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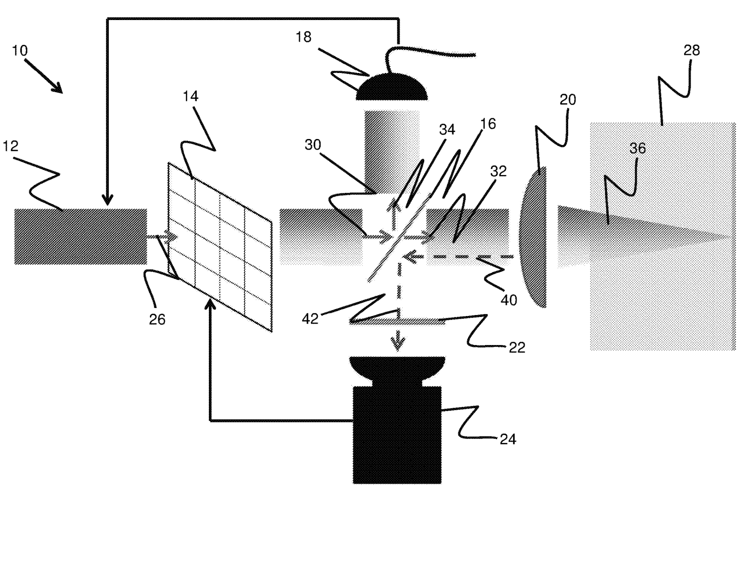
(54) Title of the Invention: **Apparatus and method for projecting light through a light dispersive medium**
Abstract Title: **Projection of light through a light dispersive medium**

(57) The apparatus comprises a light modifier (14) for modifying the characteristics of incident light (26) before it reaches the medium (28), a controller for the light modifier (14), and a detector (24) for detecting an intensity of light backscattered (40) by the medium. The backscattered light arises from an interaction between the incident light and the medium, and may comprise light having a frequency which is equal to, or a harmonic of, a frequency of the incident light. The detector provides a feedback signal for the light modifier that is dependent on the intensity of backscattered light detected, and the controller is configured to determine the modification of at least one characteristic of the incident light that is applied by the light modifier using an optimisation algorithm having the feed back signal as a parameter. The light modifier may alter the instantaneous phase of the incident light or apply a phase shift to the incident light. The invention allows an image to be focused through a light dispersive medium by compensating for scattering or diffuse reflection.

<u>Figure 1</u>



GB 2544337 A

Figure 1

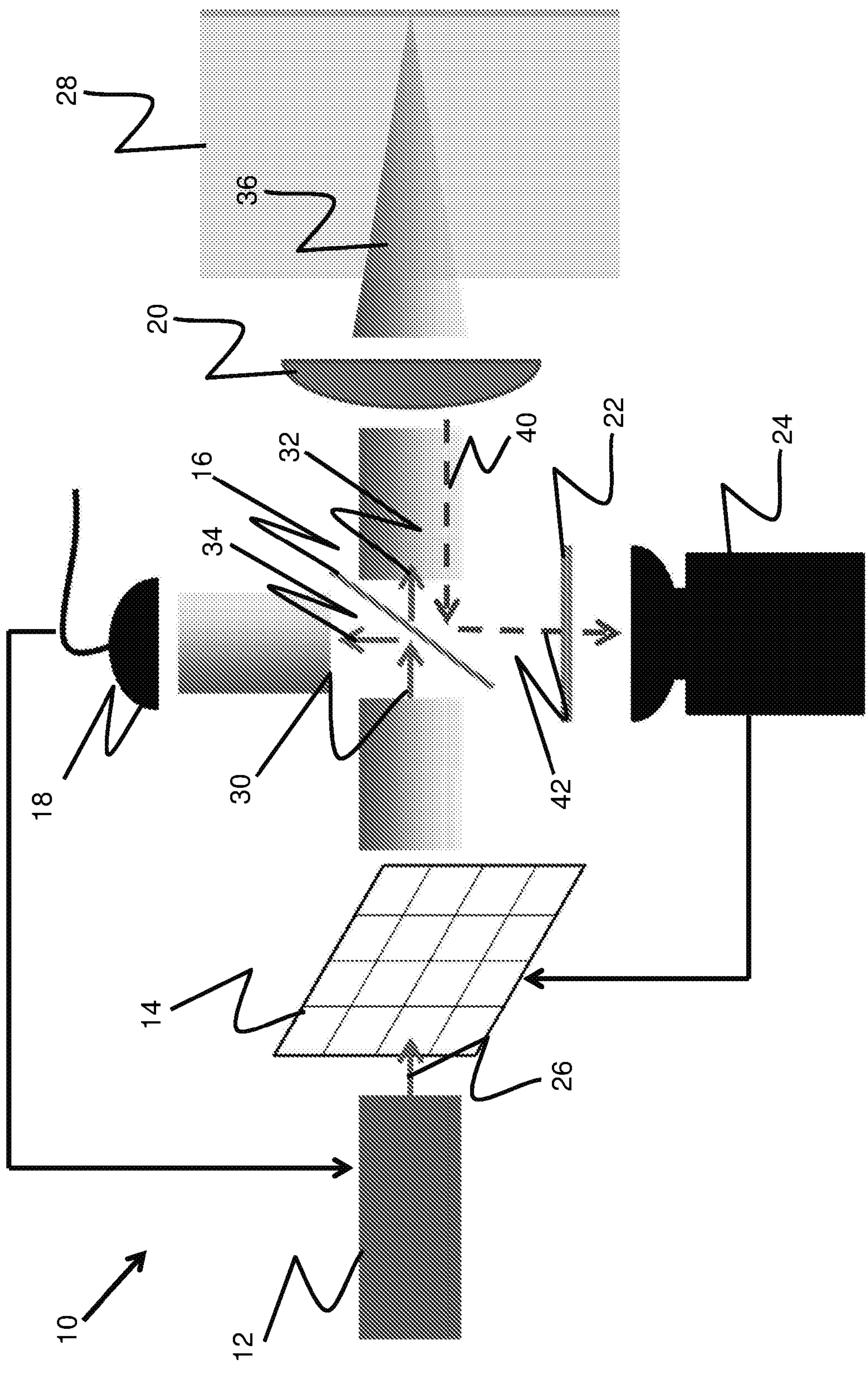
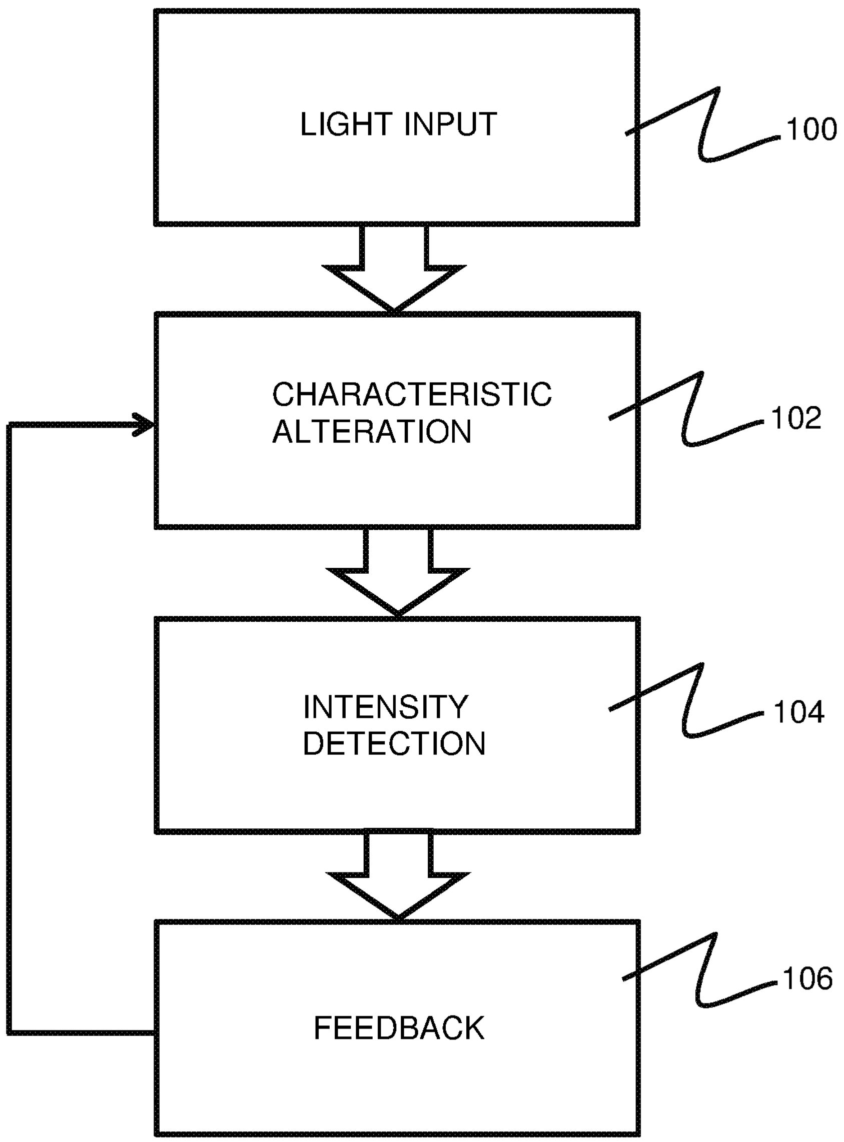


Figure 2



LIGHT INPUT
100
CHARACTERISTIC ALTERATION
102
INTENSITY DETECTION
104
FEEDBACK
106

Figure 3(a)

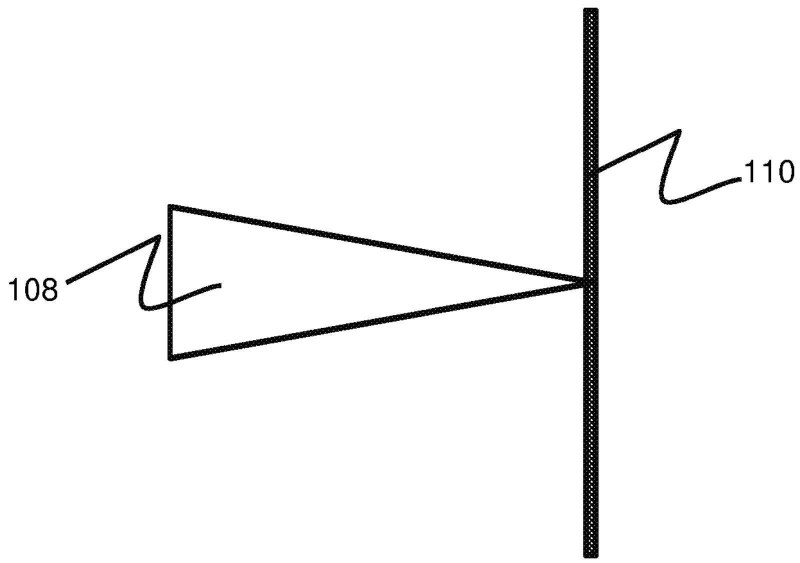


Figure 3(b)

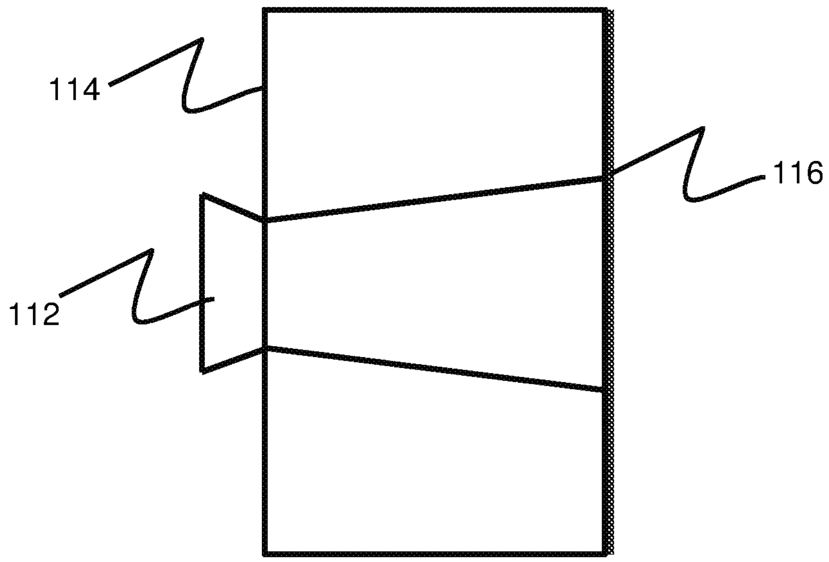


Figure 3(c)

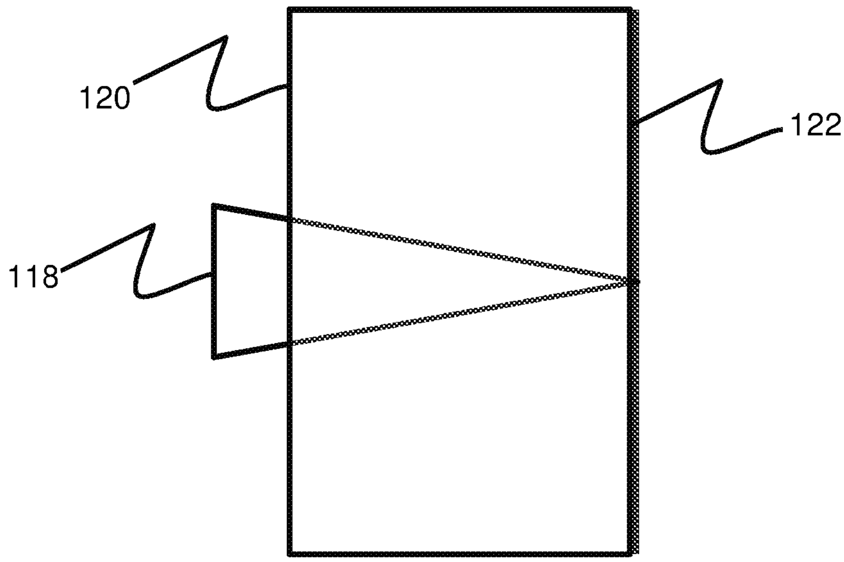
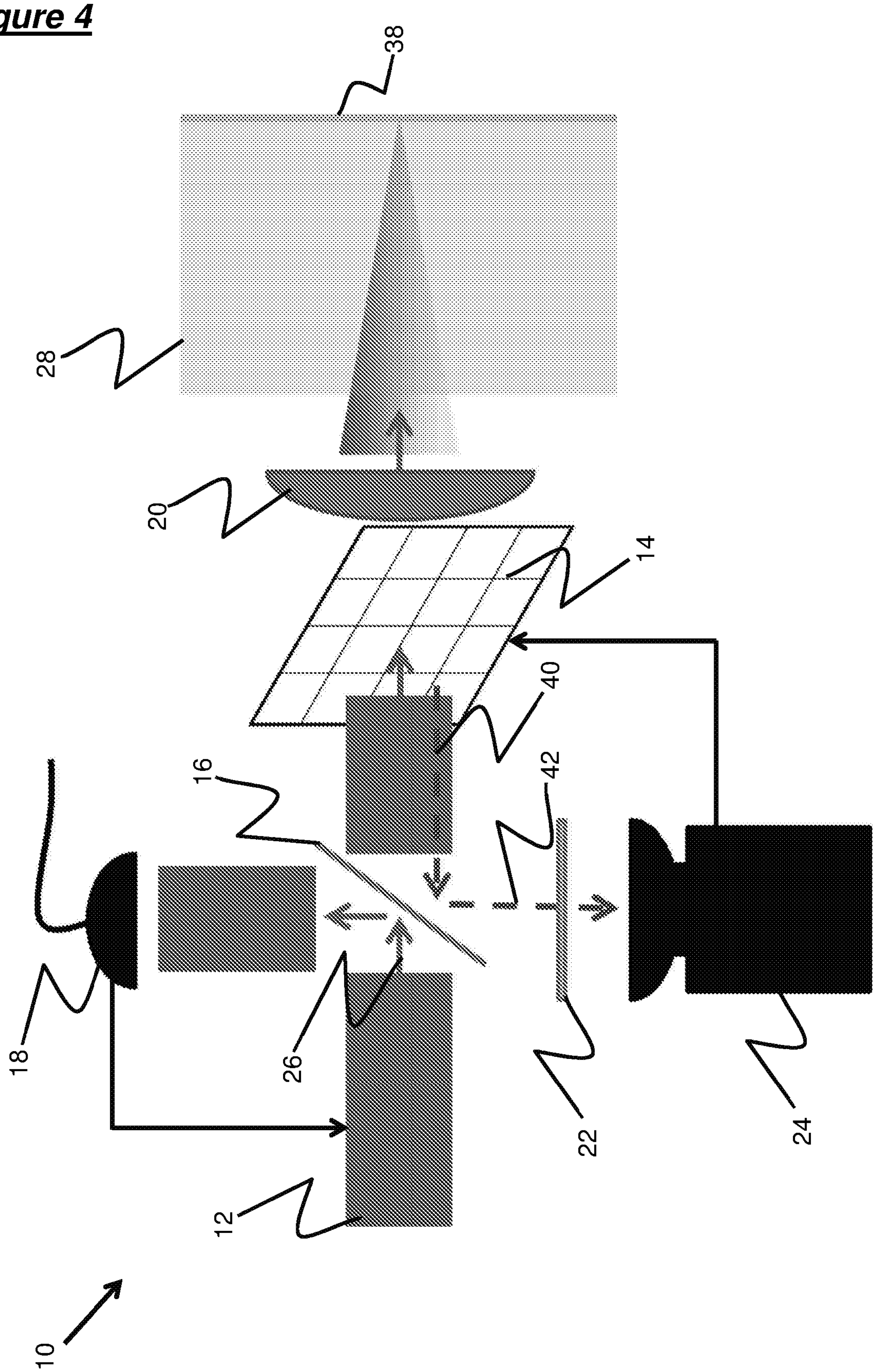


Figure 4



The following terms are registered trade marks and should be read as such wherever they occur in this document:

Texas Instruments (pages 5, 15)

Thor Labs (pages 6, 15, 16)

Title – Apparatus and Method for Projecting Light through a Light Dispersive Medium

The present invention relates to light dispersive media, and in particular to an apparatus and a method for projecting light through such media.

As used herein, the term “light dispersive” is used to refer to the spatial dispersion of light caused by scattering of light by a medium. This is distinct from chromatic dispersion where the phase velocity of light (and its angle of refraction) is dependent on its frequency.

When light passes through a light dispersive medium, it will typically exit the medium with a wider and more diffuse field than that with which it entered the medium. In particular, If the input field is considered as an array of individual beams (with a position-dependent amplitude and phase described by $A_i(x_i,y_i)$), then dispersion can be considered independently for each beam, as it takes a unique path through the material and has its phase relationship with respect to the other beams modified. As a beam travels through the material it scatters randomly, changing the phase and direction of the beam. The light field exiting the material, or at some arbitrary image plane within it, can be considered as an array of individual beams with an amplitude and phase relation that differs from how the input field would have evolved through free space (to $A_f(x_f,y_f)$) by a time-varying dispersion factor (to give a final field in the form $A(x_f,y_f).D(x,y,t)$).

If the input field carries a pattern or image then, on exiting the medium, the pattern or image may become blurred and difficult to see. As the depth of the light dispersive medium is increased, this blurring effect becomes more pronounced, and the ability to discern the original image is rapidly diminished.

Whilst such an effect may be desirable for some known uses, for example in frosted glass, the effect is generally viewed as undesirable for most applications, and in particular is undesirable for most imaging applications.

There has now been devised apparatus for projecting light through a medium, and a method of projecting light through a medium, which overcome or substantially mitigate the aforementioned and/or other disadvantages associated with the prior art.

According to a first aspect of the present invention there is provided apparatus for use in the projection of incident light through a medium, the apparatus comprising a light modifier for modifying at least one characteristic of the incident light, before interaction between the incident light and the medium, a controller for the light modifier, and a detector for detecting an intensity of light backscattered by the medium, wherein the detector is configured to provide a feedback signal to the controller for the light modifier that is dependent on the intensity of backscattered light detected, and the controller is configured to determine the modification of at least one characteristic of the incident light that is applied by the light modifier, in use, using an optimisation algorithm having the feedback signal as a parameter.

The apparatus according to the invention is advantageous principally as the detector is configured to provide a feedback signal to the controller for the light modifier that is dependent on the intensity of backscattered light detected, and the controller is configured to determine the modification of at least one characteristic of incident light that is applied by the light modifier, in use, using an optimisation algorithm having the feedback signal as a parameter. In particular, the apparatus may provide compensation for any scattering, or spatial dispersion, effects caused by the medium, by modifying at least one characteristic of incident light, in order to reduce the optical dispersive effect of the medium.

This may, for example, allow incident light to be focussed through the medium with little or substantially no spatial dispersion, thereby providing a light beam or an image at a focal plane within or beyond the medium. In particular, the apparatus may enable the size, ie cross-sectional or transverse size, of the projected beam or image to be reduced relative to non-modified incident light, and relative to prior art apparatus and methods. The intensity of the projected beam or image may therefore be increased relative to non-modified incident light, and relative to prior art apparatus and methods. Furthermore, the visible spot or image may be better defined, with reduced blurring.

The apparatus according to the invention may find particular utility in medical applications, for example in monitoring fetal response to light in utero, or in optical activation of a drug by focussing light through living tissue. These applications and methods of use are discussed in more detail below.

By “backscattered” light is meant light that is scattered, or diffusely reflected, upon interaction with a medium, such that the light returns in substantially the opposite direction relative to the direction of the incident light. The backscattered light may be scattered, or diffusely reflected, by any scattering mechanism, for example, Mie scattering, Brillouin scattering, Raman scattering, Rutherford backscattering, Bragg diffraction, or Compton scattering.

The medium may be a light dispersive medium, for example a medium which causes the spatial dispersion of light by scattering. The medium may be any medium capable of causing diffuse reflection, for example a medium capable of causing scattering or reflection of light such that an incident ray of light is scattered or reflected at more than one angle. The medium may be living tissue, eg human or animal tissue, which may, for example, comprise any of skin, blood, fat, muscle, or the like.

The intensity of backscattered light on which the feedback signal is dependent may exclude any reflection from a first surface, eg the incident surface, of the medium. This may be achieved by either arranging the apparatus to reduce the proportion of this reflected light that is detected (eg via use of Brewster’s angle and polarised light), or configuring the controller to remove or lessen the dependence of the feedback signal to the intensity of this reflected light.

The at least one characteristic of incident light that is modified by the light modifier may be the phase of the incident light, and may be the instantaneous phase of the incident light. The light modifier may therefore be configured to apply a phase shift to incident light. The light modifier may be configured to apply a spatially dependent phase shift to incident light. For example, the phase shift applied may vary across a transverse plane of a field of incident light. The phase shift applied may vary according to the existing phase of the incident light.

The phase shift applied to the incident light may at least partially compensate for a phase shift gained by incident light as a result of interaction with a medium, for example a phase shift gained by scattering in the medium. The phase shift applied to incident light may be opposite in value to a phase shift gained by incident light as a result of interaction with the medium. For example, where incident light is phase shifted by a factor of $\pi/2$ as a result of interaction with a medium, the incident light may be phase shifted by a factor of $-\pi/2$ by the light modifier. The phase shift applied to incident light may at least partially cancel out a phase shift gained by incident light as a result of interaction with a medium.

The at least one characteristic of the incident light that is modified by the light modifier may affect the intensity of backscattered light detected by the detector. The intensity of the backscattered light may be indicative of the intensity of the projected light, such that increase of the intensity of the backscattered light may increase the intensity of the projected light. Similarly, the intensity of the backscattered light may be indicative of the size, ie cross-sectional or transverse size, of the projected beam or image, such that increase of the intensity of the backscattered light may reduce the size, ie cross-sectional or transverse size, of the projected beam or image. The at least one characteristic of incident light may therefore be modified, in use, to increase or maximise the intensity of backscattered light detected by the detector.

The light modifier may be configured to modify at least one characteristic of incident light continuously during a period of projection. The detector may be configured to provide the feedback signal to the controller either at regular intervals or continuously during a period of projection, and the controller may be configured to use the optimisation algorithm either at regular intervals or continuously to determine the modification of at least one characteristic of the incident light that is applied by the light modifier. This optimisation enables the apparatus to improve the projection of light through media with time-varying optical properties, such as living tissues.

The optimisation algorithm may comprise the application of iterative changes to the modification of at least one characteristic of the incident light that is applied by the light modifier, until an optimal or satisfactory feedback signal is obtained.

The light modifier may be configured to modify at least one characteristic of the incident light at a rate that is faster than the rate at which the dispersion by the medium varies. The controller may be configured to determine the modification of at least one characteristic of the incident light that is applied by the light modifier, in use, without user intervention. The controller may comprise a microprocessor.

The light modifier may comprise at least one phase modulator, for example at least one device capable of modifying the instantaneous phase of the incident light. The at least one phase modulator may comprise an array or grid or matrix of independent phase modulator devices, each connected separately to the controller, for example a two-dimensional (2D) array of phase modulators. Each phase modulator in the array of phase modulators may be configured to modify the instantaneous phase of the incident light. Alternatively, the light modifier may comprise a phase modulator device having an array of operative pixels for receiving the incident light, and the operative pixels may be configured to independently modify the instantaneous phase of the incident light transmitted through the operative pixels. The phase modulator device having an array of operative pixels may include the controller, as an integral component of the device, or may be connectable to an external controller.

The light modifier may comprise a microelectromechanical system (MEMS), and may, for example, comprise a micromirror array. An example of a suitable micromirror array is the Digital Light Processing (DLP®) technology available from Texas Instruments. Alternatively, the light modifier may comprise an array of independent phase modulators, for example an array comprising independent phase modulators such as those available from Thor Labs (for example part number LN65S-FC,). The light modifier may have any desired resolution, and may, for example, have a resolution of at least 16 pixels, at least 64 pixels, or at least 256 pixels.

For some applications, the light modifier may be configured to transmit the incident light through a window of the light modifier, eg through only some operative pixels. Furthermore, the light modifier may be configured to change the position of the window, and hence provide a moving light beam or image, without any need for movement of the apparatus. Alternatively, a moving light beam or image may be achieved by a variable optical diversion arrangement, or by moving the apparatus relative to the medium.

The detector for detecting the backscattered light may be any detector suitable for detecting light intensity. The detector may comprise a point detector or a 2D detector, and may, for example, comprise a CCD detector, a CMOS detector or the like. The detector may include a lens or other optics for directing the backscattered light onto the detector, for example to focus the backscattered light onto a point detector.

The feedback signal provided to the controller for the light modifier may be representative of the intensity of backscattered light detected by the detector. In addition, the feedback signal may be dependent on the size and shape, eg an image, of the intensity of the backscattered light detected by the detector. The feedback signal provided to the controller may be continuous or pulsed. The feedback signal provided to the controller may be provided at a rate that is faster than the rate at which the dispersion by the medium varies.

The apparatus may include a light source for directing incident light towards the medium. The light source may be a spatially coherent light source, and, for example, may be a laser light source. The light source may output incident light at a pre-determined wavelength. The pre-determined wavelength may be chosen dependent on the medium through which it is desired to project light. The pre-determined wavelength may be in the region of 100nm to 1500nm, in the region of 200nm to 1400nm, in the region of 400nm to 1200nm, or in the region of 400nm to 700 nm, or in the region of 600-700nm. The pre-determined wavelength may be a wavelength in the visible region of the electromagnetic spectrum. The light source may output incident light at a pre-determined power and/or intensity. The pre-determined power and/or intensity may be chosen dependent on the medium through which it is desired to project light. The pre-determined power may be less than 1mW, less than 10 mW, or less than 100mW.

The apparatus may comprise a light focussing device for focussing incident and/or backscattered light, and may, for example, comprise a light focussing device for focussing incident and/or backscattered light either prior to, or after, incident and/or backscattered light has interacted with the medium. The apparatus may comprise at least one lens for focussing incident and/or backscattered light.

The apparatus may comprise at least one filter for filtering the incident and/or the backscattered light, and may, for example, comprise at least one filter for filtering the incident and/or the backscattered light either prior to, or after, the incident and/or the backscattered light has interacted with a medium. The apparatus may comprise at least one filter for filtering the backscattered light prior to the backscattered light being detected by the detector.

The at least one filter may be configured to allow the passage of only certain wavelengths, or certain ranges of wavelengths, of light. The at least one filter may comprise any, or any combination of, the following: a notch filter; a band-pass filter; a long-pass filter; or a short-pass filter.

The at least one filter for filtering the backscattered light prior to the backscattered light being detected by the detector may be configured to transmit backscattered light in a range of wavelengths that corresponds to light that is generated by a specific scattering process. For example, the range of transmitted wavelengths may correspond to light that is generated by a non-linear process. This may improve the sensitivity of the apparatus. Suitable non-linear processes may comprise frequency doubling, four-wave mixing, Raman scattering, or the like.

The apparatus may comprise a power monitor for monitoring the power of the light source. The power monitor for monitoring the power of the light source may comprise an optical intensity monitor which monitors the optical intensity, ie the power transferred per unit area, of the light source. The power monitor may comprise a photodiode or the like. The power monitor may be configured to provide a feedback signal to a controller for the power source, and may, for example, be configured to provide a feedback signal dependent on the monitored optical intensity. The controller for the power source may be configured to increase and/or decrease the power output of the power source, dependent on the feedback of monitored optical intensity, eg to maintain a consistent optical intensity.

The apparatus may comprise a first light diverter for diverting at least a portion of incident light to the power monitor, and/or may comprise a second light diverter for diverting at least a portion of backscattered light to the detector for detecting intensity of backscattered light. The first light diverter and the second light diverter may comprise a single component. The first light diverter and/or the second light diverter may comprise a beam-splitter.

The apparatus may be enclosed within a housing, such that the apparatus forms a self-contained device. The device may be handheld, ie may be held in the hand of a user, in use, and may be manipulated by a user's hand, in use. The device may be portable. The device may be mains-powered, or battery-powered.

According to a further aspect of the present invention there is provided a method of projecting incident light through a medium, the method comprising the steps of:

(a) directing the incident light through the medium,

(b) detecting an intensity of light backscattered by the medium,

(c) determining a modification of at least one characteristic of the incident light that is to be applied, in use, before interaction between the incident light and the medium, using an optimisation algorithm having the intensity of light backscattered by the medium as a parameter, and

(d) applying the determined modification to the incident light, before interaction between the incident light and the medium.

The method may utilise the apparatus defined above, such that the light source directs the incident light through the medium, the detector detects an intensity of light backscattered by the medium, the controller for the light modifier determines a modification of at least one characteristic of the incident light that is to be applied, in use, before interaction between the incident light and the medium, using an optimisation algorithm having the intensity of light backscattered by the medium as a parameter, and the light modifier applies the determined modification to the incident light, before interaction between the incident light and the medium.

The method may comprise directing incident light through a light dispersive medium, for example a medium which causes the spatial dispersion of light by scattering. The medium may be any medium capable of causing diffuse reflection, for example a medium capable of causing scattering or reflection of light such that an incident ray of light is scattered or reflected at more than one angle. The medium may be living tissue, eg human or animal tissue, which may, for example, comprise any of skin, blood, fat, muscle, or the like.

The method may comprise modifying the phase, eg the instantaneous phase, of the incident light. The modification of the phase of the light may be spatially dependent. For example, the phase shift applied may vary across a transverse plane of a field of incident light. The phase shift applied may vary according to the existing phase of the incident light.

Where the method comprises modifying the phase of incident light, the method may comprise applying a phase shift to the incident light. The method may comprise applying a spatially dependent phase shift to incident light. For example, the phase shift applied may vary across a transverse plane of a field of incident light.

The phase shift applied to the incident light may at least partially compensate for a phase shift gained by incident light as a result of interaction with a medium, for example a phase shift gained by scattering in the medium. The method may comprise applying a phase shift to the incident light which is opposite in value to a phase shift gained by the incident light as a result of interaction with a medium. For example, where the incident light is phase shifted by a factor of $\pi/2$ as a result of interaction with a medium, the method may comprise phase shifting incident light by a factor of $-\pi/2$. The phase shift applied to incident light may at least partially cancel out a phase shift gained by incident light as a result of interaction with a medium.

The at least one characteristic of the incident light that is modified by the light modifier may affect the intensity of backscattered light detected by the detector. The intensity of the backscattered light may be indicative of the intensity of the projected light, such that increase of the intensity of the backscattered light may increase the intensity of the projected light. Similarly, the intensity of the backscattered light may be indicative of the size, ie cross-sectional or transverse size, of the projected beam or image, such that increase of the intensity of the backscattered light may reduce the size, ie cross-sectional or transverse size, of the projected beam or image. The at least one characteristic of incident light may therefore be modified, in use, to increase or maximise the intensity of backscattered light detected by the detector.

The method may comprise modifying at least one characteristic of incident light continuously during a period of projection. The method may comprise determining the modification to be applied either at regular intervals or continuously during a period of projection, and the optimisation algorithm may be utilised either at regular intervals or continuously to determine the modification of at least one characteristic of the incident light that is applied. This optimisation enables the apparatus to improve the projection of light through media with time-varying optical properties, such as living tissues.

The optimisation algorithm may comprise the application of iterative changes to the modification of at least one characteristic of the incident light that is applied by the light modifier, until an optimal or satisfactory feedback signal is obtained.

The method may comprise modifying at least one characteristic of incident light on a timescale that is faster than the rate at which the dispersion by the medium varies. The method may comprise determining the modification of at least one characteristic of the incident light that is applied by the light modifier, in use, without user intervention.

The method may comprise focussing incident and/or backscattered light, and may, for example, comprise focussing incident and/or backscattered light either prior to, or after, incident and/or backscattered light has interacted with a medium.

The method may comprise filtering incident and/or backscattered light, and may, for example, comprise filtering incident and/or backscattered light either prior to, or after, the incident and/or backscattered light has interacted with a medium. The method may comprise filtering backscattered light prior to backscattered light being detected by the detector.

The method may comprise detecting certain wavelengths, or certain ranges of wavelengths, of backscattered light. The method may comprise detecting a range of wavelengths that corresponds to light that is generated by a specific scattering process. For example, the range of transmitted wavelengths may correspond to light that is generated by a non-linear process. This may improve the sensitivity of the method. Suitable non-linear processes may comprise frequency doubling, four-wave mixing, Raman scattering, or the like.

According to a further aspect of the present invention there is provided a method of monitoring fetal response to a light stimulus in utero, the method comprising the steps of:

(a) projecting light into the uterus of a patient by means of the method of projecting incident light through a medium that is defined above, and

(b) monitoring fetal response to the light that is projected into the uterus.

The method according to this aspect of the present invention may be advantageous in that it monitors fetal response to light that is projected into the uterus, whilst utilising the method of projecting incident light through a medium previously defined. In particular, the method of projecting light through a medium that has previously been defined may allow for light to be projected through the uterus with substantially no dispersion, such that a focussed light beam is formed within the uterus. This may allow fetal response to a light stimulus to be more accurately monitored than, for example, fetal response to a diffuse light source.

The method according to this aspect of the present invention may also be advantageous in that it may allow fetal vision to be examined in utero, for example by ascertaining fetal head movement in response to light stimulus provided in utero. This may thereby provide an early indicator for failure of vision to develop, and may, for example provide an early indication of retinal formation or maladaptive rod/cone development for peripheral vision reorientations.

Furthermore, the method according to this aspect of the present invention may also be advantageous in that it may provide an early indicator of infantile muscular atrophy (Werdnig-Hoffmann disease), for example by repeated failure of a fetus to orient to the light stimulus provided in the uterus.

The method may comprise a step of ascertaining fetal orientation, which may be undertaken prior to, or during, projection of light into the uterus of a patient. The fetal orientation may be ascertained using any conventional means, including for example, an ultrasound imaging device.

The fetal response to light may be monitored using any conventional means, including, for example, an ultrasound imaging device. The method may comprise monitoring fetal movement in response to a light stimulus, and the light stimulus may comprise the light that is projected into the uterus of the patient. The method may comprise monitoring fetal head movement in response to a light stimulus.

The method may comprise monitoring duration of fetal fixation on a light stimulus and the light stimulus may comprise the light that is projected into the uterus of the patient.

According to a further aspect of the present invention there is provided apparatus for monitoring fetal response to a light stimulus, in utero, the apparatus comprising apparatus as defined above, and an imaging device for providing a real-time image of a fetus, in utero.

The imaging device may comprise any conventional imaging device, and may, for example, comprise an ultrasound imaging device. The ultrasound imaging device may provide a 2D scan (ie a 2 dimensional image), a 3D scan (ie a 3 dimensional image), or so-called 4D scan (ie a succession of 3 dimensional images, eg in the form of a video).

According to a further aspect of the present invention there is provided a method of optical activation of an active substance, in vivo, the method comprising the steps of:

(a) providing an active substance to a patient such that the active substance is located with the body of the patient; and

(b) projecting light into the body of the patient in the region in which the active substance is located by means of the method of projecting incident light through a medium that is defined above.

The method according to this aspect of the present invention is advantageous particularly as the method comprises projecting light into the body of the patient in the region in which the active substance is located by means of the method of projecting incident light through a medium that is defined above. In particular, by using the method of projecting incident light through a medium that is defined above, the focussed light beam produced may ensure maximum exposure to the target location, without exposure to nearby tissue. This is in contrast to current photodynamic therapies, which introduce drugs to non-target regions of internal tissue as intense light cannot be accurately focussed on target locations.

It will be recognised that preferential features of the aspects of the present invention may be equally applied to other aspects of the present invention, where appropriate.

Practicable embodiments of the invention will now be described in further detail, with reference to the accompanying drawings, of which:

Figure 1 is a schematic view of a first embodiment of apparatus according to the present invention;

Figure 2 is a flow diagram illustrating a method of use of the apparatus of Figure 1;

Figure 3(a) is a schematic view of light projected where no light dispersive medium is present;

Figure 3(b) is a schematic view of light projected through a light dispersive medium without use of the apparatus and method of the present invention;

Figure 3(c) is a schematic view of light projected through a light dispersive medium when the apparatus and method of the present invention are used; and

Figure 4 is a schematic view of a second embodiment of apparatus according to the present invention.

Apparatus according to the present invention, generally designated 10, is shown schematically in Figure 1. Although the apparatus 10 is depicted here as separate components, it will be recognised that the components of the apparatus 10 can be housed in a common housing, so as to facilitate use of the apparatus 10 as a device, for example a hand-held device.

The apparatus 10 comprises a light source 12, a phase modulator array 14 a beam-splitter 16, a photo-diode 18, a lens 20, a filter 22, and a detector 24.

The light source 12 is a laser (ie a spatially coherent) light source, which has a wavelength chosen dependent on both the media through which it is desired to project light, and the intended application of the projected light. Where light is intended to be projected through human tissue, and is intended to be detected by a human eye, for example, a wavelength of 660nm may be appropriate. An example of a suitable light source 12 is part number HL6545MG available from Thorlabs (http://www.thorlabs.de/thorproduct.cfm?partnumber=HL6545MG). The light source 12 is an optional feature of the present invention, and embodiments where the apparatus 10 is used with a separate light source are envisaged. Thus the apparatus 10 may be used in combination with existing light sources.

The phase modulator array 14 may be an array of individual phase modulator elements, where incident light 26 has been expanded to a beam of sufficient diameter to illuminate each of the individual phase modulator elements. Suitable individual phase modulator elements are part numbers EO-PM-NR-C1 (http://www.thorlabs.de/thorproduct.cfm?partnumber=EO-PM-NR-C1) and LN65S-FC (http://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=3918&pn=LN65S-FC) available from Thorlabs.

Alternatively, the phase modulator array 14 may be a single device comprising an array of phase control elements, such as a micromirror array. An example of a suitable micromirror array is the DLP® chip available from Texas Instruments (http://www.ti.com/lsds/ti/dlp-technology/about-dlp-technology/how-dlp-technology-works.page).

The phase modulator array 14 is located intermediate the light source 12 and the beam splitter 16. The beam splitter 16 is in turn located intermediate the phase modulator array 14 and the lens 20.

The beam-splitter 16 is either an angled glass slide, or a pellicle beam-splitter. Suitable pellicle beam-splitters are available from Thorlabs (http://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=898). The beam-splitter 16 is preferably not a 50:50 beam-splitter, and is configured to send a majority of incident light to a medium, and as much backscattered light to the detector 24, as possible.

The photo-diode 18 is any device capable of outputting a signal that is correlated to the intensity of light incident on the device, and needs to be a device which is sensitive to the wavelength of the light source 12. A suitable photo-diode 18 may be part number DET10A/M (http://www.thorlabs.de/thorproduct.cfm?partnumber=DET10A/M) available from Thorlabs.

The lens 20 is a conventional lens, the size and numerical aperture of which is chosen dependent on the physical size of the apparatus as a whole. It is envisaged that plastic lenses will be suitable for most applications.

The filter 22 is a conventional optical filter, and may be a band-pass filter. A suitable filter 22 may be any of the band-pass filters available from Thorlabs (http://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=1001).

The detector 24 is a 2D arrayed light detector which is sensitive to the wavelength of the light to be monitored, for example a silicon CCD or CMOS detector for visible or near infra-red signals. A suitable detector 24 may be any of the CCD cameras available from Thorlabs (http://www.thorlabs.co.uk/newgrouppage9.cfm?objectgroup_id=2916).

The operation of the apparatus 10 will now be described with reference to Figures 1 and 2.

As an initia step 100, the light source 12 directs incident light 26 towards a medium 28. The incident light 26 passes through the phase modulator array 14, and is phase-shifted to give phase-engineered light 30. The phase engineered light 30 passes through the beam-splitter 16, such that a first portion 32 of the phase engineered light 30 is directed toward the medium 28, whilst a second portion 34 of the phase engineered light 30 is directed toward the photo-diode 18. The photo-diode 18 monitors the intensity of the second portion 34 of the phase engineered light 30, and provides feedback to the light source 12. The light source 12 may modify its light output dependent on the feedback provided by the photo-diode 18.

The first portion 32 of the phase engineered light 30 passes through the lens 20, and focussed light 36 passes through the medium 28. As the focussed light 36 passes through the medium 28, some of the light is backscattered by the medium 28. Backscattered light 40 passes through the lens 20 and hits the beam-splitter 16, such that the backscattered light 40 is directed toward the detector 24. The backscattered light 40 passes through the filter 22, and is detected by the detector 18.

The detector 24 provides feedback of the intensity 106 to the phase modulator array 14. When the intensity of the first portion 42 of the backscattered light 40 is maximized, the optimal correction parameters for the phase modulator array 14 have been found, and the light dispersion of the medium 28 is partially or fully compensated.

The effects of the apparatus 10 are shown in Figures 3(a)-3(c). In Figure 3(a), incident light 108 is projected directly toward a focal plane 110, in the absence of any light dispersive medium. As can be seen, the incident light 108 is projected onto the focal plane 110 without any dispersive effects. In Figure 3(b), incident light 112 is projected through a medium 114, with a focal plane 116 located within or beyond the medium 114, without use of the apparatus 10. As the incident light 112 passes through the medium 114, the light 112 is dispersed, ie scattered, by the medium 114, such that the field of light at the focal plane 116 is diffuse and has a low power density. In Figure 3(c), incident light 118 is projected through a medium 120, with an focal plane 122 located within or beyond the medium 120, with use of the apparatus 10. As the incident light 118 passes through the medium 120, due to the corrective factors applied by the apparatus 10, the light

118 is not dispersed, ie scattered, by the medium 120, and is instead focussed such that the field of light at the focal plane 122 is focussed and has a high power density.

A second embodiment of apparatus according to the present invention, generally designated 10, is shown schematically in Figure 2, and like reference numerals are used for like components. The second embodiment of apparatus 10 is substantially the same as the first embodiment of apparatus 10, and differs only in the location of the phase modulator array 14. In particular, the phase modulator array 14 in the second embodiment of the apparatus 10 is located intermediate the beam splitter 16 and the lens 20.

Backscattered light 40 from the focal plane 38 now passes through the phase modulator array 14 prior to being directed toward the detector 24 by the beam-splitter 22. This allows a real image of the field intensity on the focal plane 38 to be detected by the detector 24, and feedback of this real image can be used to optimise the modification applied by the phase modulator array 14.

Apparatus 10 according to the first and second embodiments of the present invention may find particular use as apparatus for monitoring fetal vision in utero, and an example of such use will now be described.

Initially the orientation of the fetus is ascertained via an initial 2d ultrasound scan. Prior to presenting the light stimuli from the light source 12, an initial ultrasound is used to determine the amount of maternal tissue between the light source and the fetal face. The light source 12 can be modified to account for the impedance and diffusion measures related to the depth of maternal tissue. This will ensure that the correct amount of light is released. The levels of light presented to the fetus will be of an intensity to produce the desired percept but at the lower end of the normal spectrum in order to avoid discomfort or signs that the fetus finds the light to be aversive. At this point in time the apparatus 10 can be used.

Importantly, light will not be directly shone into the eyes of the fetus. To determine the state of the fetus (sleep, alert), an initial orienting response is required. The stimuli will be small in size but with a lumens intensity that will allow for the percept of a stimulus to be observed by the fetus. Via this means fetal fixation time towards the light stimulus can be measured. Head rotation towards stimuli when the stimuli are moved away from an initial fixation presentation location can also be measured.

Continual feedback via the apparatus 10 can provide refined focus as a function of change in maternal tissue depth during fetal movement. When combined with a so-called 4D ultrasound scan, the apparatus 10 can be synchronised so that the sonographer can determine the appropriate application of the apparatus 10 as a function of fetal orientation and behavioural state.

Claims

1. An apparatus for use in the projection of incident light through a medium, the apparatus comprising a light modifier for modifying at least one characteristic of the incident light, before interaction between the incident light and the medium, a controller for the light modifier, and a detector for detecting an intensity of light backscattered by the medium, wherein the detector is configured to provide a feedback signal to the controller for the light modifier that is dependent on the intensity of backscattered light detected, and the controller is configured to determine the modification of at least one characteristic of the incident light that is applied by the light modifier, in use, using an optimisation algorithm having the feedback signal as a parameter.

2. An apparatus as claimed in Claim 1, wherein the at least one characteristic of incident light that is modified by the light modifier is the instantaneous phase of the incident light.

3. An apparatus as claimed in Claim 1 or Claim 2, wherein the light modifier is configured to apply a phase shift to incident light.

4. An apparatus as claimed in Claim 2 or Claim 3, wherein the phase shift applied to the incident light at least partially compensates for a phase shift gained by incident light as a result of interaction with a medium.

5. An apparatus as claimed in any preceding claim, wherein the controller is configured to modify at least one characteristic of incident light, in use, to increase the intensity of backscattered light detected by the detector.

6. An apparatus as claimed in any preceding claim, wherein the light modifier is configured to modify at least one characteristic of incident light continuously during a period of projection.

7. An apparatus as claimed in any preceding claim, wherein the detector is configured to provide the feedback signal to the controller either at regular intervals or continuously during a period of projection.

8. An apparatus as claimed in any preceding claim, wherein the controller is configured to use the optimisation algorithm either at regular intervals or continuously to determine the modification of at least one characteristic of the incident light that is applied by the light modifier.

9. An apparatus as claimed in any preceding claim, wherein the optimisation algorithm comprises the application of iterative changes to the modification of at least one characteristic of the incident light that is applied by the light modifier, until an optimal or satisfactory feedback signal is obtained.

10. An apparatus as claimed in any preceding claim, wherein the light modifier is configured to modify at least one characteristic of the incident light at a rate that is faster than the rate at which the dispersion by the medium varies.

11. An apparatus as claimed in any preceding claim, wherein the light modifier comprises at least one phase modulator, capable of modifying the instantaneous phase of the incident light.

12. An apparatus as claimed in any preceding claim, wherein the light modifier comprises an array or grid or matrix of independent phase modulator devices, each connected separately to the controller.

13. An apparatus as claimed in any preceding claim, wherein the light modifier comprises a phase modulator device having an array of operative pixels for receiving the incident light, the operative pixels being configured to independently modify the instantaneous phase of the incident light transmitted through the operative pixels.

14. An apparatus as claimed in any preceding claim, wherein the feedback signal provided to the controller for the light modifier is dependent on the size and shape of the intensity of the backscattered light detected by the detector.

15. An apparatus as claimed in any preceding claim, wherein the apparatus includes a light source for directing incident light towards the medium.

16. An apparatus as claimed in Claim 15, wherein the light source outputs incident light at a pre-determined wavelength in the visible region of the electromagnetic spectrum.

17. An apparatus as claimed in any preceding claim, wherein the apparatus comprises at least one filter for filtering the backscattered light prior to the backscattered light being detected by the detector.

18. An apparatus as claimed in Claim 17, wherein the at least one filter is configured to transmit backscattered light in a range of wavelengths that corresponds to light that is generated by a specific scattering process.

19. An apparatus as claimed in Claim 18, wherein the range of transmitted wavelengths corresponds to light that is generated by a non-linear process.

20. An apparatus as claimed in any preceding claim, wherein the apparatus is enclosed within a housing, such that the apparatus forms a self-contained device.

21. An apparatus as claimed in Claim 20, wherein the device is a handheld device.

22. A method of projecting incident light through a medium, the method comprising the steps of:

(a) directing the incident light through the medium,

(b) detecting an intensity of light backscattered by the medium,

(c) determining a modification of at least one characteristic of the incident light that is to be applied, in use, before interaction between the incident light and the medium, using an optimisation algorithm having the intensity of light backscattered by the medium as a parameter, and

(d) applying the determined modification to the incident light, before interaction between the incident light and the medium.

23. A method as claimed in Claim 22, wherein the method utilises an apparatus as claimed in any one of Claims 1 to 21, such that a light source directs the incident light through the medium, the detector detects an intensity of light backscattered by the medium, the controller for the light modifier determines a modification of at least one characteristic of the incident light that is to be applied, in use, before interaction between the incident light and the medium, using an optimisation algorithm having the intensity of light backscattered by the medium as a parameter, and the light modifier applies the determined modification to the incident light, before interaction between the incident light and the medium.

24. A method of monitoring fetal response to a light stimulus in utero, the method comprising the steps of:

(a) projecting light into the uterus of a patient by means of the method of projecting incident light through a medium as defined in claim 22 or Claim 23, and

(b) monitoring fetal response to the light that is projected into the uterus.

25. A method as claimed in Claim 24, wherein the method comprises a step of ascertaining fetal orientation, which is undertaken prior to, or during, projection of light into the uterus of a patient.

26. A method as claimed in Claim 24 or Claim 25, wherein the fetal response to light is monitored using an ultrasound imaging device.

27. A method as claimed in any one of Claims 24 to 26, wherein the method comprises monitoring fetal head movement in response to a light stimulus.

28. A method as claimed in any one of Claims 24 to 26, wherein the method comprises monitoring duration of fetal fixation on a light stimulus.

29. Apparatus for monitoring fetal response to a light stimulus, in utero, the apparatus comprising apparatus as claimed in any one of Claims 1 to 21, and an imaging device for providing a real-time image of a fetus, in utero.

30. Apparatus as claimed in Claim 29, wherein the imaging device comprises an ultrasound imaging device.

31. A method of optical activation of an active substance, in vivo, the method comprising the steps of:
(a) providing an active substance to a patient such that the active substance is located with the body of the patient; and
(b) projecting light into the body of the patient in the region in which the active substance is located by means of the method of projecting incident light through a medium as defined in Claim 22 or Claim 23.

Intellectual Property Office

Application No:	GB1520076.9	**Examiner:**	Mr Zac Stentiford
Claims searched:	1-31	**Date of search:**	13 May 2016

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1-31	US 2012/070817 A1 (WANG et al.) see especially paragraphs [0053], [0076], [0079], [0096], and figure 2(a) noting light source 220, medium 204, light modifier SLM or DMD, controller 230, detector 216 feeding back to controller and light modifier, and backscattered light 212
X	1-4, 6-9, 11-16 & 20-23	US 2015/285739 A1 (NADAKUDITI et al.) see especially figure 2 noting light source 204, medium 100, light modifier 202, controller 224, detector 220 feeding back to controller and light modifier, and backscattered light 210
X	1-8, 11-13, 15, 16 & 20-23	EP 2479546 A1 (MENG) see especially figure 1 noting light source 105, medium 110, light modifier 135, controller 150, detector 147 feeding back to controller, light modifier and light source, and backscattered light 165
X	1-8, 11-13, 15, 16 & 20-23	US 2012/182591 A1 (MASUMURA) see especially paragraph [0019]-[0025] and figure 1 noting light source 100, medium 106, light modifer 102, controller 199 and detector 105 feeding back to controller and light modifier
X	1-7, 11, 12, 15, 16 & 20-23	US 2009/137990 A1 (SHEINIS) see especially figure 3 noting light source 52, medium 26, light modifier 58, controller 55, and detector 74 feeding back to controller and light modifier
A,E	-	WO 2016/011043 A1 (YANG et al.) see especially figures 1 and 2 noting light source 120, 260, medium 111, light modifier 125, 270, 275, controller 145, detector 140, and feedback signal 150

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{X} :

Intellectual Property Office

Worldwide search of patent documents classified in the following areas of the IPC

G01N; G02B; G05D

The following online and other databases have been used in the preparation of this search report

EPODOC, WPI

International Classification:

Subclass	Subgroup	Valid From
G05D	0025/02	01/01/2006
G01N	0021/47	01/01/2006
G02B	0026/06	01/01/2006