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(54) Title: CLOSED LOOP OPTICAL COHERENCE TOPOGRAPHY
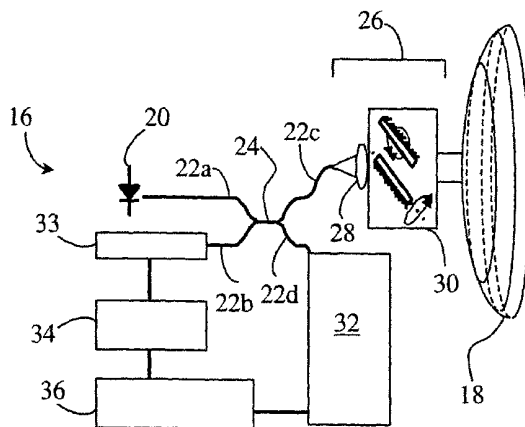
(57) Abstract: The present invention provides an optical coherence topography apparatus and method for determining the topology of a surface of or within a sample, the apparatus having: a light source for providing a beam of light; a beam splitter for splitting the beam into first and second components; a sample arm for receiving the sample and characterized by a first path length; scanning means for scanning the sample with the first component of the beam; a reference arm with a reference means for receiving the second component, the reference arm characterized by a second path length; and a light detector for detecting interference patterns due to interference of a reference beam from the reference means and a sample beam from the sample; wherein one of the first and the second path lengths is controllably adjustable and the apparatus includes control means responsive to changes in the interference patterns due to differences in the first path length as the sample is scanned, by adjusting the one of the first and the second path lengths to compensate for the changes in the first path length, whereby the adjustment in the one of first and second path lengths is indicative of the changes in the first path length and thereby of the topology.

CLOSED LOOP OPTICAL COHERENCE TOPOGRAPHY

The present invention relates to the field of optical
coherence topography, of particular but by no means

5   exclusive application in the area of corneal topography.

Existing Optical Coherence Tomography (OCT) has been used
widely for creating three dimensional images of
(especially) biological samples, and has found widespread

10   application in the imaging of the cornea and other
structures in the human eye. OCT is a non-intrusive
technique, it has a dynamic range that can exceed 100 dB
and - importantly for ophthalmic applications - it performs
well with dry eyes, from which scattered light can be

15   detected with a good signal to noise ratio.

However, conventional OCT systems generate volume rather
than surface maps, as they detect light scattered from a
series of depths in the Z-axis as the reference mirror of

20   the OCT interferometer is correspondingly scanned along its
Z-axis. The actual depth within the sample of a feature is
determined from the Z coordinate of the scanned reference
mirror at the time of detection. Detected features may be
on the surface of the sample or, if the incident light can

25   penetrate the sample (as is the case with many biological
samples), within the sample. In either case, a large three
dimensional data cube must be collected even though, in
many applications, a surface topology is all that is of
interest. The resolution of the three dimensional data is

30   ordinarily limited by the coherence envelope (typically 10
to 20 μm).

This large OCT data set or "volume map" must then be
analyzed to extract the desired information, a lengthy data

35   reduction task. For example, if the sample is corneal
tissue, the results of an OCT scan will reveal the
transitions or boundaries between layers of differing

refractive index. The most significant of these will be
between the air and the cornea itself, so extracting the
three dimensional location of this boundary is equivalent
to generating, from the original volume map, a surface map
5   of the cornea.

Figure 1 is a perspective view of the volume map 10 of OCT
data that would be collected in order to obtain a surface
map 12 of a cornea 14, which surface map 12 represents a
10   small subset of the volume map 10.

Thus, this technique is slow as a complete volume scan must
first be performed - during which the sample must remain
essentially motionless - and then the data set must be
15   reduced to extract the desired information. This
effectively eliminates this technique as a real-time
observational tool during, for example, surgery, as real-
time surface profiling of macroscopic biological objects
such as the human cornea must avoid motion artefacts
20   occurring on time scales of order ten milliseconds. The
sample - such as an eye - may be difficult to immobilize,
and the available computing resources may not be adequate
to reduce the vast volume data set sufficiently quickly.

25   It is an object of the present invention, therefore, to
provide an OCT system that eliminates the need to collect
the volume data set, by compensating for movement in a
surface of a sample and collecting data only at that
surface. Such a surface may be the external surface, or -
30   in some applications - a surface defined by the boundary
between two layers within the sample. In one aspect of the
invention, it is an object to provide such a system with
resolution sufficient for the measurement of corneal
topography.
35

According to the present invention, therefore there is
provided an optical coherence topography apparatus for

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determining the topology of a surface of or within a
sample, having:

        a light source for providing a beam of light;

        a beam splitter for splitting said beam into
5   first and second components;

        a sample arm for receiving said sample and
characterized by a first path length;

        scanning means for scanning said sample with said
first component of said beam;

10   a reference arm with a reference means for
receiving said second component, said reference arm
characterized by a second path length; and

        a light detector for detecting interference
patterns due to interference of a reference beam from said
15   reference means and a sample beam from said sample;

        wherein one of said first and said second path
lengths is controllably adjustable and said apparatus
includes control means responsive to changes in said
interference patterns due to differences in said first path
20   length as said sample is scanned, by adjusting said one of
said first and said second path lengths to compensate for
said changes in said first path length, whereby said
adjustment in said one of first and second path lengths is
indicative of said changes in said first path length and
25   thereby of said topology.

The light source may comprise a broadband source of low
coherence light or a narrowband source. A broadband source
has a short coherence function, which therefore 'gates' the
30   region from which reflections may be detected.

Preferably one of said first and second path lengths is
said second path length, and said control means is operable
to adjust said second path length by controlling said
35   reference means.

The control means may be operable to adjust said first path

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length, such as by moving said sample or, where said sample
arm includes an optic fibre, stretching said optic fibre.

Thus, the topology of the sample can be deduced from the
5   degree, at any point in the scanning of the sample, that
the first or second path length is adjusted to compensate
for variations in the first or sample arm path length due
to that topology. Although this would be of principal
application in determining the surface topology of a
10   sample, if the sample transmits sufficient light, it may
also be possible to detect and determine the topology of an
internal surface or boundary.

The scanning means is preferably operable for scanning the
15   sample in two orthogonal axes perpendicular to the
direction of the first component of the beam.

The beam splitter may comprise a partially silvered mirror
or, preferably, an optical coupler such as a fused
20   biconical taper coupler.

Preferably said light source is a superluminescent diode or
other broad bandwidth source. The light source may be an
incandescent source, a mode-locked laser or a narrowband
25   continuous wave laser.

Preferably said reference arm includes an optical delay
line, including dispersing means (such as a diffraction
grating) for dispersing light received by said reference
30   arm and a reflecting means with adjustable tilt for
receiving light from said dispersing means and introducing
a path difference according to said tilt.

In one embodiment said optical delay line is operable to
35   decouple phase and group delay so that said phase delay can
be used to provide a control signal and said group delay
can be used to gate the zone from which a reflection can be

received.

Alternatively, the optical delay line may be implemented
using acousto-optic or electro-optic devices.

In one specific embodiment said light source comprises a
narrowband laser and said reference arm includes an optical
delay line, said delay line includinga reflecting means
with adjustable tilt for introducing a path difference
according to said tilt.

The reflecting means may comprise any suitable mirror or
prism (such as a 90° retro-reflector prism).

According to the present invention, there is also provided
an apparatus for determining the topology of a corneal
surface including the apparatus described above.

The present invention further provides a method for
determining the topology of a sample, comprising:
            splitting a beam of light into first and second
components;
            scanning said sample characterized by a first
path length with said first component and directing said
second component to a reference means characterized by a
second path length;
            forming an interference pattern of light
reflected by said sample and from said reference means;
            detecting changes in said interference pattern
due to variations in said first path length due to said
topology of said sample;
            adjusting one of said first and second path
lengths to compensate for said changes; and
            determining said topology from said adjustments.

The beam of light may be a beam of low coherence light, and
the beam may be a narrowband beam of light.

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Preferably said one of said first and second path length is
said second path length.

5   Preferably said adjusting of said second path length is by
means of said reference means.

Preferably said reference means includes dispersing means
for dispersing light received by said reference means, and
10   a reflecting means with adjustable tilt for receiving light
from said dispersing means and introducing a path
difference according to said tilt.

In one embodiment, said method includes providing said beam
15   of light by means of a narrowband continuous wave laser,
and said reference means includes a reflecting means with
adjustable tilt for introducing a path difference according
to said tilt.

20   Preferably said scanning said sample is in a manner which
minimises the rate of change of the first path length due
to said topology.

Where said topology is spherical, preferably said scanning
25   is in a spiral pattern.

The present invention still further provides a method for
determining the topology of a corneal surface, said method
including the method described above.
30
In order that the present invention may be more clearly
ascertained, preferred embodiments will now be described,
by way of example, with reference to the accompanying
drawings, in which:
35   Figure 1 is a perspective view of an OCT data
volume map collected in order to obtain a surface map of a
cornea according to a prior art technique;

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Figure 2 is a schematic view of an optical coherence tomograph apparatus according to a preferred embodiment of the present invention;

Figure 3 is a schematic representation of delay
5   line of the apparatus of figure 2;

Figure 4 is an interferogram depicting three possible interferograms from the apparatus of figure 2;

Figure 5 is a schematic view of the apparatus of figure 2 in a test configuration with a mirror as a test
10   sample and PZT fibre stretcher for simulating variations in the path length of the sample arm;

Figures 6a, 6b and 6c are graphs of results from the test configuration;

Figure 7 depicts a preferred scanning pattern for
15   the apparatus of figure 2;

Figure 8 is a schematic view of a typical post-cut or operative) corneal profile; and

Figure 9 depicts the path that the tracking system would need to follow if the corneal profile in
20   figure 8 were traced using the spiral of figure 7.

An optical coherence tomography apparatus according to a preferred embodiment of the present invention is shown generally at 16 in figure 2, for determining the topology
25   of a sample, for example cornea 18. A broadband light source in the form of superluminescent diode 20 illuminates a fibre-based Michelson interferometer, including optic fibres 22a,b,c,d, optical coupler 24, sample arm 26 (including focussing lens 28 and orthogonal scanners 30),
30   reference arm 32 and detector 33.

The detector 33 detects interference fringes only if the optical paths of the sample arm 26 and reference arm 32 match to within the coherence length of the source
35   (~10 μm). The apparatus 16 also includes a lock-in amplifier 34 and PID controller 36. In some embodiments the lock-in amplifier 34 may not be required.

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Referring to figure 3, the reference arm 32 comprises a
grating-based optical delay line (ODL), which utilizes the
phase delay generated by tilted mirror to generate a
5   control signal and the group delay in combination with the
coherence function of the source to gate the zone in the
sample from which a reflection can be detected. The light
beam entering the reference arm 32 along fibre 22d is
collimated by collimator 40 and dispersed by grating 42
10   before passing through lens 44 and impinging upon piezo-
tilted mirror 46. The mirror 46 is controlled by PID
controller 36 (see figure 2). The beam then passes back
through lens 44, via grating 42 to second pass mirror 48,
before retracing the same optical path and exiting the
15   reference arm 32.

Optionally, the grating 42 and lens 44 may clearly be
replaced by a concave grating.

20   The optical phase associated with the path length of the
reference arm 32 is thus adjustable, and determined by the
angle of mirror 46. This piezo-tilted mirror 46 provides
the phase ramp, and the angle of tilt corresponds to an
effective linear translation of the mirror 46. The
25   proportionality is set by mirror tilt angle σ and the
offset of the pivot of the piezo-tilted mirror x_0 from the
optical axis of the grating and lens. The path length
difference so generated δ is given by

$$\delta = \sigma x_0 \ .$$

30   By virtue of the independence of group and phase delay in
the ODL, the frequency of the interference fringes
generated by altering the tilt angle σ may be up- or down-
converted in a controlled way. The zero-crossing of a
fringe defines the position of the sample 18. Hence,
35   "closing the servo loop" (by means of the detector 33 to
lock-in amplifier 34 to PID controller 36 to piezo-tilted
mirror 46 connection shown in figure 2) allows the optical

path length of the reference arm 32 to be locked to that of
the sample arm 26, which - when expressed as a function of
the instantaneous position of scanners 30 - corresponds
directly to the topology of the sample 18.

The operation of the grating based ODL is based on the
Fourier correspondence between the phase ramp in the
frequency domain and the group delay in time domain. By
virtue of the decoupling of the phase and group delay, the
frequency of the interference fringes is controlled by the
offset x_0. Three interferograms 50 generated by scanning
the tilt angle σ are shown schematically in figure 4.
Complete demodulation at zero offset results in the
envelope 52, which does not produce a zero crossing and
therefore cannot be used as a control signal.

There are two separate essentially sinusoidal oscillations
under the envelope 52: the higher frequency oscillation
represents an up-converted fringe pattern 54. The lower
frequency oscillation represents a down-converted fringe
pattern 56. The frequency of the fringe pattern will,
therefore, determine the angle of the zero-crossing point
(of fringes with horizontal axis), and therefore the
resolution with which this point - and therefore the sample
18 - can be located. The advantage of the adjustability of
the fringe frequency is that one can trade off high
stability of the apparatus (i.e. with low fringe frequency)
versus high resolution (i.e. with high fringe frequency) as
preferred or required.

Example

Figure 5 depicts a test arrangement of the apparatus of
figure 2, where the sample is a plane mirror 60 and sample
arm fibre 22c has been provided with a PZT fibre stretcher
62 for simulating variations in the path length of the
sample arm 26.

For the purposes of this example, the bandwidth was about
10 Hz and the tracking range about 1 µm.

5   Figure 6a depicts the signal obtained without controlling
the piezo-tilted mirror 46: the sample arm path length
varies slowly and randomly. However, at about t = 6.8 s
(indicated by 70), the closed-loop system was switched on
and the sample arm length tracked by the reference arm.
10

Next, PZT fibre stretcher 62 was driven with a saw-toothed
signal 64 to effect an optical path variation in the sample
arm 26: the effect on the position of the sample 60 is
shown in figure 6b, where the corresponding movement of the
15   sample is clearly visible.

Finally, the closed-loop system was introduced; the
resulting, compensating error signal (which should be the
exact opposite of the variation in the sample arm path
20   length) is shown in figure 6c. As expected, the error
signal closely mirrors that variation.

A resolution of about 0.2 µm was obtained.

25   In corneal surgical applications, a spiral scan path (see
72 in figure 7) is preferred, so that the rate of change in
the Z-axis of the sample is minimized. Some stability can
then be sacrificed for improved resolution.

30   Figure 8 shows schematically a typical corneal profile
after surgery in section. Figure 9 shows schematically the
change in Z-axis coordinate of the tracking reference arm
when the optical beam traces out a spiral path 72 on the
cornea, plotted as delay d versus time t.
35

An optical coherence tomography apparatus according to an
alternative embodiment, while generally similar to

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apparatus 16, employs a continuous wave laser light source, and a mirror rather than a diffraction grating.

In this embodiment, however, the laser can lock on to any
5   fringe, so if there were two reflectors in a system that both produce approximately equal signals, it may be difficult to deduce which reflector is being tracked. In the apparatus 16 (with a broadband source in the form of superluminescent diode 20) one only detects a reflection
10   when the reflection location matches the group delay (also set by the tilt and offset) to within the coherence length, thereby discriminating other reflectors that are located more than this length from the matched location.

15   Modifications within the spirit and scope of the invention may readily be effected by persons skilled in the art. It is to be understood, therefore, that this invention is not limited to the particular embodiments described by way of example hereinabove.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. An optical coherence topography apparatus for
determining the topology of a surface of or within a
sample, having:
            a light source for providing a beam of light;
            a beam splitter for splitting said beam into
first and second components;
            a sample arm for receiving said sample and
characterized by a first path length;
            scanning means for scanning said sample with said
first component of said beam;
            a reference arm with a reference means for
receiving said second component, said reference arm
characterized by a second path length; and
            a light detector for detecting interference
patterns due to interference of a reference beam from said
reference means and a sample beam from said sample;
            wherein one of said first and said second path
lengths is controllably adjustable and said apparatus
includes control means responsive to changes in said
interference patterns due to differences in said first path
length as said sample is scanned, by adjusting said one of
said first and said second path lengths to compensate for
said changes in said first path length, whereby said
adjustment in said one of first and second path lengths is
indicative of said changes in said first path length and
thereby of said topology.

2. An apparatus as claimed in claim 1, wherein said light
source comprises a broadband source of low coherence light.

3. An apparatus as claimed in claim 2, wherein said light
source is a superluminescent diode .

4. An apparatus as claimed in claim 1, wherein said light
source is an incandescent source or a mode-locked laser.

5.   An apparatus as claimed in claim 1, wherein said light
source comprises a narrowband laser source.

5   6.   An apparatus as claimed in any one of the preceding
claims, wherein one of said first and second path lengths
is said second path length, and said control means is
operable to adjust said second path length by controlling
said reference means.

10

7.   An apparatus as claimed in any one of the preceding
claims, wherein said control means is operable to adjust
said first path length.

15   8.   An apparatus as claimed in claim 7, wherein said
control means is operable to adjust said first path length
by moving said sample or, where said sample arm includes an
optic fibre, stretching said optic fibre.

20   9.   An apparatus as claimed in any one of the preceding
claims, wherein said scanning means is operable for
scanning the sample in two orthogonal axes perpendicular to
the direction of the first component of the beam.

25   10.   An apparatus as claimed in any one of the preceding
claims, wherein said beam splitter comprises a partially
silvered mirror.

11.   An apparatus as claimed in claim 10, wherein said beam
30   splitter comprises an optical coupler.

12.   An apparatus as claimed in any one of the preceding
claims, wherein said reference arm includes an optical
delay line, including dispersing means for dispersing light
35   received by said reference arm and a reflecting means with
adjustable tilt for receiving light from said dispersing
means and introducing a path difference according to said

tilt.

13.   An apparatus as claimed in claim 12, wherein said
reflecting means comprises any suitable mirror or prism.

14.   An apparatus as claimed in either claim 12 or 13,
wherein said optical delay line is operable to decouple
phase and group delay so that said phase delay can be used
to provide a control signal and said group delay can be
used to gate the zone from which a reflection can be
received.

15.   An apparatus as claimed in any one of claims 1 to 11,
wherein said reference arm includes an optical delay line
implemented using acousto-optic or electro-optic devices.

16.   An apparatus as claimed in claim 1, wherein said light
source comprises a narrowband laser and said reference arm
includes an optical delay line, said delay line including a
reflecting means with adjustable tilt for introducing a
path difference according to said tilt.

17.   An apparatus for determining the topology of a corneal
surface including the optical coherence topography
apparatus as claimed in any one of the preceding claims.

18.   A method for determining the topology of a sample,
comprising:
        splitting a beam of light into first and second
components;
        scanning said sample characterized by a first
path length with said first component and directing said
second component to a reference means characterized by a
second path length;
        forming an interference pattern of light
reflected by said sample and from said reference means;
        detecting changes in said interference pattern

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due to variations in said first path length due to said
topology of said sample;

    adjusting one of said first and second path
lengths to compensate for said changes; and

5   determining said topology from said adjustments.

19. A method as claimed in claim 18, wherein said beam of
light is a beam of low coherence light.

10 20. A method as claimed in claim 18, wherein said beam is
a narrowband beam of light.

21. A method as claimed in any one of claims 18 to 20,
wherein said one of said first and second path length is

15 said second path length.

22. A method as claimed in any one of claims 18 to 21,
wherein said adjusting of said second path length is by
means of said reference means.

20

23. A method as claimed in any one of claims 18 to 22,
wherein said reference means includes dispersing means for
dispersing light received by said reference means, and a
reflecting means with adjustable tilt for receiving light

25 from said dispersing means and introducing a path
difference according to said tilt.

24. A method as claimed in claim 18, wherein said method
includes providing said beam of light by means of a

30 narrowband continuous wave laser, and said reference means
includes areflecting means with adjustable tilt for
introducing a path difference according to said tilt.

25. A method as claimed in any one of claims 18 to 24,

35 wherein said scanning said sample is in a manner that
minimises the rate of change of the first path length due
to said topology.

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26.   A method as claimed in claim 25, wherein, where said
topology is spherical, said scanning is in a spiral
pattern.

5

27.   A method for determining the topology of a corneal
surface, said method including the method for determining
the topology of a sample as claimed in any one of claims 18
to 26.

10

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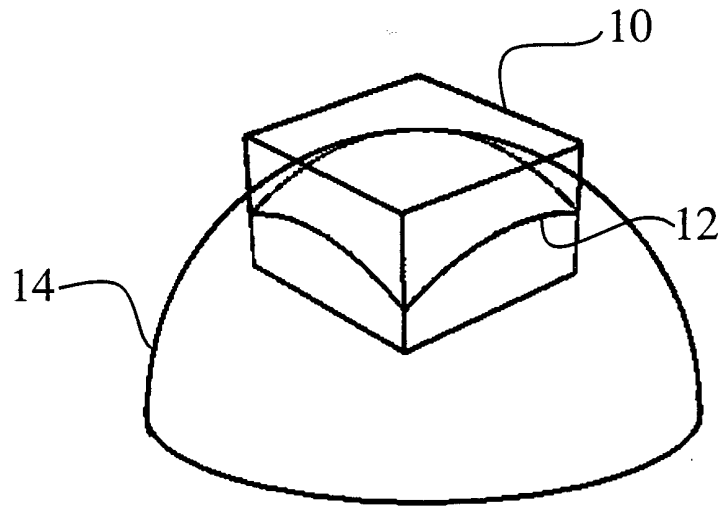
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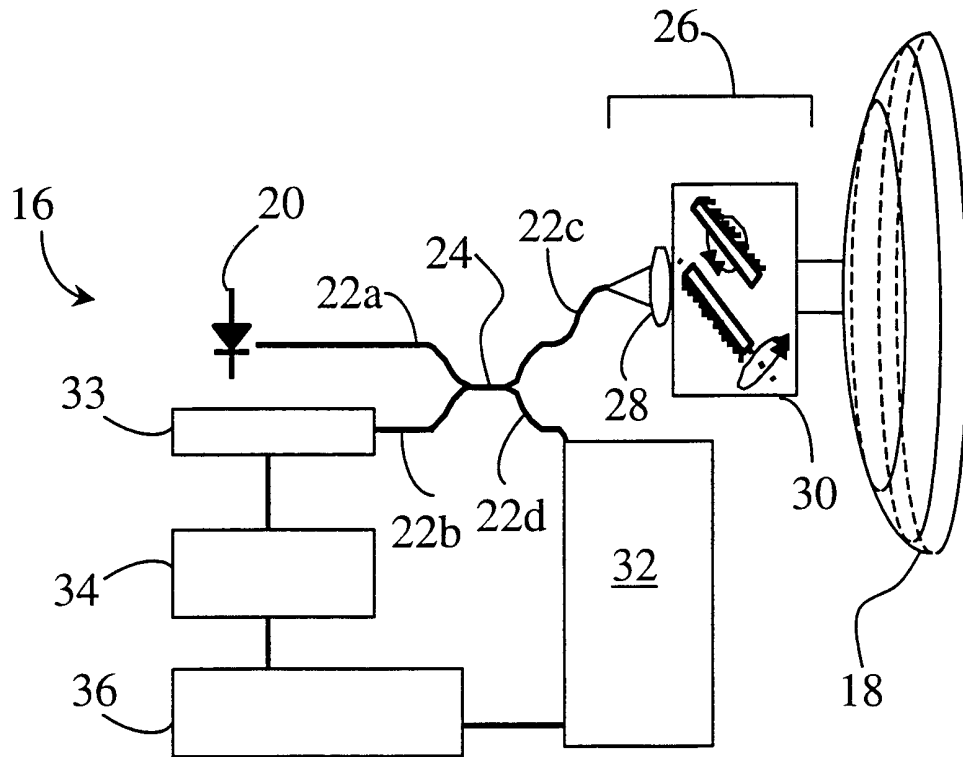
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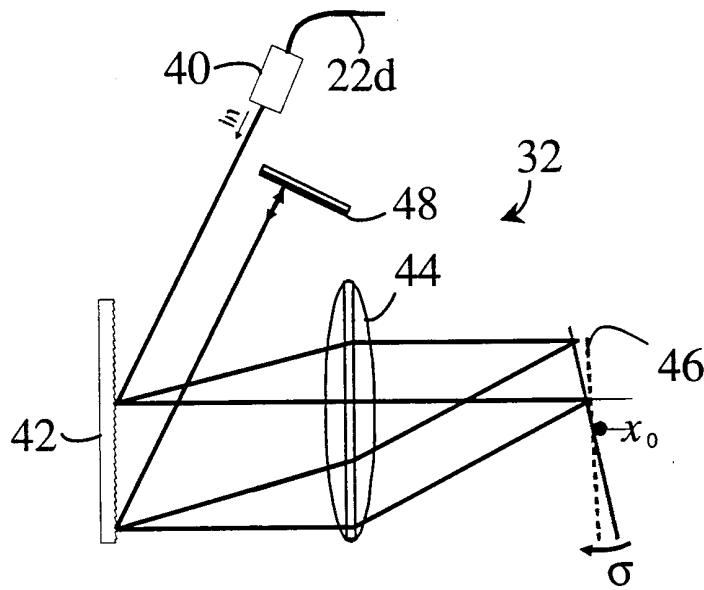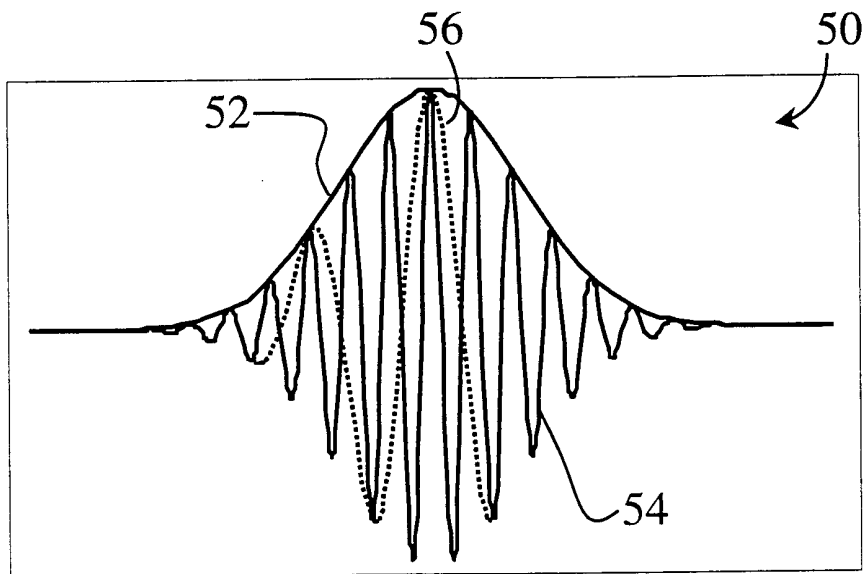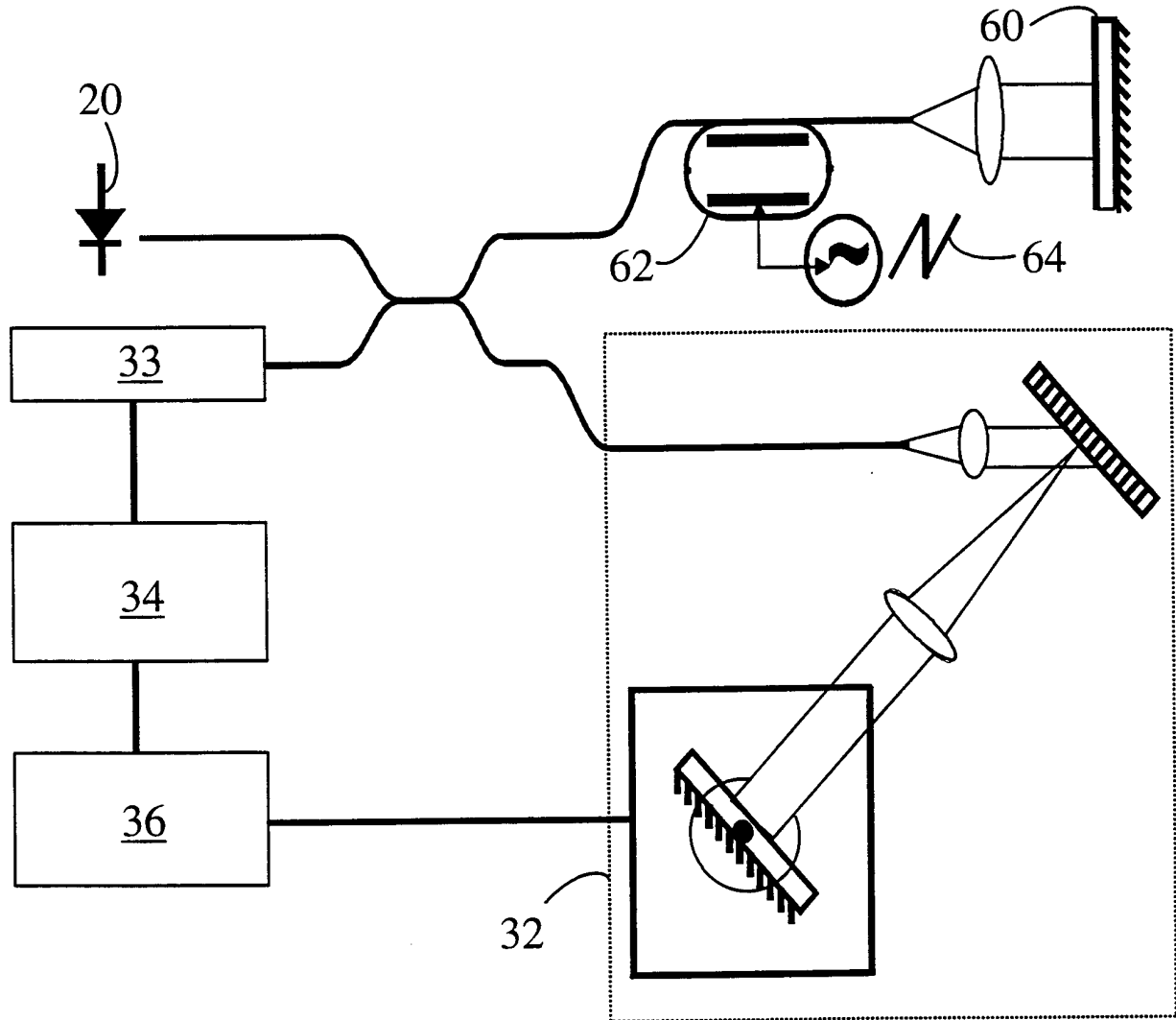
Figure 3

Figure 4

Figure 5

4/5

Figure 6a
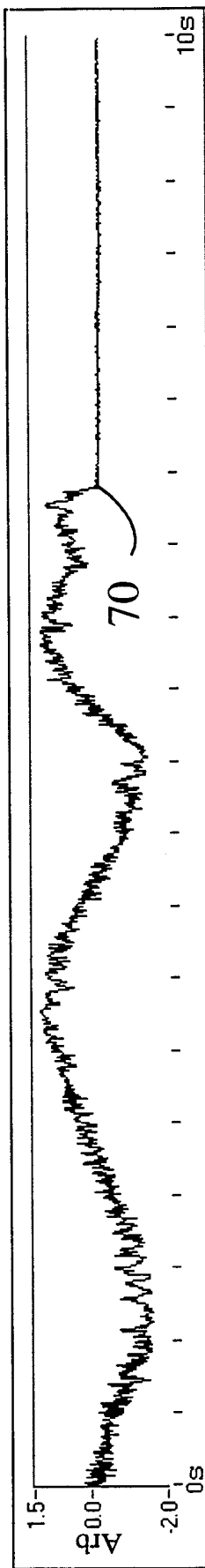
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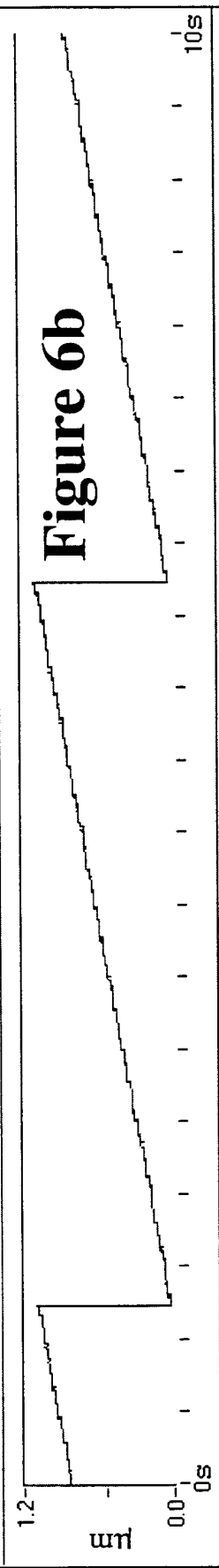
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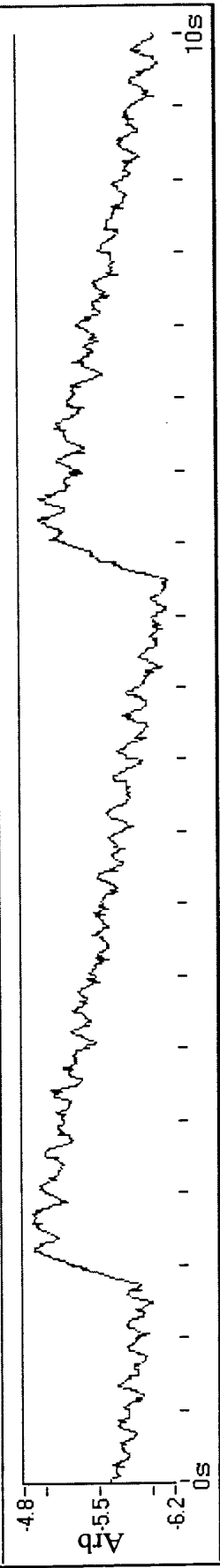
5/5
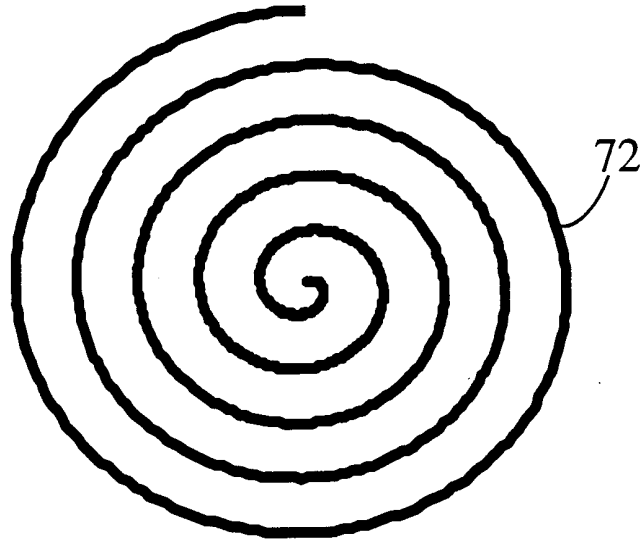
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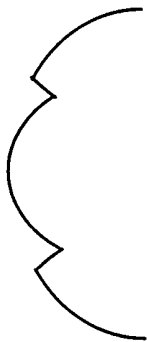
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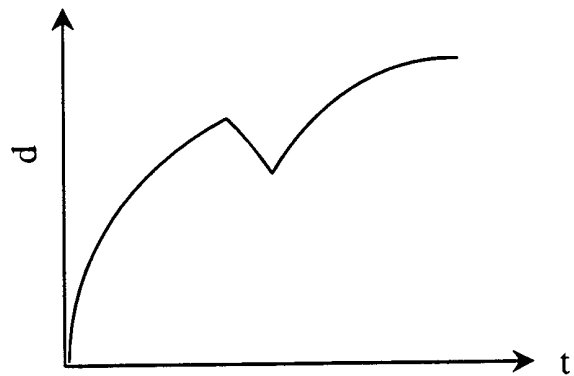
Figure 9

	International application No.
	PCT/AU00/00802

A.	**CLASSIFICATION OF SUBJECT MATTER**

Int. Cl. [7]:   A61B 3/107 G01B 11/24

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)
A61B 3/-, G01B 11/-

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)
WPAT

C.	**DOCUMENTS CONSIDERED TO BE RELEVANT**	

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 99/01716 A (MACPHERSON) 14 January 1999	
A	WO 94/18521 A (ZYGO CORPORATION) 18 August 1994	
A	WO 94/18523 A (ZYGO CORPORATION) 18 August 1994	

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

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Date of the actual completion of the international search	Date of mailing of the international search report
8 September 2000	**13 SEP 2000**
Name and mailing address of the ISA/AU	Authorized officer
AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. (02) 6285 3929	**BRENDAN BOURKE** Telephone No : (02) 6283 2148

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This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member			
WO	9901716	AU	82743/98		
WO	9418521	EP	682771	US	5398113
WO	9418523	EP	746745	US	5402234

END OF ANNEX