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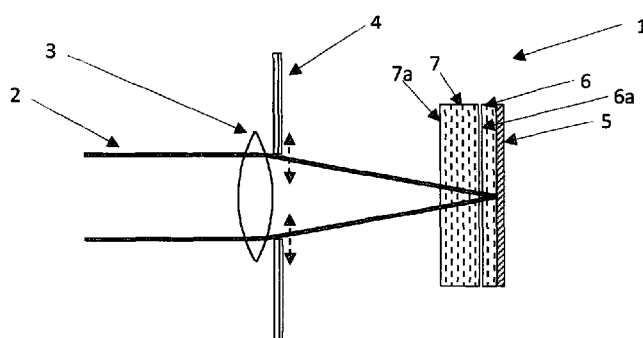


Fig 2.

(57) Abstract: A camera for operating resiliently in the event of a pulsed laser attack, comprising an adjustable optical aperture (4, e.g. iris) and an optical limiter device. The optical limiter comprises two layers (6, 7) of non-linear optical limiter material, and at least the one closest to the image sensor (5) has a front surface that is vulnerable to high intensity light, such that in a maximum-aperture size (lowest f number) situation if an incoming laser pulse was sufficiently intense to otherwise damage the image sensor, then this would instead cause blackening and/or distortion to that location on that front surface of the optical limiter material, thereby offering enhanced protection to the image sensor. Whilst the blackened and/or distorted patch that is formed leads to a dark spot on the resulting images and this persists afterwards, it has been found that this can be partially addressed using software and is far preferable to the image sensor not working.



A camera for operating resiliently in the event of a pulsed laser attack

The present invention relates to cameras operable wholly or predominantly in the visible wavelength band, with optical filters adapted to operate resiliently against damage from lasers, and to optical filters that are designed for use in cameras of known configuration to provide such resilience against damage from lasers. The invention is applicable to the field of camera design. Laser attacks come in two main forms, dazzle and damage. Laser attacks intended to damage an image sensor generally utilise pulsed sources. The invention is primarily discussed with reference to pulsed laser attacks, however it is also relevant to continuous (non-pulsed) laser attacks that are sufficiently powerful to pose a risk of permanently damaging the image sensor of a camera, and as the design of a cameras that is intended to withstand damaging laser attacks generally is also designed with a desire for resilience against laser dazzle, this invention is applicable to the field of laser attack resilient cameras.

In the past, various approaches have been proposed to combat the problem that camera sensors need to be as sensitive as possible in order to operate effectively without being unnecessarily large. One known method involves providing a layer of non-linear optical limiting (E.g. two-photon) material in the light path leading to the image sensor. Non-linear optical limiting materials provide a non-linear increase in attenuation with increasing light intensity (usually within a relevant wavelength band), however they generally only provide a strongly attenuating effect if the light is very intense, and/or if the light is moderately intense and passed through a large thickness of the material.

Optical limiting materials inherently also absorb a proportion of light in a linear fashion at low intensities, which means that use of a very thick layer causes a disadvantageous loss of light at low light intensities. The intensity of light caused by an incident laser will be highest at an optical plane of the lens of the camera, so most conventional designs involve a thin layer of optical limiter material at or immediately adjacent to a focal plane, for example as a layer placed directly upon the image sensor.

Whilst some modern arrangements offer excellent protection against short (nanosecond) pulses of laser light, slightly longer pulses with slightly lower intensity, such as microsecond pulses, are often equally capable of damaging an image sensor, and it is more challenging for an optical limiting material to protect against these types of laser attacks since the non-linear optical limiter material will attenuate a smaller proportion of the laser light.

Since most cameras need to be able to adjust their aperture size (f-number) to ensure high quality images can be collected both in daytime and at night, the size of the aperture through which an incoming laser attack pulse will come varies, and also the range of angles from which the light converges onto the image sensor can either be a narrow range of angles (corresponding to a small aperture or high f-number such as 16 or 22), or can be a wide range of angles (corresponding to a wide aperture or low f-number such as 1 or 2).

Additionally, it is not possible to anticipate how much light energy or radiance from an attacker's laser pulse will pass into and through the camera lens. This depends not only on the attacker and their laser system, but the divergence of their laser beam, their distance and weather conditions and the lens aperture. What is possible to anticipate however, is that irrespective of what range of radiances a camera has been designed to cope well with, it is always possible that the incoming radiance in a particular attack might be somewhat outside of that range. Typically, designers worry that the radiance will be slightly too high, but as explained above, if the laser pulse is longer than is typically the case, the attacker might be able to achieve sensor damage by making the radiance slightly too low so that the non-linear absorbing effect of the optical limiter material provides insufficient protection.

The inventor has identified that at two different f-numbers, the manner in which a high intensity laser pulse is attenuated or intensity limited in the optical limiter material differs. If the camera is set to a small aperture (high f-number) and the laser pulse radiance passing through that aperture is otherwise sufficient to threaten the image sensor integrity, then the front half (i.e. away from the sensor) of the absorber will be activated by the intense laser light and the light will be mostly absorbed in that front half of the non-linear absorber. By contrast if the camera is set to a large aperture (low f-number) and the laser pulse radiance passing through that aperture is otherwise sufficient to threaten the image sensor integrity, then the front half of the absorber will have little effect on it and instead only the back half (i.e. near the image sensor) of the non-linear absorber will be strongly activated by the intense laser light (since that is where the light

cone converging on the sensor becomes most intense) and the light will be mostly attenuated in that back half of the non-linear absorber.

That said, describing this as a simple front half / back half dichotomy is an excessive simplification. The point is that the region where the most vital attenuation activity happens varies depending on the aperture setting of the camera.

The inventor has further identified that solid optical limiter materials exhibit a burn/blackening or deformation type effect, but only at their surface. The reasons for this are not understood with certainty, and while this might partially have to do with the presence of oxygen at the surface, it is believed to be related both to the differing behaviour of free charges liberated by photons at the surface as compared to in the bulk of the material, and/or being caused by the sudden discontinuity in absorbance as the concentrating light cone passes into the non-linear material.

The inventor has further identified a range of other materials which can provide such a self-damaging effect, for example polymer materials such as plastics, where necessary with pigments to make them more easily damaged by high intensity light. Thus the effect can be achieved by a range of materials, and not only by the optical limiter material itself.

At high incident intensities, the absorption volume decreases rapidly as the intensity of the laser pulse increases. By way of illustration, take a laser pulse that is at some arbitrarily low intensity (but high enough to be non-linearly absorbed), then this absorption will occur within the bulk of the material. As the intensity increases, the location where the absorption first takes place moves further away from the detector, because the threshold intensity now occurs closer to the focussing lens. At some point, this absorption location will reach the front surface of the material, and the absorption volume will decrease, resulting in damage to the front surface.

The rate of energy absorption at the surface is much higher than within the bulk of the absorber layer by a substantial margin, since despite the concentrating effect of the light cone, the absorbing action of the material at that surface reduces the light intensity within the bulk, meaning that the light intensity at the surface is the most intense.

The inventor has further identified that the reason that an optical limiter material type camera is most vulnerable is when it is set to its largest aperture is not simply because the amount of incoming energy is likely to be greatest. Rather, at the camera's widest aperture, the laser energy

focusses onto the image sensor from the widest possible range of angles, meaning that it only concentrates into a highly intense beam very close to the image sensor and thus there is only a very short path-length through the optical limiter material through which the optical limiter material will be highly activated, and thus the non-linear material does not have such a strong overall attenuation effect.

The inventor has identified that the blackening/deformation surface effect can be useful in certain circumstances. In particular it is possible to position the front surface of the optical limiter material layer in such a position that when the aperture is at its widest, and the radiance of an incoming laser pulse is sufficient to cause damage to the image sensor, then that surface of the absorber will blacken and/or deform (in the region of the light cone only), and this will contribute towards reducing the radiance of laser light impinging onto a focal point on the image sensor, thus protecting the sensor.

However, the disadvantage of this would be that if the camera is set to a much smaller aperture (high f-number) and radiant laser light comes through the lens/aperture at a radiance that is at, say, only half the total power in the scenario above, then because this light will be focussed into a very narrow beam it will be extremely intense when it impinges the front surface of the absorber, and therefore will also burn/blacken/deform the absorber surface, and this is a worse outcome than if a thicker layer of absorber had been used (since an appropriately thick layer would provide even greater protection to the image sensor in this small aperture situation).

The inventor has further identified that it is possible to provide enhanced protection at the maximum (most vulnerable) camera aperture, whilst still providing strong protection at a small aperture. The object of the present invention is to solve this problem.

According to an aspect of the present invention there is provided a camera as set out in claim 1.

The invention works by providing two layers of (e.g. two-photon) non-linear material instead of one, with the surface position of the layer adjacent the sensor being arranged such as to enhance protection at the maximum camera aperture via a burn/blackening/deformation effect, whilst the second layer helps provide a required level of protection particularly at the smaller aperture size, and avoids unnecessary risk of damage to the first front surface when the aperture is small. The thickness of the second layer can be selected according to the level of protection required at the smaller aperture size.

This has the advantage that at the maximum camera aperture, the protection afforded to the camera is enhanced, whilst at a smaller aperture strong protection can still be provided.

The term “layer of non-linear optical material” means a layer of material and the material is such that at low light intensities the material transmits nearly all the light in a largely transparent and non-translucent manner such as to permit an image, such as a focal spot or airy pattern, to be formed on an image sensor behind it resulting from a ray of incident light, but at high light intensities it exhibits an effect which interferes with the transmission of the light to the focal spot. Depending on the material chosen the effect can be a non-linear increase in absorption (absorptivity of the material) with respect to light intensity. Alternatively or additionally, the effect can be a non-linear change in refractive index of the material with respect to light intensity, which would interfere with the tendency of the ray of light to focus to a small spot or airy pattern. Ample published literature exists to point the reader to select a material which exhibits at least one of these non-linear effects.

Optionally the non-linear material is a two-photon non-linear material, meaning that the effect results from the interaction of free-charges liberated by the absorption of two photons, such that the two liberated free charges interact to influence further photons of light, and due to the requirement for two free-charges to interact this is more likely to occur when there is intense light, which is why a two-photon optical material will generally be a non-linear optical material.

Typically the camera would be adapted to operate at a pre-set number of discrete aperture sizes. For example it might operate at only two specific aperture sizes (as an example F2 and F8), with the position of the first surface providing the enhanced protection at the wider/larger aperture (e.g. F2) and the two layers together providing the required protection at the smaller aperture (e.g. F8).

Preferably the optical limiter device is substantially adjacent to a front face (i.e. facing the lens arrangement) of the image sensor. However, if the lens arrangement provides an additional focal plane within the camera (e.g. within the lens arrangement itself) then there is the choice of placing the optical limiter in the aforementioned position, or at or adjacent to the additional focal plane. Indeed, both focal planes could be provided with optical limiting materials, and indeed both could be provided with a multiple layer optical limiter device as described herein.

The aperture of a camera is normally an iris. The term 'aperture size' covers circular, polygonal and similar aperture shapes common in the art, as well as any other shape, with the size being a measure related to the aperture area, and in any normal case (i.e. the aperture being an iris) the size is also related to the iris diameter (so a larger aperture size typically means a wider iris and vice versa). The term 'maximum effective' is used because if the aperture is able to open beyond a certain point, the amount of light passing through it then becomes limited by the size of one or more other optical elements in the lens arrangement, in the simplest possible case this would be the diameter of the lens itself.

The maximum effective aperture may in one embodiment simply be the largest effective aperture that movement of the aperture (iris) will in practice achieve. Alternatively the predetermined maximum effective aperture may be a pre-set arrangement (typically a pre-set iris setting) that is smaller than the maximum effective aperture that could physically be achieved. For example, if without the iris in place a particular lens arrangement may offer an f number of 1.2, however to avoid reduction in optical performance at the edges of the field of view (e.g. spherical and/or chromatic aberrations) it might be decided that the aperture (iris) will open only to an f-number of 1.4. In practice, the lens arrangement is designed to provide a desired level of performance at a chosen maximum f-number, and the aperture opens up to either the equivalent size or possibly very slightly wider, so there is usually little or no difference between the maximum aperture size and maximum effective aperture size.

Typically the iris is adapted to close to a minimum non-zero aperture size, and preferably this size is the smaller size aperture referred to above. Optionally the iris is adapted to switch between only two aperture sizes (the maximum effective aperture and the minimum smaller non-zero aperture). Generally, the position of the front surface of the first layer is arranged to extend the tolerable intensity range in the fully open aperture condition (M) and the second layer is arranged to protect the front surface of the first layer in the case that the iris is closed to the smaller non-zero aperture.

The optical limiter material is generally either a multiple-photon absorbing material, such as a two-photon absorber, or an excited state absorber material, such as a reverse saturable absorber. In more detail, the optical limiter material is generally a non-linearly absorbing material and/or a non-linear scattering material and/or a non-linear induced aberration material and/or a non-linear refractive index changing material. Any suitable optical limiter material can be used,

provided that it's surface (either the surface of the bulk of the material itself, or an added surface layer of a different material) is one which is vulnerable to optical radiation damage resulting in enhanced local optical limiting (e.g. attenuation and/or scattering). Preferably the vulnerable surface is the surface of the bulk of the optical limiter material itself. Experimentation has found that a wide range of optical limiting materials have greater sensitivity to optical damage compared to the bulk of the material (a range of suitable examples is provided herein). This is believed to be due to the reduced number of degrees of freedom of movement of free charge carriers generated by the absorption of photons, at the surface of the material as compared to in the bulk of the material, and generally the surface of typical optical limiter materials will either blacken or whiten in response to such damage threshold being exceeded – both of which provide the required extra reduction in optical transmission.

This vulnerable surface can be arranged at a suitable distance from the sensor surface, through simple trial and error to enhance the range of protection offered by the optical limiter, taking into account the maximum optical aperture that the camera is adapted to open its iris to. Furthermore, a suitable thickness of optical limiting material (which, again can be of any of the above described types) can be arranged in front of the vulnerable surface, so as to protect the vulnerable surface when the iris is at its smaller but non-zero aperture size arrangement (e.g. the minimum aperture that the camera is adapted or arranged to close to), and it is a matter of simple trial and error to choose a suitable thickness for this layer. Furthermore, rather than trial and error, modelling of the arrangement, as is common in the art, can be used to choose thicknesses of the selected materials which suit the damage threshold of the sensor and the aperture sizes that the iris is adapted or arranged to open to.

In practice the layers are either arranged (in the case of two layers separated by a gap which may be any transparent material such as air, glass or plastic etc. or even vacuum) such that the first layer has a front surface at which the crystalline properties of that first layer either entirely come to an end at a plane, or (in the case of two layers of the same material pressed together) there is a discontinuity in the bulk properties of that the crystalline (or polycrystalline) structure, and that discontinuity is in the form of a plane. What is required is a discontinuity in the bulk properties (non-linear parameters, crystalline structure and/or conductivity (axial conductivity with regards to the optical axis) and/or band gap), or the inclusion of a film of a material that blackens when subjected to sufficiently intense illumination. Whilst it has been found that the surface of an optical limiter material is more sensitive to damage than the bulk of that material, and so its own

surface may be used as the material that permanently reduces its transmission (e.g. blackens in the location of the focal spot), alternatively a different material may be introduced, such as a plastic, arranged so as to burn if subjected to sufficiently intense light, thereby providing the required permanent reduction in transmission (E.g. a white or black spot at the focal point of the laser light).

Whilst a non-zero separation distance between the optical limiter materials (of air, vacuum or transparent dielectric) is believed to enhance the effect thanks to the concentrating light cone passing from non-optical limiter material into optical limiter material, the effect is believed to work even without an actual separation provided that there remains a structural discontinuity in the bulk of the material (as would be the case when two flat surfaces of solid materials, are placed against each other) because at the discontinuity the free carriers in the optical limiter material have reduced freedom, causing the material to be more sensitive to damage from intense light as compared to the bulk of the optical limiter material. Additionally the effect is expected to work well if the two materials are different materials.

There is no absolute maximum gap thickness beyond which the principle could not be implemented since the size and geometry of cameras varies greatly, however greater than 10,000 μ m is not expected to be practical. The size of the gap however is not the key issue. The point is to A) correctly set the position of the first (and preferably any other) front surface(s), so as to enhance the protection offered by the materials at respective predefined f-numbers, or to provide so many gaps that the protection enhancement is achieved across a wide range of f-numbers, and B) to provide the relevant front surface(s) with reduced free charge mobility compared to the bulk of the respective optical limiter material, so that blackening and/or distortion of the front surface occurs immediately beyond the threshold level of illumination which the materials can otherwise (i.e. by means of non-linear absorption) protect an image sensor from at those respective f-numbers.

Optionally, the second layer of optical limiter material comprises a second front surface thereof, being of a material that provides for permanently reduced optical transmission to a focal point on the image sensor, through being optically damaged by intense light above a threshold intensity,

the second front surface being arranged at a second distance from the image sensor such that in the case (Case S) that:

the aperture is open at its Smaller aperture size and the camera is subject to a pulse of light from a pulsed laser source that is focussed by the lens onto a focal point on the image sensor;

the reduced optical transmission due to damage of the second front surface is effected in a third range of radiant intensity of light incident in through the lens arrangement (Intensity Range C);

and wherein:

in Case S the bulk of the optical limiter materials of the first and second layers are arranged to protect the image sensor from permanent damage in the range of up to a second maximum value of radiant intensity of light incident in through the lens arrangement (Intensity Range A'); and

The second distance is selected such that in Case S, the lower limit of Intensity Range C is at or proximal to the upper limit of Intensity Range A'.

This has the advantage that protection is further enhanced when the aperture is at its small aperture size (e.g. for use in bright daylight conditions).

Preferably in Case S, Intensity Range C begins in the upper quartile of Intensity Range A'. Ideally this approach is applied to the front surfaces of all of the layers.

Optionally the camera comprises a further layer (preferably three or more layers) of optical limiter material arranged between the first and second layers, each having a respective front face arranged to provide for protection of the image sensor from permanent damage across respectively enhanced ranges of intensities, at respective intermediate aperture sizes.

This has the advantage of providing enhanced protection at the maximum (E.g. F2) aperture, an intermediate (E.g. F3) aperture, with the layers together providing the required protection at the smallest aperture (e.g. F8).

The additional layer(s) provide enhanced protection at specific aperture sizes, and with greater numbers of layers the range of aperture sizes over which enhanced protection is afforded may provide a contiguous range of aperture sizes over which enhanced protection is afforded. This

enables the camera to operate with enhanced protection at more, preferably many aperture sizes, or even across a contiguous range of aperture sizes.

Optionally the adjustable optical aperture is configured to be selectable exclusively to discrete aperture sizes corresponding to the respective front faces.

This provides for a camera with optimised protection at each aperture size it operates at, thus providing for a more resilient camera that operates across a range of aperture sizes, and has protection optimised for any aperture selected.

Alternatively the adjustable optical aperture is configured to be selectable from any of a continuous range of aperture sizes, and wherein the front surfaces of each of the layers provides enhanced protection over the continuous range of aperture sizes.

This provides for greater flexibility to vary the aperture according to conditions, whilst still benefiting from enhanced protection across the range.

Preferably the second layer is thicker than the first layer, preferably by a factor of at least 4.

Investigation by the inventor has led to the identification that the first layer can advantageously be much thinner than the second layer, since it is the widest aperture situation which most benefits from enhanced protection, whilst operation at a small aperture would typically then require a much thicker second layer. Also if the camera operates across a continuous range of apertures, it is beneficial to offer enhanced protection at the maximum aperture situation only, but a thick second layer permits operation down to a much smaller aperture size.

Preferably the layers in order from the first (nearest to the image sensor) to the last (furthest from the image sensor) are in order of increasing thickness.

This has the advantage of providing enhanced protection at multiple apertures having decreasing aperture areas, each being of smaller area than the previous but in reducing amounts (for example F2, F4, F8 – each offering a quarter of the inlet area compared to the previous), thus a selection of aperture sizes with enhanced protection is provided that is more useful (in practical terms when adjusting for daylight, night-time and intermediate ambient brightness situations) than would otherwise be the case.

Optionally at least two of the layers are of the same optical limiter material. Preferably all of the layers are of the same material.

This offers optimal protection if the anticipated attack wavelengths expected at daytime and night time are no different.

At least one of the layers may be advantageously selected from the following materials, preferably all of the layers are selected from the following materials:

ZnTe in zincblende form; CdSe in wurtzite form; CdTe in zincblende form; CdTe in zincblend polycrystalline form; $\text{CdS}_{0.5}\text{Se}_{0.5}$ in wurtzite form; $\text{CdS}_{0.25}\text{Se}_{0.75}$ in wurtzite form; GaAs in zincblend form; ZnS in zincblend polycrystalline clear form; ZnS in zincblend polycrystalline yellow form; ZnSe in zincblend polycrystalline form; CdS in wurtzite form; and ZnO in wurtzite form.

These materials offer protection in the visible or near-visible wavelength bands and are solid and have a damage threshold of radiance which can be determined experimentally. Selecting one of these materials provides enhanced protection at a specific wavelength band in which that material has optimal properties. Generally the camera provides protection across a selected wavelength band, one example of which is the visible spectrum.

According to one embodiment the first front surface of the first layer is of optical limiter material. Typically in this case, the first front surface of the first layer is a front surface of the optical limiter material of the first layer.

The inventor has found through experimentation that optical limiter materials (in particular solid, e.g. crystalline or polycrystalline semiconductor, ones) have a different damage threshold at the front surface as compared to the bulk of the material. Thus the front surface of the optical limiter material behaves differently than the rest, and the front surface acts to self-damage, leading to a darkened and/or roughened surface, typically both.

Alternatively the first front surface of the first layer may be a polymer film arranged on the optical limiter material of the first layer.

An example of a suitable self-damaging material is a plastic film, which generally should be a transparent rather than translucent one, but may have a pigment or dye added to enhance its sensitivity. For example a thermoset plastic or a thermoplastic, for example containing a very

small quantity of black pigment. Other alternatives include other substantially transparent dielectrics capable of being damaged by intense radiation, as an example being transparent meltable wax or a coating of a type of oil that readily chars in response to heat. A carbon layer deposited by sputter coating method could also be applied to increase linear absorption at the surface only and therefore aid in lowering the surface damage threshold. By contrast most types of glass are unsuitable since they would have to be very strongly absorbing to be sufficiently damaged by intense light, which would limit the utility of the camera.

Optionally the first non-linear optical limiting material is a two-photon absorber non-linear optical limiting material. Preferably the first non-linear optical limiting materials is a two-photon absorber non-linear optical limiting material, and the second non-linear optical limiting materials is a two-photon absorber non-linear optical limiting material.

According to a second aspect there is provided a camera for operating resiliently in the event of a pulsed laser attack, the camera comprising, arranged along an optical axis thereof:

- A lens arrangement providing at least one focal plane within the camera;

- An image sensor arranged with a front thereof exposed to a focal plane of the lens arrangement;

- An adjustable optical aperture to the front of the image sensor, arranged to open to a predetermined wider effective aperture size, and to close to a smaller non-zero aperture size; and

- An optical limiter device substantially at a focal plane of the lens arrangement, comprising:

- A first two-photon optical limiter material layer arranged to protect the image sensor from permanent damage up to a first value of radiant intensity of light incident in through the lens arrangement (Intensity Range A), in the case that the aperture is open at its wider effective aperture size, and the camera is subject to a pulse of visible light from a pulsed laser source that is focussed by the lens onto a focal point on the image sensor (Case M); and

- A first front surface of the two-photon optical limiter material layer, being more vulnerable to damage from optical radiation than the bulk of the two-photon optical material of the two-photon optical limiter material layer, the front

surface being arranged to be optically damaged by intense light so as to provide local permanently reduced optical transmission, wherein the first front surface is arranged at a first distance from the image sensor such that in Case M, the reduced optical transmission due to such damage is provided across a second range of radiant intensity of light incident in through the lens arrangement (Intensity Range B);

Characterised in that:

The first distance is selected such that in Case M, Intensity Range B is adjacent to or partially overlaps Intensity Range A such as to provide enhanced protection in Case M; and

The optical limiter device comprises a second two-photon optical limiter material layer arranged in front of the first two-photon optical limiter material layer, so as to protect at least the first front surface in the case that the aperture is open at the smaller aperture size.

Preferably the second layer is thicker than the first layer, preferably by a factor of at least 4. Preferably the layers are of the same two-photon optical limiter material. Preferably the first front surface of the first layer is a front surface of the two-photon optical limiter material of the first layer. Preferably the first front surface of the first layer is a polymer film arranged on the two-photon limiter material of the first layer. Preferably in Case M, Intensity Range B begins in the upper half of Intensity Range A, preferably in the upper quartile, and most preferably substantially at the upper end of Intensity Range A.

This provides the benefit of avoiding unnecessary damage to the first front surface. For the same reason, preferably in Case S, Intensity Range C begins in the upper half of Intensity Range A', preferably in the upper quartile, and most preferably substantially at the upper end of Intensity Range A. Ideally this approach is applied to the front surfaces of all of the layers.

Generally the lower limit of Intensity Range B is substantially at the upper limit of Intensity Range A. This extends the intensity range across which the sensor is protected, but without significantly reducing the minimum intensity at which a permanent effect is caused by the incident light.

Generally, the second non-linear optical limiter material layer is arranged and sized such that in the case that the aperture is at its smaller non-zero aperture size, and the camera is subject to a pulse of light from a pulsed laser source that is focussed by the lens onto a focal point on the image sensor, the second layer protects the first front surface from permanent damage at a value (generally across a range of values) of radiant intensity of light incident in through the lens arrangement which in the absence of the second layer would otherwise cause permanent damage to the first front surface. This provides the sensor with enhanced protection compared to what would be achieved by an arbitrary choice of the position and size of the second/additional layer(s).

Thus, at large aperture (Case L), the first layer provides adequate protection until the intensity is too great for it to ensure protection of the sensor (N.B. non-zero attenuation will also be offered by the second layer, but the effect will be dominated by the first layer), at which point it's surface blackens (or is otherwise affected to permanently reduce transmission), and since the light comes in through the layer as a cone the position of this front surface must be selected so that the blackening (etc) effect kicks in only at the intensity which otherwise would be where damage to the sensor would begin. The location for the first surface will generally be much closer to the sensor (or focal plane) than would normally be chosen for a camera with two aperture settings, since for a small/smaller aperture a thick/thicker layer of material would ordinarily be chosen because the cone of light is very narrow and thus non-linear absorber material is needed further away from the sensor. Accordingly a second layer of non-linear absorber material is positioned to protect the first surface up to higher intensities than would otherwise blacken (etc) the first surface in case S.

Embodiments and advantages described with respect to the first aspect are equally applicable to the second aspect, and vice versa.

A preferred embodiment of the invention will now be described by way of example only, with reference to the figures, in which:

Figure 1 is a diagram of a conventional camera with an optical limiter material;

Figure 2 is a diagram of an embodiment of the present invention, showing two layers of optical limiter material;

Figure 3 is a diagram showing one layer of optical limiter material on an image sensor, showing certain measurements useful for calculating the positioning at which the front surface is at its damage threshold;

Figure 4 is a diagram showing one layer of optical limiter material on an image sensor, showing measurements useful for calculating the f-number inside a material; and

Figure 5 is a diagram showing one layer of optical limiter material on an image sensor, illustrating a ratio of fluences at different distances from the image sensor.

Turning to figure 1, a conventional camera 2 is shown with a laser pulse shown as a column of light 2 being focussed through a lens 3, passing through adjustable aperture 4 and converging conically through a layer of optical limiter material 6 to impinge on an image sensor 5. The optical limiter material is stimulated by the incident light to generate free charge carriers e.g. electrons (or holes in the free electron band of the crystalline lattice of the material). The free charge carriers interact with each other and with additional photons of the light beam/pulse to absorb (and/or scatter) those photons, with the effect that if/where the light beam is most intense the absorbance of the material is greatest. The thickness of the layer of the material 6 is optimised to be able to protect the image sensor 5 against a range of laser pulse intensities and across a range of wavelengths solely by means of the non-linear mechanism, such as multi-photon absorption or excited state absorption effects (in conjunction with the linear absorption coefficient bulk property of the material and the size of the aperture).

Figure 2 shows a camera according to a preferred embodiment of the present invention. The camera has the elements shown in figure 1 and like elements are given like numbering, however there is an additional feature – the additional layer of optical limiter material 7.

Furthermore the front surface of the first layer of optical limiter material (the layer closest to the image sensor) is positioned in such a manner that if a laser pulse is transmitted through the lens and through the aperture at its widest setting, with such a radiance that it would otherwise damage the image sensor, the effect of the first front surface 6 is to blacken or distort so as to absorb and/or scatter the incoming light, thereby offering enhanced protection to the image sensor. So, up to a threshold radiance level the two layers of optical limiter material operate to adequately protect the image sensor, and above that threshold radiance level the effect of the

first surface blackening and/or distorting contributes to further protection, thereby providing enhanced protection up to a greater level of radiance.

In practice this gives rise to a dark spot thereafter which is not ideal. However this has been found not to be as dark as might be anticipated, and is therefore not particularly problematic. If desired, a software solution, such as a non-uniformity correction, can be implemented to compensate for the reduced light reaching the image sensor through the darkened damage spot. This outcome is therefore greatly preferable to a damaged sensor which does not produce an image at all.

The camera has its second layer of optical limiter material 7 a distance away from the front surface 6a of the first layer 6. This distance can be very small, for example smaller than a micron, however the two layers should not be pressed together so firmly that they operate electrically as a bulk material. The gap between them can be air, vacuum, plastic, glass or any other transparent, clear, dielectric. In a preferred embodiment it is an air gap, preferably a very narrow air gap. In another preferred embodiment it is a film of transparent plastic.

Whilst the distance between the image sensor 5 and the first front surface 6a is selected such that in the aperture open situation, beyond the threshold for damage protection of the image sensor as a result of the bulk properties of the optical limiter materials, the front surface reacts to an incoming pulse of light by blackening and/or deforming, such as to offer enhanced protection to the image sensor beyond that threshold.

The second layer of optical limiter material 7 offers protection to the image sensor when the aperture is set at a smaller aperture size.

In one preferred embodiment therefore the camera is adapted to select between any one of a predetermined discrete aperture sizes (or f-numbers), and the first front surface is arranged to offer enhanced protection at the maximum aperture size (smallest f-number), and the second layer provides the required protection at the smaller predetermined aperture size.

There could be three or more layers, with at least all but the last one optimised to blacken and/or distort in a manner so as to provide an enhanced level of protection at a predetermined respective aperture size. Generally each layer will be thicker than the last so as to provide a more optimal selection of aperture sizes for use across a range of ambient brightnesses that vary by many orders of magnitude.

With reference to figures 3 to 5, an explanation will be provided as to how to appropriately select thicknesses of layers of optical limiter materials.

The fluence at the front surface of a material, at a distance x_1 away from the detector plane is given by:

$$\text{Fluence (@ } x_1) = \frac{\text{Energy}}{\text{Area}} = \frac{E_{in}}{\pi \left(\frac{x_1}{2F_{effective}} \right)^2}$$

where E_{in} is the input energy in Joules, and $F_{effective}$ is the effective F-number in the material bulk.

The fluence at x_1 must be greater than the damage threshold of the material LDT_{mat} (units Jcm^{-2}):

$$\frac{E_{in}}{\pi \left(\frac{x_1}{2F_{effective}} \right)^2} > LDT_{mat}$$

$$\therefore x_1 < 2F_{effective} \sqrt{\frac{E_{in}}{\pi LDT_{mat}}}$$

Given an F-number incident at the first surface of the material, $F_{effective}$ is given as:

$$F_{effective} = \sqrt{\frac{n^2}{4} (4F^2 + 1) - \frac{1}{4}}$$

Worked example:

From experimental data, when 6.36uJ of 10ns 532nm pulses are focussed at the back of a 4mm ZnSe material in an F8 configuration, macroscopic front surface damage can be observed under a 20x microscope objective. This gives an approximate macroscopic damage threshold of $22mJcm^{-2}$.

For F-numbers of 2.8, 5.6, 8, and 10, and input energies derived from the $0.1Jcm^{-2}$ damage threshold of a silicon camera (see table below), the front surface of each layer should be placed

at $x = 58\mu\text{m}$, 0.23mm , 0.47mm , and 0.74mm , or less in order to achieve front surface damage to the protection material before the sensor itself is damaged

The following values are the theoretical damage input energies, given a 0.1Jcm^{-2} damage threshold (silicon, 10ns , 532nm) and perfect lens:

F-number of 2.8: 10.4nJ ,

F-number of 5.6: 41.5nJ ,

F-number of 8: 84.7nJ , and

F-number of 10: 132nJ .

As the damage threshold of the protection material and camera is wavelength dependant, these x distances are optimised for one wavelength (532nm).

Placing the each surface closer to the detector plane would serve to cause sacrificial damage to the material earlier (at lower energies).

Referring now to figure 4, the effective F-number inside a material can be determined. This calculation is done to determine $F_{\text{effective}}$ from the input F-number and refractive index of the material. This can then be substituted into the main equation, as follows:

$$F = \frac{1}{2\tan\theta}$$

$$F' = \frac{1}{2\tan\varphi}$$

where F' is another notation for $F_{\text{effective}}$.

Snell's law gives:

$$\sin\theta = n\sin\varphi \quad \text{and} \quad \sin\varphi = \frac{\sin\theta}{n}$$

Using the rules:

$$\tan\varphi = \frac{\sin\varphi}{\cos\varphi} \quad \text{and} \quad \sin^2\varphi + \cos^2\varphi = 1$$

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$$\therefore \tan \varphi = \frac{\sin \varphi}{\sqrt{1 - \sin^2 \varphi}}$$

Substituting into (2):

$$F' = \frac{1}{2 \frac{\sin \varphi}{\sqrt{1 - \sin^2 \varphi}}}$$

Write $\sin \varphi$ in terms of $\sin \theta$:

$$F' = \frac{1}{2 \frac{\frac{\sin \theta}{n}}{\sqrt{1 - \frac{\sin^2 \theta}{n^2}}}}$$

Simplifying:

$$F' = \frac{n \sqrt{1 - \frac{\sin^2 \theta}{n^2}}}{4 \sin^2 \theta}$$

$$(F')^2 = \frac{n^2 - \sin^2 \theta}{4 \sin^2 \theta} = \frac{n^2}{4 \sin^2 \theta} - \frac{1}{4}$$

Writing $\sin^2 \theta$ in terms of $\tan \theta$ so we can re-arrange for F:

$$\tan \theta = \frac{1}{2F} = \frac{\sin \theta}{\cos \theta} = \frac{\sin \theta}{\sqrt{1 - \sin^2 \theta}}$$

$$\frac{1}{4F^2} = \frac{\sin^2 \theta}{1 - \sin^2 \theta}$$

$$1 - \sin^2 \theta = 4F^2 \sin^2 \theta$$

$$1 = \sin^2 \theta (4F^2 + 1)$$

$$\sin^2 \theta = \frac{1}{4F^2 + 1}$$

Substituting back in:

$$(F')^2 = \frac{n^2}{4 \left(\frac{1}{4F^2 + 1} \right)} - \frac{1}{4}$$

Simplifies to:

$$(F')^2 = \frac{n^2}{4}(4F^2 + 1) - \frac{1}{4}$$

Referring now to figure 5, the ratio of radiances between DL (the diffraction-limited spot – the best theoretical focus from an ideal lens) spot and a plane some distance x away can be determined.

This ratio can be used to see the fluence at x_1 when the fluence at the DL spot is the damage threshold. If the fluence at x_1 is greater than the LDT_{material} (Laser Damage Threshold of the protection material) at the point of damage threshold fluence, then the material will provide sacrificial protection before the camera is damaged. If it doesn't, the material could still prevent damage to the sensor through other non-linear mechanisms, such as absorption and refraction, but would be sub-optimal.

The derivation is as follows:

$$\frac{D}{f} = \frac{d}{x}$$

$$d = \frac{Dx}{f} = \frac{x}{f}$$

$$Fluence = \frac{4E_{in}}{\pi \left(\frac{x}{f}\right)^2}$$

$$Fluence_{DL} = \frac{E_{in}}{\pi(1.22\lambda F)^2}$$

$$\frac{Fluence}{Fluence_{DL}} = \frac{4E_{in}}{\pi \left(\frac{x}{f}\right)^2} \times \frac{\pi(1.22\lambda F)^2}{E_{in}}$$

$$= \frac{4(1.22)^2(\lambda^2 F^2)F^2}{x^2}$$

$$\frac{Fluence}{Fluence_{DL}} \approx \frac{6\lambda^2 F^4}{x^2}$$

More generally, there is provided a camera for operating resiliently in the event of a pulsed laser attack, comprising an adjustable optical aperture (e.g. iris) and an optical limiter device. The optical limiter comprises two layers of optical limiter material, and at least one of them has its front surface that is vulnerable to high intensity light, such that in a maximum-aperture size (lowest f number) situation if an incoming laser pulse was sufficiently intense to otherwise damage the image sensor, then this would instead cause blackening and/or distortion to that location on that front surface of the absorber material, thereby offering enhanced protection to the image sensor.

Optionally the second layer is also arranged to provide similarly enhanced protection at a smaller predetermined aperture size (at a higher f number). There may be more than two layers each arranged to provide enhanced protection at a specified aperture size in which case the camera is adapted to switch between those aperture sizes. There can potentially be so many layers, that they provide enhanced protection across a continuum of aperture sizes.

Whilst the blackened and/or distorted patch that is formed leads to a dark spot on the resulting images and this persists afterwards, it has been found that this can be partially addressed using software and is far preferable to the image sensor not working.

CLAIMS

1. A camera for operating resiliently in the event of a pulsed laser attack, the camera comprising, arranged along an optical axis thereof:

A lens arrangement providing at least one focal plane within the camera;

An image sensor arranged with a front thereof exposed to a focal plane of the lens arrangement;

An adjustable optical aperture to the front of the image sensor, arranged to open to a predetermined larger effective aperture size, and to close to a smaller non-zero aperture size; and

An optical limiter device, operable across a predetermined wavelength band, substantially at or adjacent to a focal plane of the lens arrangement, comprising:

A first non-linear optical limiter material layer wherein the bulk of the non-linear optical limiter material thereof is arranged to protect the image sensor from permanent damage up to a first value (Intensity Range A) of radiant intensity of light incident in through the lens arrangement, in the case that the aperture is open at its Larger effective aperture size, and the camera is subject to a pulse of light from a pulsed laser source that is focussed by the lens onto a focal point on the image sensor (Case L); and

A first front surface of the non-linear optical limiter material layer, being more vulnerable to damage from optical radiation than the bulk of the non-linear optical material of the non-linear optical limiter material layer, the front surface being arranged to be optically damaged by intense light so as to provide local permanently reduced optical transmission, wherein the first front surface is arranged at a first distance from the image sensor such that in Case L, a permanent reduction in optical transmission by means of such damage is effected in the event of incident light within a second range (Intensity Range B) of radiant intensity of light incident in through the lens arrangement;

Characterised in that:

The first distance is selected such that in Case L, the lower limit of Intensity Range B is at or proximal to the upper limit of Intensity Range A, such as to protect the image sensor in Case L from permanent damage up to a second value of radiant intensity of light that is higher than the first value; and

The optical limiter device comprises a second non-linear optical limiter material layer arranged in front of the first non-linear optical limiter material layer, so as to provide additional protection from incident light to at least the image sensor, at least in the case that the aperture is at the smaller aperture size.

2. The camera of claim 1 wherein the second layer is thicker than the first layer.
3. The camera of claim 2 wherein the second layer is thicker than the first layer by a factor of at least 4.
4. The camera of any preceding claim wherein the layers are of the same non-linear optical limiter material.
5. The camera of any preceding claim where in the first front surface of the first layer is a front surface of the non-linear optical limiter material of the first layer.
6. The camera of any one of claims 1 to 4 wherein the first front surface of the first layer is a polymer film arranged on the non-linear optical limiter material of the first layer.
7. The camera of any preceding claim wherein the in Case L, the lower limit of Intensity Range B is in the upper quartile of Intensity Range A, where Intensity Range A is taken to have a lower limit of zero.
8. The camera of any one of claims 1 to 6, wherein the lower limit of intensity range B is substantially at the upper limit of intensity range A.
9. The camera of any one of the preceding claims, wherein the second non-linear optical limiter material layer is arranged and sized such that in the case that the aperture is at its smaller non-zero aperture size, and the camera is subject to a pulse of light from a pulsed laser source that is focussed by the lens onto a focal point on the image sensor, the second layer protects the first front surface from permanent damage at a value of radiant intensity of light incident in through the lens arrangement which in the absence of the second layer would otherwise cause permanent damage to the first front surface.
10. The camera of any one of the preceding claims, wherein the first non-linear optical limiting materials is a two-photon absorber non-linear optical limiting material, and the second non-linear optical limiting materials is a two-photon absorber non-linear optical limiting material.

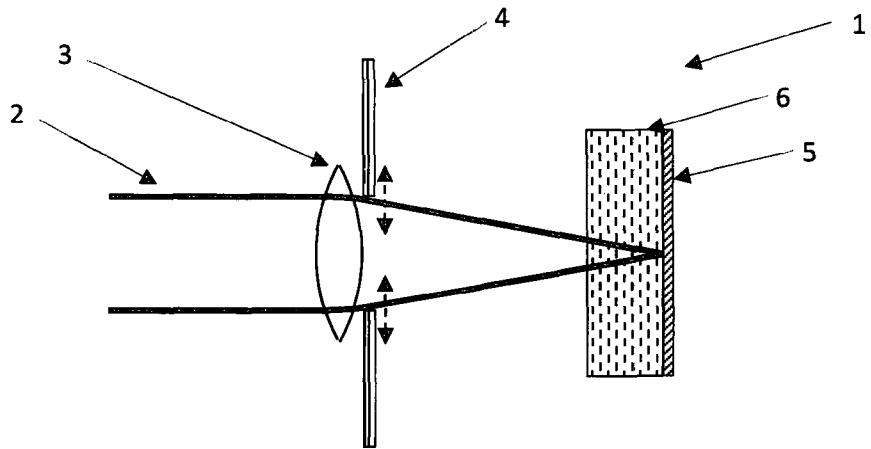


Fig 1. PRIOR ART

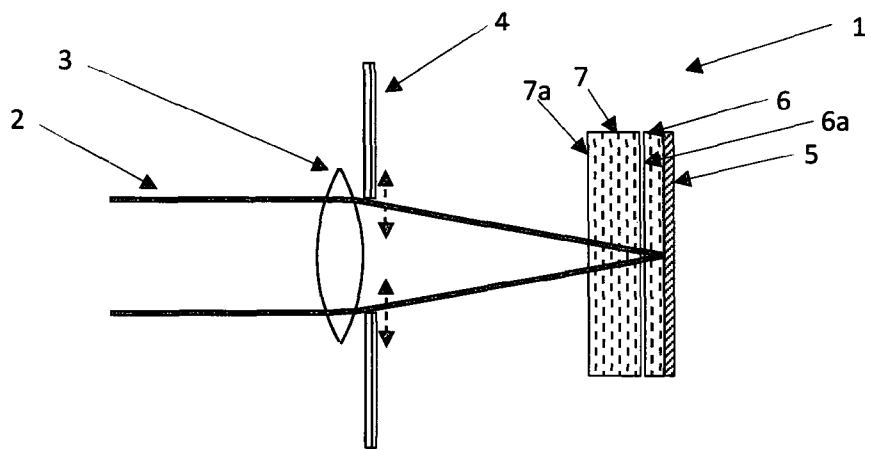


Fig 2.

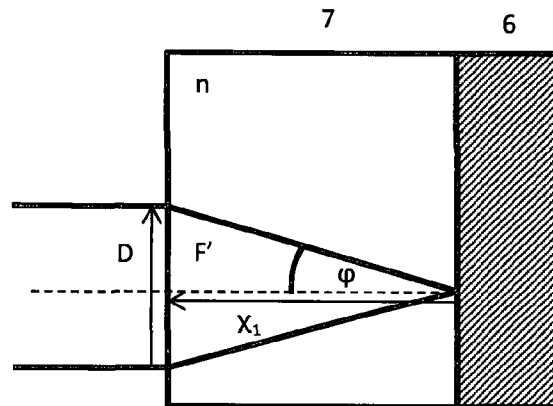


Fig 3.

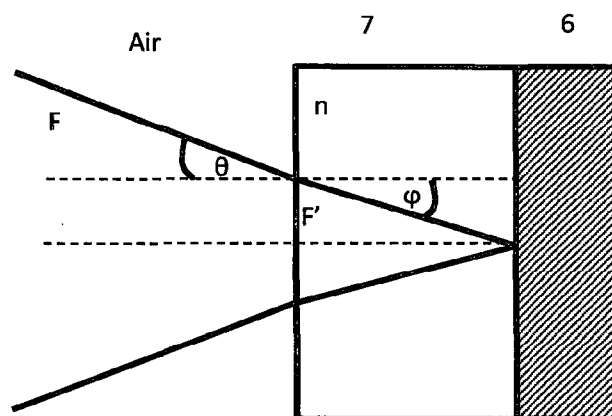


Fig 4.

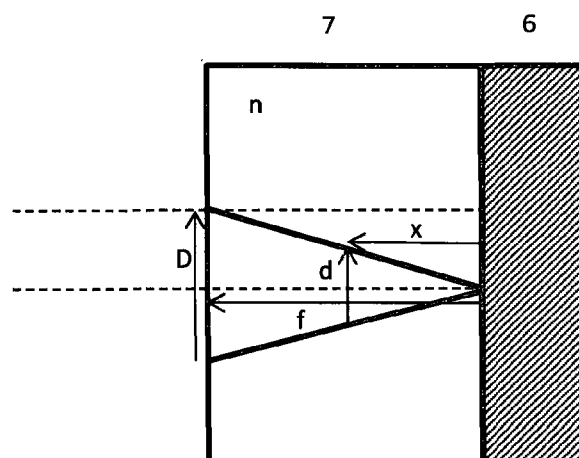


Fig 5.

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2020/000013

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B26/02 G02F1/35
ADD.

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)
G02B G02F

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)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ALI A. SAID ET AL: "Self-protecting optical limiters using cascading geometries", SPIE - INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING. PROCEEDINGS, vol. 1692, 18 August 1992 (1992-08-18), pages 37-43, XP055678672, US	1-3,5, 7-10
Y	ISSN: 0277-786X, DOI: 10.1117/12.138066 ISBN: 978-1-5106-3377-3 the whole document ----- -/--	4,6



Further documents are listed in the continuation of Box C.



See patent family annex.

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

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

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

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

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Date of the actual completion of the international search

30 April 2020

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14/05/2020

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INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2020/000013

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	MILES P A: "BOTTLENECK OPTICAL LIMITERS: THE OPTIMAL USE OF EXCITED-STATE ABSORBERS", APPLIED OPTICS, OPTICAL SOCIETY OF AMERICA, WASHINGTON, DC, US, vol. 33, no. 30, 20 October 1994 (1994-10-20), pages 6965-6979, XP000476194, ISSN: 0003-6935, DOI: 10.1364/AO.33.006965 page 6977, column 1, paragraph 3 - page 6978, column 1, paragraph 3; figure 18 -----	4
Y	US 2014/036369 A1 (USHINSKY MICHAEL [US] ET AL) 6 February 2014 (2014-02-06) paragraph [0009] paragraph [0013] -----	6
Y	US 2015/171234 A1 (USHINSKY MICHAEL [US] ET AL) 18 June 2015 (2015-06-18) paragraph [0005]; figure 7 -----	6

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2020/000013

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