperture 31 that limits the light scattered from the object surface 15 and a lens 28 that focuses the light passing through the aperture 31 onto the image receiver 34. Additionally, the system of preferred embodiment can include a first beamsplitter 33 such that inbound light 39 is combined with light from a reference illumination source including a reference optical fiber 32 prior to receipt by an image receiver 34. The image receiver 34 captures the image of the surface of the object 15 and displays an interferometric phase image of the object surface.

[0023] As shown in FIGURE 3, the object 15 is disposed at a distance from the paraboloid mirror 24 approximating the focal length of the paraboloid mirror 24. As such, a diverging light bundle 35 is collimated by the paraboloid mirror 24 into parallel beam that passes through the aperture on its way to being focused on the image receiver 34 by the lens 28. The system is also operable in circumstances in which the distance between the object 15 and the paraboloid mirror 24 is not approximately equal to the focal length of the paraboloid mirror 24. In such a case, the position of the lens 28 can be adjusted to refocus the light bundle 35 onto the image receiver 34.

[0024] A second variation of preferred embodiment of the system can also include a computer (not shown) connected to the image receiver 34. The computer functions to capture and display phase images of the surface of the object 15 at different relative phases between the reference illumination source 32 and the illumination source 30 and different wavelengths of light from the reference illumination source 32 and the illumination source 30. The computer further functions to construct synthetic phase images and holograms from the phase and wavelength data, functions that are known generally in the art of interferometry.

[0025] In a third variation of the system of the preferred embodiment, the illumination source 30 can be a laser light source, a diode laser light source, a light emitting diode (LED) light source, a gas discharge light source, an optical fiber laser, or an arc or incandescent light source.

[0026] In a fourth variation of the system of the preferred embodiment, the system includes a beam splitter adapted to divide light carried by a third optical fiber 332 into the illumination optical fiber 30 and the reference optical fiber 32. In one alternative to the fourth variation of the system of the preferred embodiment, the beam splitter is controllable such that the ratio of the light carried by the illumination optical fiber 30 to the light carried by the reference optical fiber 32 is controllable.

[0027] As shown in FIGURE 3, the beam splitter 330 splits the light from the third optical fiber 332 into the illumination optical fiber 30 and the reference optical fiber 32. As noted above, the beam splitter 330 can be controllable beam splitter, where the percentage of the light in optical fiber 322 delivered to optical fibers 30 and 32 may be varied. The controllable beam splitter is usable when the objects investigated change often, and have different reflectivity, color, and surface scattering coefficients. Most imaging systems are operable when the amplitude of the reference beam and the amplitude of the light scattered from the object 15 measured at the image receiver 34 are comparable, so that the variation of the resultant intensity as measured by the image receiver 34 is comparable with the intensity of the reference or object beams alone as the relative phases of object and reference beam are changed.

[0028] As such, when changing from a object having a high degree of backscattering of the object illumination beam to a more absorbing object or more diffusely scattering object, the proportion of the light carried by fiber 322 is changed by a controllable beam splitter 330 to put more light into illumination optical fiber 30 and less into reference optical fiber 32. The total amount of light falling on the image receiver 34 will drop, but the gain of the image receiver 34 or the total amount of power carried by the third optical fiber 322 is raised, and the amplitude variation of the interference intensity remains constant.

[0029] In a fifth variation of the system of the preferred embodiment, the system includes a beam combiner 320 that is adapted to receive and combine light from two or more light sources. As shown in FIGURE 3, the beam combiner 332 receives light from a first source 300 and a second source 302 through a first optical fiber 310 and a second optical fiber 312, respectively. The beam combiner 332 functions to combine the light from the respective sources into the third optical fiber 332, which can then be split by the beam splitter 330 as described above. Each of the first source 300 and the second source 302 can include a laser light source, a diode laser light source, a light emitting diode (LED) light source, a gas discharge light source, an optical fiber laser, an arc or incandescent light source or any combination thereof.

[0030] In a sixth variation of the system of the preferred embodiment, the system includes a phase changing element adapted to change the phase of the light directed by the optical fiber. As shown in FIGURE 4, a phase changing element 40 is connected to the reference optical fiber 32. In one alternative, the reference optical fiber 32 is stretchable such that a mechanical, electronic, electro-mechanical or thermal device can alter and/or extend the length of the optical fiber 60 thereby providing a corresponding change in the phase of the light directed by the reference optical fiber 32. Correspondingly, the phase changing element 40 can include for example a mechanical, electronic, electro-mechanical or thermal device that is adapted to alter and/or extend the length of the reference optical fiber 32 thereby providing a corresponding change in the phase of the light directed by the reference optical fiber 32.

[0031] One alternative to the variation of the system of the preferred embodiment is shown in FIGURE 5. In this alternative, the phase changing element 40 includes a piezoelectric tube 70, a portion of which is attached to the reference optical fiber 32 by an adhesive 74, epoxy, or other similar bonding agent. Another portion of the tube 70 is joined to a base 72 that is fixed with respect to the paraboloid mirror 24. In operation, the application of a voltage to the piezoelectric tube 70 lengthens piezoelectric tube 70, thereby stretching the reference optical fiber

32 and changing the relative phase of the reference beam by a predetermined number of wavelengths.

[0032] As a person skilled in the art will recognize from the previous detailed description and from the figures and claims, modifications and changes can be made to the preferred embodiments of the invention without departing from the scope of this invention defined in the following claims.

CLAIMS

We claim:

1. An interferometric imaging system comprising:

a paraboloid mirror defining an axis,

an illumination source adapted to radiate light from an illumination point of an illumination optical fiber at an off-axis portion of the paraboloid mirror, the illumination point disposed remotely from the axis of the paraboloid mirror, wherein the illumination point is disposed relative to the axis of the paraboloid mirror such that light diverges from the illumination point and proceeds to the paraboloid mirror such that the paraboloid mirror reflects light from the illumination source into a substantially parallel beam of light for illumination of an object,

an image receiver optically coupled to the illumination source and the paraboloid mirror;

an optical system adapted to receive light reflected from the surface of the object and to transmit an image of the object on the image receiver; and

a reference illumination source adapted to illuminate the surface of the image receiver through a reference optical fiber with a reference beam having a predetermined phase with respect to the illumination source, wherein light from the reference illumination source and light from the optical system cooperate to form a phase image of object on the image receiver.

2. The system of claim 1 further comprising a computer system connected to the image receiver, wherein the computer system is adapted to receive phase images from the image receiver and construct a synthetic phase image of the object in response thereto.

3. The system of claim 1 wherein the illumination source comprises a light emitting diode (LED) light source.

4. The system of claim 1 wherein the illumination source comprises a gas discharge light source.

5. The system of claim 1 wherein the illumination source comprises a tunable wavelength optical illumination source.

6. The system of claim 1 further comprising a beam splitter adapted to divide light carried by a third optical fiber into the illumination optical fiber and the reference optical fiber.

7. The system of claim 6 wherein the beam splitter is controllable such that the ratio of the light carried by the illumination optical fiber to the light carried by the reference optical fiber is controllable.

8. The system of claim 1 further comprising a phase changing element adapted to control the relative phase of the light carried by the reference optical fiber.

9. The system of claim 8 wherein the reference optical fiber is stretchable to change the phase of the light directed there through.

10. The system of claim 8 wherein the phase changing element is adapted to stretch the reference optical fiber such that the phase of the light directed by the reference optical fiber is changed in response thereto.

11. The system of claim 8 wherein the phase changing element comprises a piezoelectric tube having a first portion connected to the reference optical fiber and a second portion fixed with respect to the paraboloid mirror, such that in response to an input the piezoelectric tube causes a change in the length of the reference optical fiber.

12. The system of claim 6 further comprising a phase changing element adapted to control the relative phase of the light carried by the reference optical fiber.

13. The system of claim 12 wherein the reference optical fiber is stretchable to change the phase of the light directed there through.

14. The system of claim 12 wherein the phase changing element is adapted to stretch the reference optical fiber such that the phase of the light directed by the reference optical fiber is changed in response thereto.

15. The system of claim 12 wherein the phase changing element comprises a piezoelectric tube having a first portion connected to the reference optical fiber and a second portion fixed with respect to the paraboloid mirror, such that in response to an input the piezoelectric tube causes a change in the length of the reference optical fiber.

16. The system of claim 7 further comprising a phase changing element adapted to control the relative phase of the light carried by the reference optical fiber.

17. The system of claim 16 wherein the reference optical fiber is stretchable to change the phase of the light directed there through.

18. The system of claim 16 wherein the phase changing element is adapted to stretch the reference optical fiber such that the phase of the light directed by the reference optical fiber is changed in response thereto.

19. The system of claim 16 wherein the phase changing element comprises a piezoelectric tube having a first portion connected to the reference optical fiber and a second portion fixed with respect to the paraboloid mirror, such that in response to an input the piezoelectric tube causes a change in the length of the reference optical fiber.

20. The system of claim 6 further comprising a beam combiner adapted to receive and combine light from a first source and a second source into the third optical fiber.

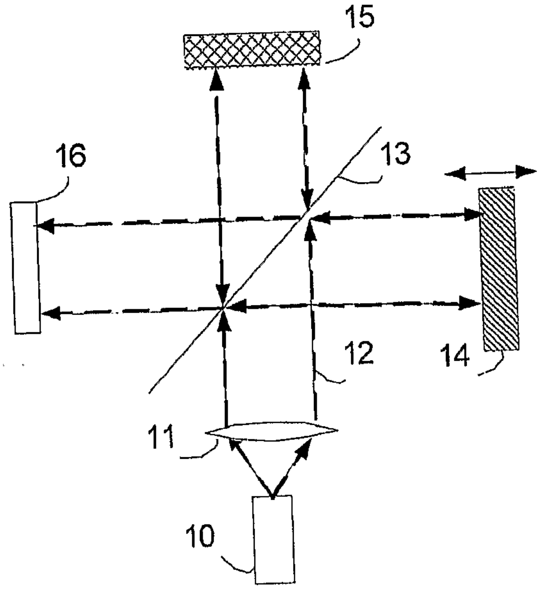


Fig. 1
Prior Art

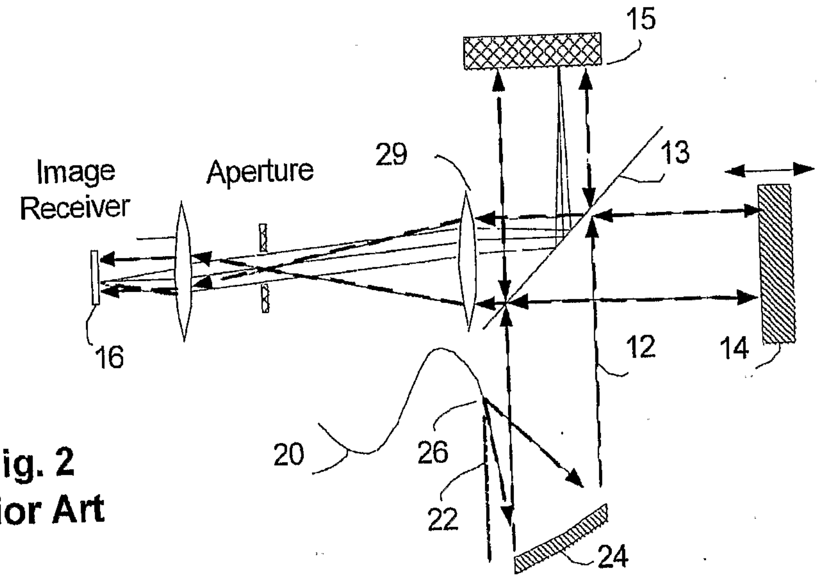
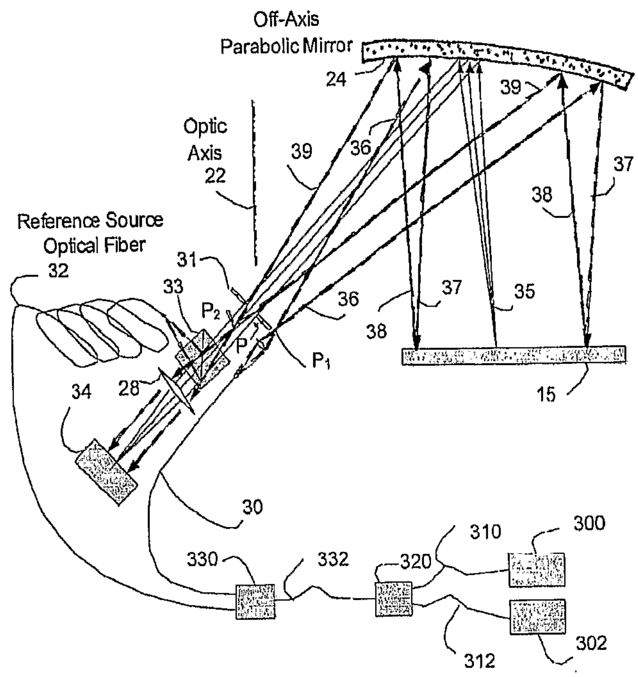


Fig. 2
Prior Art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24
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Optic
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Reference Source
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Fig. 3

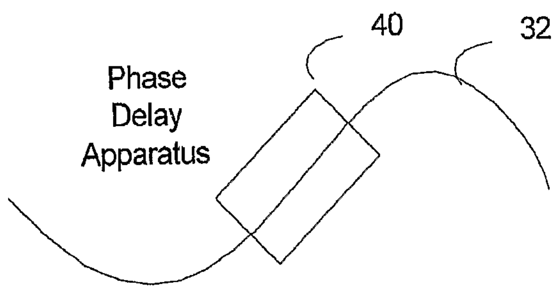
40
32
Phase
Delay
Apparatus

Fig. 4

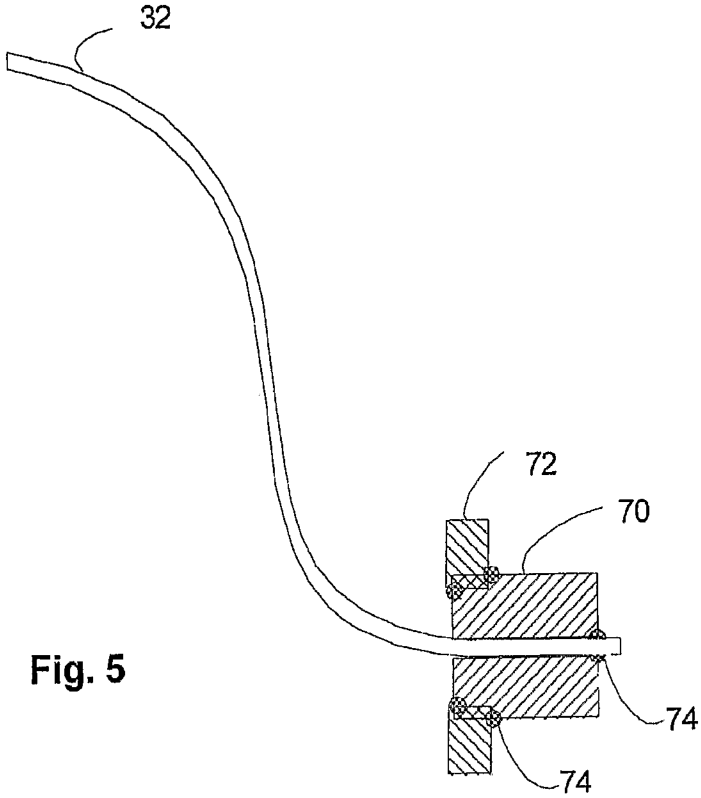

Fig. 5