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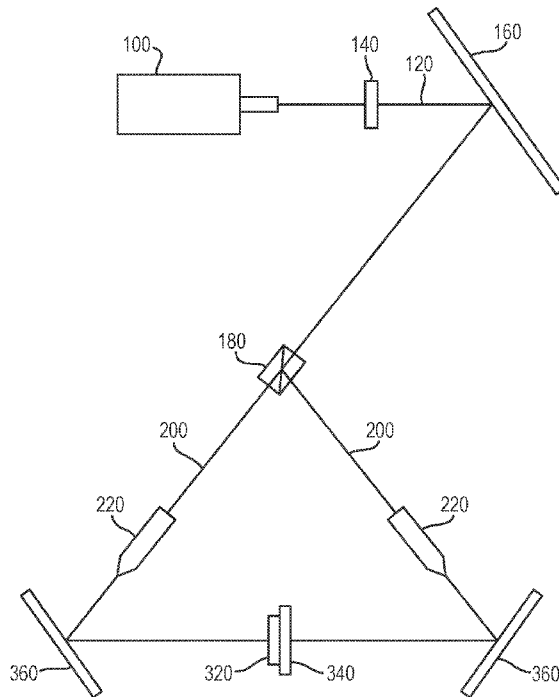
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(54) Title: FILTERS FOR LASER PROTECTION

Fig. 2



(57) Abstract: A method of forming a conformable filter, comprising the steps of: - selecting at least a first wavelength corresponding to a predetermined laser threat; - providing a conformable photosensitive film (320) and exposing said film to radiation from a focused laser source (100) of said first wavelength to create a first filter region therein configured to substantially block incident radiation thereon substantially only of said first wavelength while substantially allowing other visible wavelengths to be transmitted; - selecting a bandwidth corresponding to a first predetermined wavelength band including said first wavelength and exposing said polymeric film (320) to radiation from one or more further laser sources of respective different wavelengths within said first predetermined wavelength band to create a notch filter region therein, including said first filter region, said notch filter region being configured to substantially block incident radiation thereon at a wavelength within said first predetermined wavelength band whilst substantially allowing visible wavelengths outside of said first predetermined wavelength band to be transmitted therethrough.

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FILTERS FOR LASER PROTECTION

The present invention relates generally to filters for laser protection and, more particularly, to such filters formed by holographic exposure of a photosensitive film or films by one or more lasers, and to a method of forming
5 such filters.

It is known from, for example, US2014/0292467, to provide a generally transparent filter comprising a nanoparticle metamaterial structure such that a particular wavelength of electromagnetic radiation may be blocked. The use of such a filter at the windscreen (or windshield) of an aircraft, for example,
10 protects against laser threats, which may otherwise damage pilot eyesight or temporarily dazzle the pilot. However, this method of forming laser protective/blocking films complex and costly, and typically only permits blocking of one or up to two laser wavelength bands. Furthermore, the film is generally rigid, and not easily conformable to a curved shape of a typical windscreen.

It is also known from, for example, US2014/0009827, to provide a
15 generally transparent, conformable filter formed by holographic exposure of a photosensitive polymeric film by a plurality of coherent radiation sources for the purpose of forming eyeglasses for viewing stereoscopic images. However, there are a number of issues with the described method which make it unsuitable for
20 forming laser protective/blocking filters of the type described above. Firstly, the bandwidth (or 'wavelength band') of blocked wavelengths is inevitably relatively high which means that the overall 'colour' of the resultant film is quite pronounced and the visible light transmission (%) is relatively low (can be as low as 15%). This is clearly undesirable, and in many cases unacceptable,
25 particularly for the application referenced above – it is self evident that the pilot must be able to see clearly through the aircraft vehicle, for example.

Aspects of the present invention seek to address at least some of these issues and, in accordance with a first aspect of the present invention, there is provided a method of forming a conformable filter, comprising the steps of:

- 30 - selecting at least a first wavelength corresponding to a predetermined laser threat;

- providing a conformable photosensitive film and exposing said film to radiation from a focused laser source of said first wavelength to create a first filter region therein configured to substantially block incident radiation thereon substantially only of said first wavelength;
- 5 - selecting a bandwidth corresponding to a first predetermined wavelength band including said first wavelength and exposing said polymeric film to radiation from one or more further laser sources of respective different wavelengths within said selected bandwidth to create a notch filter region therein, including said first filter region,
10 said notch filter region being configured to substantially block incident radiation thereon at wavelengths within said first wavelength band whilst substantially allowing visible wavelengths outside of said first wavelength band to be transmitted therethrough.

Thus, by means of the claimed invention, the filter notch filter region can
15 be formed very precisely to block a relatively very small bandwidth of radiation around, or including, a specifically selected wavelength. As a result, even if a number (e.g. three or more) of such notch filter regions are provided in the same polymeric film, the visible light transmission is retained at at least 70% because the 'notch' size (i.e. the bandwidth of blocked radiation) can be made
20 so precisely and so small.

The film may be formed of a photosensitive polymer material, which may have a visible light transmission of at least 85 % and may have a thickness of 1 to 100 micrometers.

In accordance with another aspect of the present invention, there is
25 provided a conformable filter formed by the method substantially as described above.

The filter may additionally be configured to prevent transmission of radiation in a second predetermined wavelength band covering a selected second predetermined laser threat.

30 In an exemplary embodiment of the invention, the first predetermined wavelength band may cover, or be centred on, 532nm. The second predetermined wavelength band may cover, or be centred on, 445nm.

The filter may be additionally configured to prevent radiation in a third predetermined visible radiation band covering the wavelength of a third predetermined laser threat. In this case, the third predetermined visible wavelength band may cover, or be centred on, 650nm.

5 More generally, the filter, thus formed, may be configured to prevent radiation from three or more predetermined wavelength bands of bandwidth 10nm or less.

In an exemplary embodiment, the filter may be comprised of a single layer of material adapted or configured for preventing the transmission of the
10 predetermined visible wavelength band or bands.

The bandwidth of at least one of the predetermined wavelength bands may be less than 10nm, for example, 5 nm. However, the present invention is not necessarily intended to be limited in this regard, and larger bandwidths may be desirable in certain situations and comply with certain specifications.

15 Advantageously, the filter may have an optical density of at least 2 at the first predetermined wavelength band; and in one exemplary embodiment, the filter may have an optical density of at least 2 at each predetermined wavelength band. However, it will be appreciated that lower optical densities for one or more of the predetermined wavelength bands may be desirable to
20 comply with some specific specifications.

In one exemplary application, the filter may be provided as a conformal film for coupling to a window; and, in accordance with another aspect of the invention, there is provided a multi-layered window comprising a filter substantially as described above wherein the filter is interposed between layers
25 of the window.

The present invention extends to a window for a vehicle, the window comprising a filter substantially as described above.

These and other aspects of the present invention will be apparent from the following specific description, in which:

Figure 1 is a schematic perspective view of a filter according to an exemplary embodiment of the present invention applied to a substrate;

Figure 2 is a schematic diagram illustrating a process of forming a filter region for use in a method according to an exemplary embodiment of the present invention;

Figure 3 is a schematic perspective view of the filter of Figure 1 configured to detect radiation;

Figure 4 is a graph in which the transmission characteristic of the filter of Figure 1 is plotted, and

Figure 5 illustrates schematically the filter of Figure 1 implemented on the windscreen of a vehicle.

With reference to Figure 1, there is shown a layer of filter material applied to a first face of a substrate 20 to provide a window 100 adapted for mitigating laser threats such as dazzle. The substrate 20 is substantially transmissive of visible light (for example, it may have a visible light transmission (VLT%) of around 90% of normally incident light) and may be formed, for example, from a glass or plastics material such as polycarbonate.

The filter material 10 is an interference filter formed by a method according to an exemplary embodiment of the present invention for holographically exposing a photosensitive film with a plurality of lasers having a set of predetermined wavelengths, advantageously (but not necessarily essentially) within a selected wavelength band of bandwidth 10nm or less.

Conformable photosensitive (e.g. polymeric) films for use in exemplary embodiments of the present invention will be known to a person skilled in the art, and the present invention is not necessarily intended to be limited in this regard. Such photosensitive polymeric films are provided having varying degrees of inherent visible light transmission (VLT), ranging from less than 70% (and possibly, therefore, having a coloured tinge) up to 95% or more (and being substantially colourless and transparent). In respect of the present invention, suffice it to say that a photosensitive flexible/conformable (e.g. polymeric) film is selected having an inherent VLT of, for example, at least 85%. The film typically has a thickness of 1 to 100 micrometers. Thinner, currently known,

films may not achieve useful optical densities. Indeed, in respect of currently known photosensitive polymeric films, the degree to which a selected radiation wavelength can be blocked (i.e. the effectiveness of a filter region formed therein) is determined by the thickness and refractive modulation index of the film and, also, by the optical design. Thus, the filter region thickness is ideally 5 matched to the application and the potential power of the source from which protection is required (which may be dictated, at least to some extent, by the minimum distance from the target platform the laser threat may realistically be located and this, in turn, is dictated by application). In general, thicker films and 10 films with higher refractive modulation indices would be selected if it were required to provide protection from higher power radiation sources or to provide greater angular coverage, but this might then have a detrimental effect on the inherent VLT of the film, so a balance is selected to meet the needs of a specific application.

15 Whilst the present detailed description makes specific reference to a vehicle window, it is to be understood that the principles and techniques disclosed hereinafter are equally applicable to other applications such as eye-glasses, contact lenses, sensor protection films, screens or pull-down visors, laser designators, etc. and the present invention is not necessarily intended to 20 be limited in this regard. It will be understood by a person skilled in the art that the following principles and techniques can be readily adapted to different laser protective/blocking applications, simply by selection of the film and the specific wavelengths to which the film is exposed to form the filter region(s).

Thus, once the film has been selected, the required holographic 25 exposure thereof is effected to form the filter regions of a required notch filter region to be provided thereon. Referring to Figure 2 of the drawings, distinct filter regions defining a notch filter region of a predetermined bandwidth (e.g. 5nm) may be formed by exposing the film to the intersection of two counter propagating laser beams for each of a set of laser wavelengths within the 30 selected wavelength band having a selected spectral bandwidth. Each laser 100 (of a wavelength within the selected spectral bandwidth) produces a laser beam 120 which is controlled by a shutter 140. The laser beam 120 is directed by a mirror 160 into a beam splitter 180 wherein the beam is divided into equal

beam segments 200. Each beam segment 200 passes through a microscope objective 220 and is then reflected by a respective mirror 360 onto the photosensitive polymer film 320. Other optical devices (not shown) may be provided between the microscope objective 220 and the mirror 360 to, for example, focus or diverge the respective beam segments 200, as required. Furthermore, masking or other limiting techniques may be utilised to limit the extent or thickness to which the film is exposed to the beam segments 200, as will be understood by a person skilled in the art. As a specific (non limiting) example, if it is required to provide a notch filter region of bandwidth 5nm around 520nm, then a plurality of lasers 100 may be used to produce the notch filter region of (purely by way of example) 517.5nm, 518nm, 518.5nm, 519nm, 519.5nm, 520nm, 520.5nm, 521nm, 521.5nm, 522nm and 522.5nm. The above-described exposure process may be performed consecutively for each of these laser wavelengths or, in other exemplary embodiments, the exposures may be performed substantially simultaneously. Other apparatus for forming a holographic filter region at each specified wavelength is known and could, alternatively, be used.

Once the exposure process has been completed, the resultant hologram can be fixed by, for example, a bleaching process.

The transmission characteristic (which may alternatively be referred to as the transfer function) of visible electromagnetic radiation incident on the filter is illustrated in Figure 3. The transmission intensity relative to incident radiation intensity is shown on the y-axis and the wavelength of the incident radiation is shown on the x-axis.

As can be seen on the plot, across the range of wavelengths the intensity of the transmitted radiation is close to 100% of that which is incident. In general a VLT% of 90% would be acceptable if 100% was not feasible.

There are three distinct notches in the transmission characteristic associated with three wavelength bands. These are in particular a 10nm band centred on 455nm, a 10nm band centred on 532nm and a 10nm band centred on 650nm. In general any three notches from the group consisting of 405 nm, 455 nm, 520 nm, 532 nm, and 650 nm may be selected. Further, notches may

be chosen to coincide with any expected laser threat wavelength. Still further, the bandwidth may be 5 nm.

At the centre of each of these bands, the intensity of the transmitted radiation is at a minimum and has an optical density of approximately 3, which is equivalent to 0.1% of the initially incident radiation.

With reference to Figure 4 there is shown generally at 201 a window. The window 200 comprises a transparent substrate 20 a first face of which has been coupled a radiation detector in the form of a detector layer 30.

Coupled to the opposite face of the detector layer 30 there is provided a layer of the holographic filter material 10.

As such the substrate 20, detector layer 30 and filter material 10 can be considered as a stacked multi-layer structure.

The detector layer 30 may comprise an array of photodetectors 32 distributed so as to extend substantially across the window 200. The photodetectors 32 are sufficiently small to be substantially invisible to the casual observer (though in practice there may be some reduction on the VLT%). Each photodetector is electrically connected to a processor module 34. In some embodiments, including the present one, each photodetector is uniquely connected to a unique port on the processor module 34.

The processor module 34 is, in turn, connected to an alert module 36.

Figure 5 shows a window 201 as shown in Figure 4 deployed as a windscreen on a vehicle V, which in this example is an aircraft. A pilot P is positioned behind the windscreen and a laser beam L, having a wavelength of 532 nm, is shown pointing at the windscreen. Laser beam L will have some degree of divergence as the beam propagates through the atmosphere, which will result in a certain 'spot size' observed at the windscreen.

In operation the window 201 may be used to mitigate the effects of the laser beam L, and alert the pilot to the existence of the laser threat.

In particular, as the laser beam L propagates onto the window 201 it will pass through the substrate 20 and into the detector layer 30 where some laser light will fall on one or more of the photodetectors 32 (depending on spot size).

The laser light subsequently propagates from the detector layer 30 and on the filter 10 where the light becomes substantially attenuated. Assuming the filter 10 to have the transmission characteristics shown in Figure 3 and the laser beam L to be a green laser of 532 nm, the laser beam L will be attenuated to
5 0.1% of its original intensity.

Accordingly, the pilot P is able to look out of the windscreen with a reduced chance of the laser beam L harming his or her sight, or distracting him or her from flying the plane safely.

Meanwhile, the laser light having fallen on certain photodetectors 32, an
10 electrical signal is generated at each illuminated detector 32 and sent to the processing unit 34. At the processing unit 34 the electrical signals received from the illuminated photodetectors 32 are analysed to confirm or deny the detection of a laser beam. In this case, the processing module 36 generates a signal confirming the presence of the laser beam and relays this to the alert module
15 36.

Each photodetector 32 can have a unique location at the filter, registered with the processor module such that signals from each photodetector 32 can be correlated with a certain location at the filter. Further this location can be correlated with a particular point on the window provided the relationship
20 between the window and the filter is registered at the processing module. Thus the processing module can determine, from detecting which photodetectors are illuminated, not only the presence of a threat but also the general dimensions of the 'spot' and where on the window the illumination is occurring. Some information relating to the source of the threat can be derived from such
25 measurements. If embodiments are provided with layers of photodetectors, it may be possible to establish more confident estimates of the threat location.

In the present embodiment the photodetectors 32 are configured for detecting radiation at the predetermined wavelength or predetermined wavelengths. For example the photodetector 32 could be configured to send a
30 signal only if 527- 537 nm radiation illuminated it. As such the system needs less noise-rejection provisions and/or can provide fewer false positive signals.

Upon receiving the signal confirming the presence of the laser beam, the alert module issues an alert to notify the pilot P (or another operator) of the laser beam. Such alert could be a visual alert (for instance on an instrument in the cockpit) and/or an audible alert. Such alert could be a signal sent (e.g. by an
5 RF transmitter within the alert module) to a further aircraft or a further element of aerospace infrastructure such as an Air Traffic Control base.

Accordingly, should the pilot be otherwise unaware of the laser beam (for instance because it is sufficiently attenuated by the filter 10 to be negligible within the vehicle) the alert will inform as to the existence of the threat and
10 further action (reporting to ground based security personnel, warning other aircraft) can be taken to address or remove the threat.

As an alternative to window 200, the window 100 may be provided as the windscreen in vehicle V. Here there is no detection layer 30 and so there can be no automatic alert or detection of the laser threat.

15 Nonetheless the holographic filter 10 will function to attenuate the intensity of the laser beam L and thereby protect the pilot.

The above discussion has provided an overview of how the present invention may mitigate the threat of laser beams in various applications.

Presently various lasers are commercially available which could be used
20 against a number of targets at a number of different stand-off ranges. The likely distance and the power of the laser determine how effective the filter needs to be in order to prevent injury to the onlooker. An intensity-at-eyeball of 0.001 W/cm^2 or less should be sufficient to prevent eye damage.

Table 1 shows, for a 3 W laser with 0.5 mrad beam divergence and no
25 atmospheric loss at various stand-off distances, the calculated minimum optical densities (OD) such that damage to the eye can be avoided by blinking (i.e. damage is negligible at this OD unless exposure is greater than 0.5 s, which is a determined minimum multiplied by a factor of safety of 2), and such that there is enough protection to render negligible the risk of damage from a 10 second
30 exposure. Accordingly suggested ranges for ODs are proposed.

Distance (m)	Beam diameter (mm)	'Spot' Size (mm ²)	Intensity (W/Cm ²)	Typical Application	min OD for 0.5s exposure	min OD for 10s exposure	Example OD ranges (to nearest 0.5)
0	3	7.1	42.4	n/a	4.03	4.63	4.5-6.0
5	6	23.8	12.6	Car/train/bus	3.50	4.10	3.5-5.5
10	8	50.3	6.0	Car/train/bus	3.18	3.78	3.5-5.5
50	28	615.8	0.5	Car/train /bus/aircraft	2.10	2.70	2.5-4.0
100	53	2206.2	0.1	Car/train /bus/aircraft	1.40	2.00	1.5-3.5
500	253	50272.6	0.006	Aircraft	0.18	0.78	0.5-2.5
1000	503	198712.8	0.002	Aircraft	n/a	0.30	0-1.5

Table 1

Table 2 shows, for a 1 W laser with 1.2 mrad beam divergence and no atmospheric loss at various stand-off distances, the calculated minimum optical densities (OD) such that damage to the eye can be avoided by blinking (i.e. damage is negligible at this OD unless exposure is greater than 0.5 s , which is a determined minimum multiplied by a factor of safety of 2), and such that there is enough protection to render negligible the risk of damage from a 10 second exposure. Accordingly suggested ranges for ODs are proposed.

10

Distance (m)	Beam diameter (mm)	'Spot' size (mm ²)	Intensity (W/Cm ²)	Typical application	min OD for 0.5s exposure	min OD for 10s exposure	Example OD ranges (to nearest 0.5)
0	3	7.1	14.1	n/a	3.55	4.15	4.0-5.5
5	9	63.6	1.57	Car/train/bus	2.59	3.20	3.0-4.5
10	15	176.7	0.57	Car/train/bus	2.15	2.76	2.5-4.5
50	63	3117.3	0.03	Car/train /bus/aircraft	0.88	1.48	1.0-3.0
100	123	11882.3	0.008	Car/train /bus/aircraft	0.30	0.90	0.5-2.5
500	603	285577.8	0.0004	Aircraft	n/a	n/a	0.5-1.5
1000	1203	1136635.3	0.00009	Aircraft	n/a	n/a	n/a

Table 2

These experiments show that an optical density of 2 would tend to provide sufficient attenuation for aerospace applications, where attackers would struggle to get within 100 m of the aircraft.

5 So that the dazzle can be prevented (dazzle being where the vision of the operator is temporarily impaired by the laser light but not permanently damaged) the OD values given in Table 1 or Table 2 should be increase in each scenario by 1, or more preferably 1.5 (i.e. and OD of 1 should become and OD of 2 or 2.5 to prevent dazzle).

10 In a variant of the radiation detector shown in Figure 2, the radiation detector may have the form of a patch arranged in the plane of the filter, or in other words at or near a boundary of the filter. Said patch could comprise an localised photodetector or array thereof and would be interfaced with the processor module and alert module in an equivalent manner. This approach would be suited to contexts where the spot size of the laser was sufficiently
15 large to illuminate the periphery of the window, so that the patch need not be positioned in the operator's view.

In a variant of the window and substrate arrangement of Figure 1, the window may be comprised by a number of laminar substrates between which could be positioned the filter 10.

20 In a variant of the window and substrate arrangement of Figure 2, the window may be comprised by a number of laminar substrates between which could be positioned the filter and detector.

It will be apparent to a person skilled in the art, from the foregoing description, that modifications and variations can be made to the described
25 embodiments without departing from the scope of the invention as defined by the appended claims.

CLAIMS

1. A method of forming a conformable filter, comprising the steps of:
- 5 - selecting at least a first wavelength corresponding to a predetermined laser threat;
 - providing a conformable photosensitive film having a visible light transmission and exposing said film to radiation from a focused laser source of said first wavelength to create a first filter region therein configured to substantially block incident radiation thereon
10 substantially only of said first wavelength while substantially allowing other visible wavelengths to be transmitted;
 - selecting a bandwidth corresponding to a first predetermined wavelength band including said first wavelength and exposing said polymeric film to radiation from one or more further laser sources of
15 respective different wavelengths within said first predetermined wavelength band to create a notch filter region therein, including said first filter region, said notch filter region being configured to substantially block incident radiation thereon at a wavelength within said first predetermined wavelength band whilst substantially allowing
20 visible wavelengths outside of said first predetermined wavelength band to be transmitted therethrough.
2. A method according to claim 1, wherein said film is formed of a photosensitive polymer material.
3. A method according to claim 1 or claims 2, wherein said film has a
25 visible light transmission of at least 85 %, and/or a thickness of 1 to 100 micrometers.
4. A conformable filter formed by the method of any of claims 1 to 3.
5. A conformable filter according to claim 4, additionally configured to prevent transmission of radiation in a second predetermined wavelength
30 band covering a selected second predetermined laser threat.

6. A filter according to claim 4 or claim 5, wherein the first predetermined wavelength band covers, or is centred on, 532nm.
7. A filter according to claim 5 wherein the second predetermined wavelength band covers or is centred on 445nm.
- 5 8. A filter according to any of claims 4 to 7, wherein the filter is additionally configured to prevent radiation in a third predetermined wavelength band covering the wavelength of a third predetermined laser threat, and optionally wherein the third predetermined wavelength band covers or is centred on 650nm.
- 10 9. A filter according to any of claims 4 to 8, wherein the filter is configured to prevent radiation from three or more predetermined wavelength bands.
10. A filter according to any one of claims 4 to 9, wherein the filter is comprised of a single layer of material adapted or configured for preventing the
15 transmission of the predetermined visible wavelength band or bands.
11. A filter according to any of claims 4 to 10, wherein the bandwidth of at least one of the predetermined wavelength bands is between 10nm and 5nm.
12. A filter according to any of claims 4 to 11, wherein the filter has an
20 optical density of at least 2 at the first, and/or each, predetermined wavelength band.
13. A filter according to any of claims 4 to 12, wherein the filter is provided as a conformal film for coupling to a window.
14. A multi-layered window comprising a filter according to any one of
25 claims 4 to 12, wherein the filter is interposed between layers of the window.
15. A window for a vehicle, the window comprising a filter according to any of claims 4 to 12.

Fig. 1

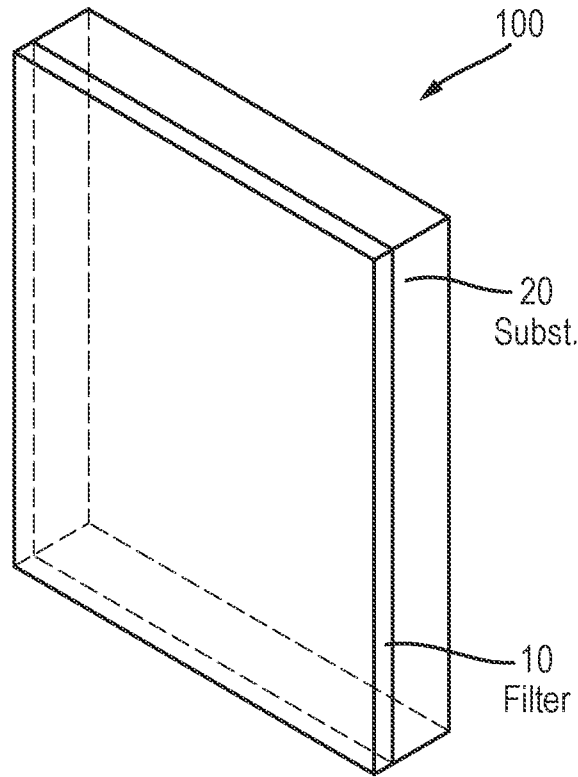


Fig. 3

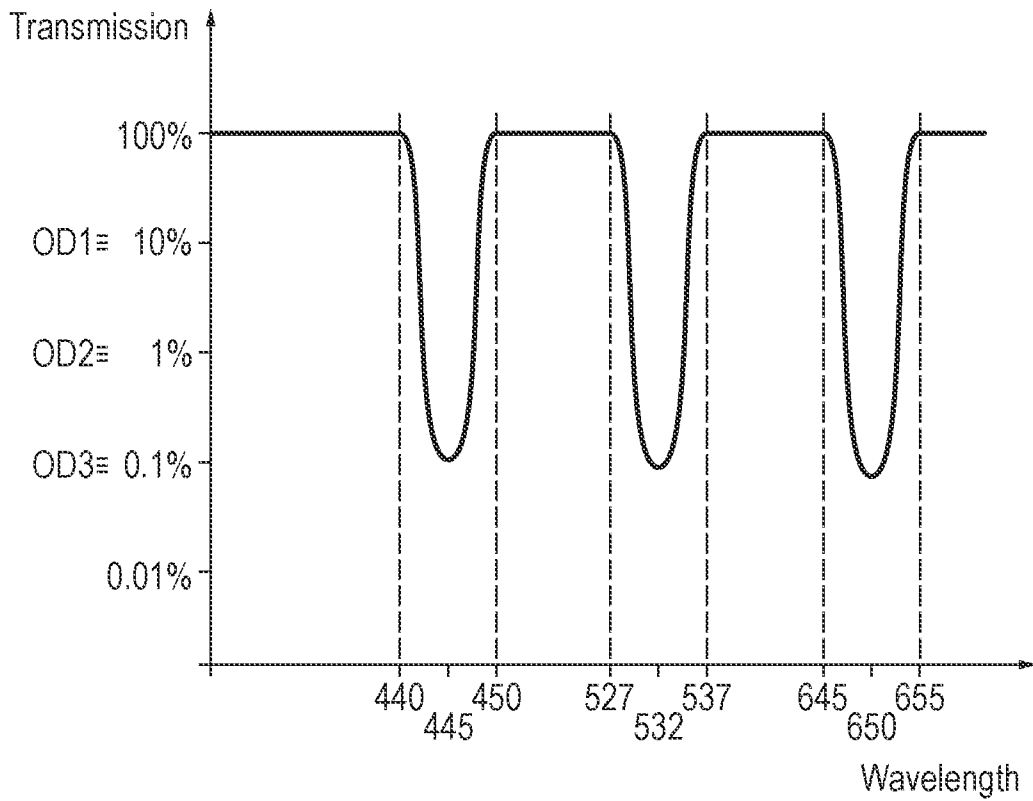


Fig. 2

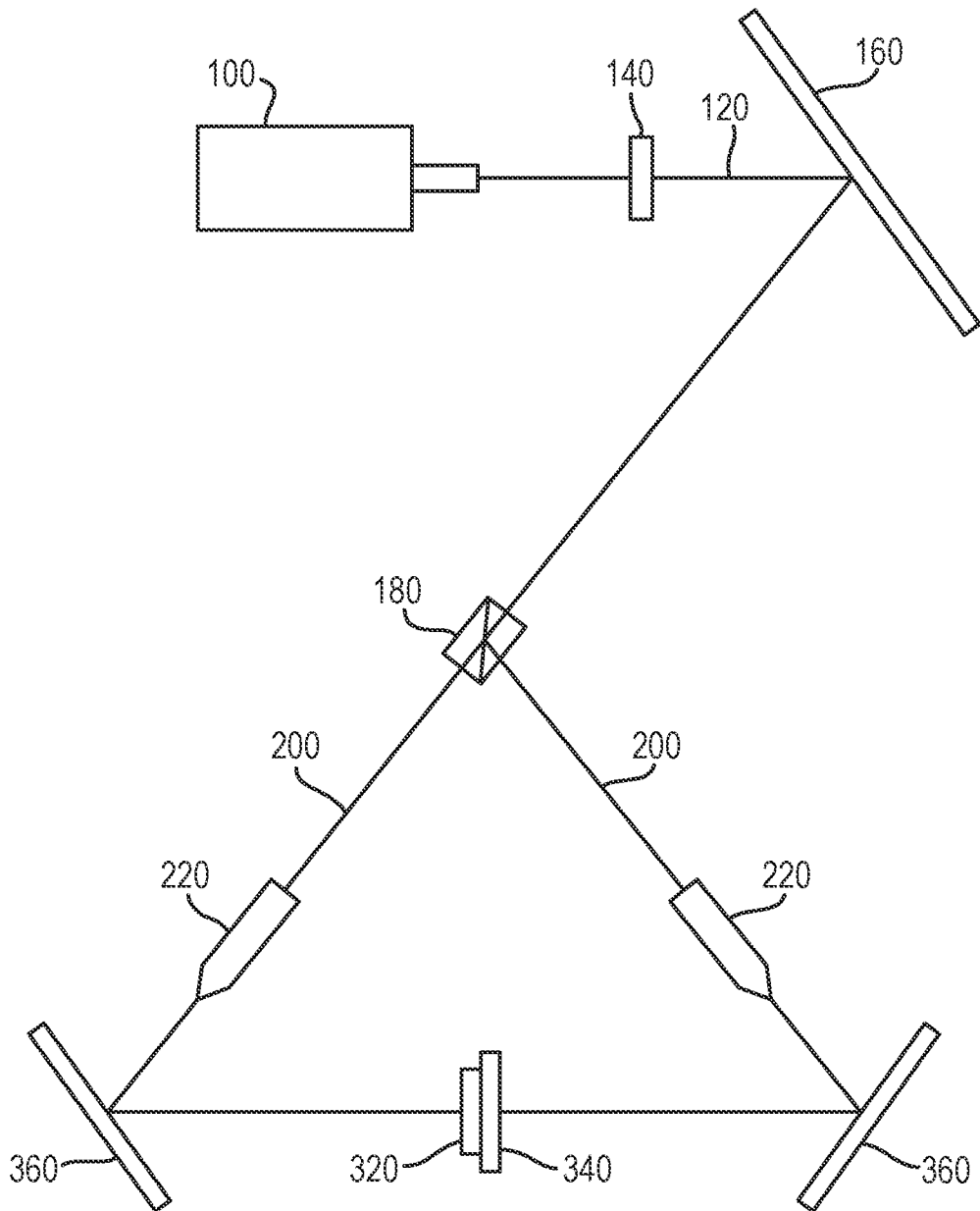


Fig. 4

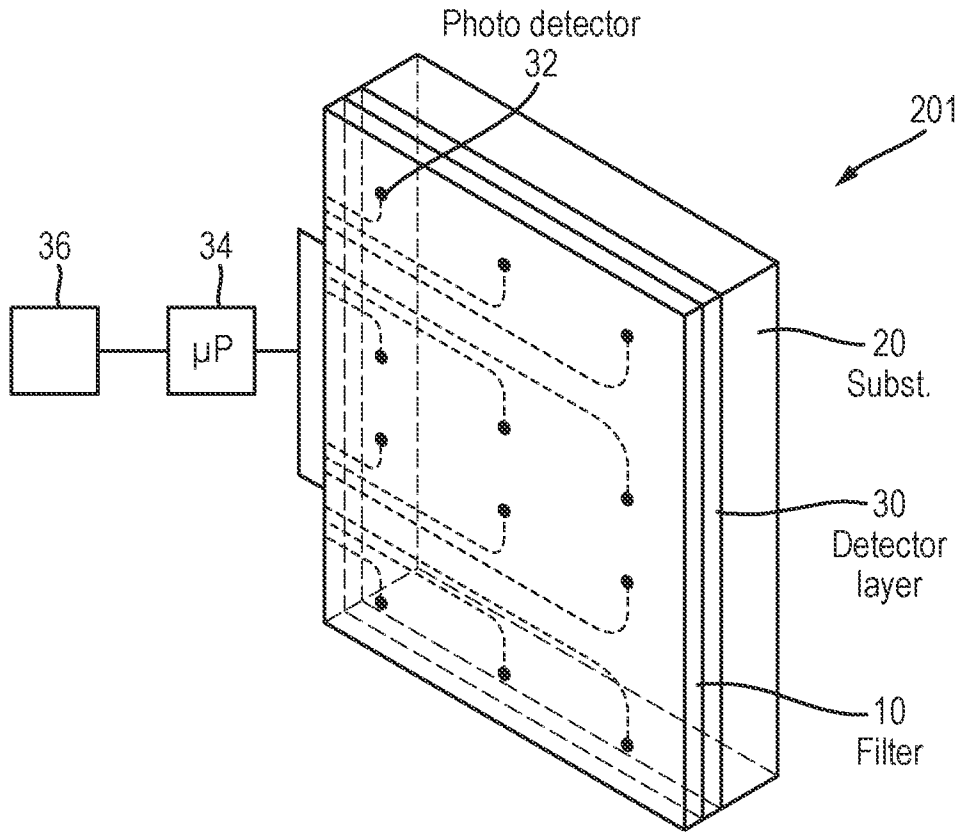
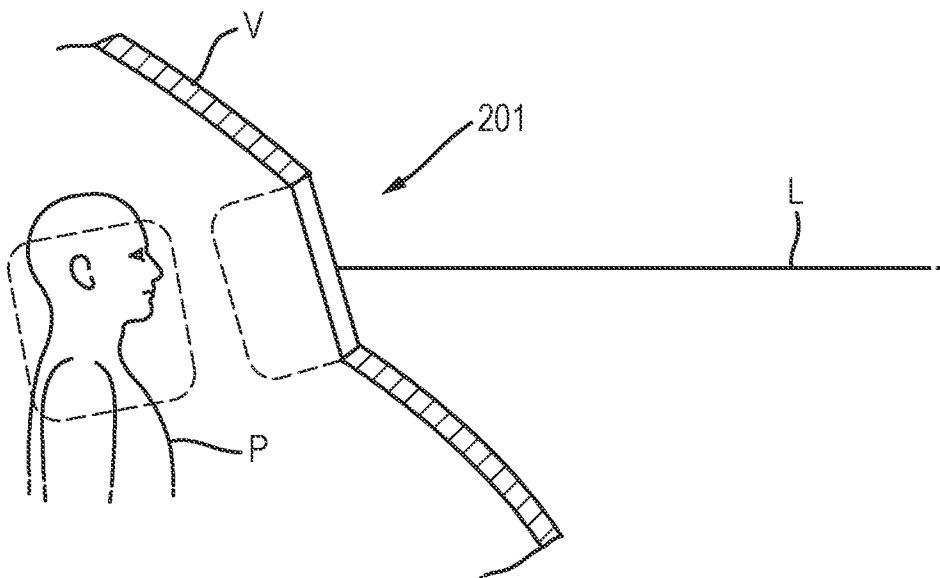


Fig. 5



INTERNATIONAL SEARCH REPORT

International application No
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A. CLASSIFICATION OF SUBJECT MATTER
 INV. G02B5/20 G02B5/28 G02C7/10 A61F9/02
 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 G02C A61F

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	EP 2 602 655 A1 (ESSILOR INT [FR]; UNIV PARIS 6 PIERRE ET MARIE CURIE [FR]) 12 June 2013 (2013-06-12)	1-4, 10-12
Y	figure 1 paragraph [0097] paragraph [0141] paragraph [0072] paragraph [0194]	5-9, 13-15
Y	----- US 2010/149483 A1 (CHIAVETTA III STEPHEN V [US]) 17 June 2010 (2010-06-17) figure 1 paragraph [0046] - paragraph [0047] -----	5-9, 13-15

Further documents are listed in the continuation of Box C.

See patent family annex.

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INTERNATIONAL SEARCH REPORT

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