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(71) Applicant (for all designated States except US): **IMPERIAL COLLEGE INNOVATIONS LIMITED**  
[GB/GB]; Sheffield Building, Imperial College, London SW7 2AZ (GB).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **NEIL, Mark, Andrew, Aquilla** [GB/GB]; 22 Poplar Road, Botley, Oxford OX2 9LB (GB). **FRENCH, Paul, Michael, William** [GB/GB]; 14 Enbrook Street, London W10 4SF (GB).

(74) Agents: **ROBINSON, Nigel, Alexander, Julian** et al.; D. Young & Co., 120 Holborn, London EC1N 2DY (GB).

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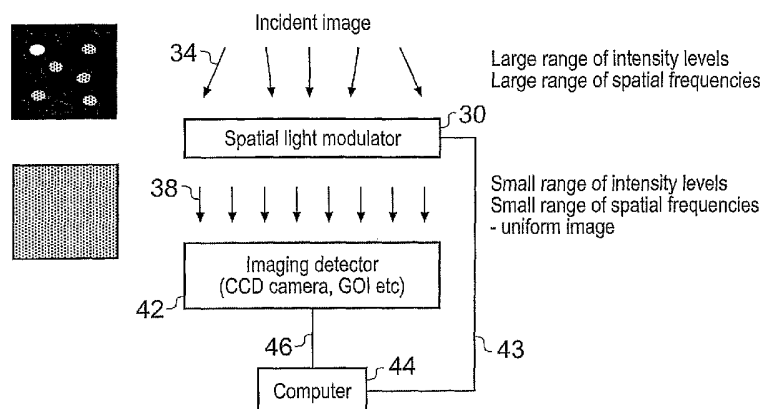
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(54) Title: IMAGING SYSTEM



(57) Abstract: An imaging apparatus comprising: A spatial light modulator (30) operable to receive incident light (34) representing an incident light image and to intensity modulate said incident light to form spatially modulated (38) light; and an image capture device (42) operable to receive said spatially modulated light and to detect an intensity value for different portions of said spatially modulated light to form a modulated light image therefrom; wherein said spatial light modulator attenuates different parts of said incident light by different proportions such that intensity values of said incident light image are given by a combination of intensity values of said modulated light image captured by said image capture device and data representing proportions of attenuation applied to corresponding parts of said incident light image by said spatial light modulator.



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*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

## IMAGING SYSTEM

This invention relates to an imaging apparatus and method.

Many wide-field imaging devices currently exist, such as charge-coupled-  
5 device (CCD) cameras and image intensifiers. Many such imaging devices have  
controllable settings that can be used to improve the quality of a resulting output  
image. These settings allow the imaging device to be used with a wide range of types  
of incident image. One such setting is the “gain” of the imaging device, which acts as  
an intensity multiplier and may be used to help distinguish between incident intensities  
10 of a similar value, thus exposing detail. Another device setting is the “exposure time”  
or “integration time”, which controls the time period over which incident light  
contributes to the resulting image. The settings of gain and exposure are particularly  
useful when capturing images of faint or dark objects.

15 Figure 1 of the accompanying drawings is an example plot of light intensities  
for an incident image that is to be captured by an imaging device, such as a CCD  
camera. The incident image has a wide range of intensity values. The majority of the  
intensity samples 10 are of a relatively low intensity value, representing relatively dark  
areas. However, there is an area of intensity samples 12 representing incident light of  
20 a high intensity level. Figure 2 of the accompanying drawings is an example cross-  
section through the plot of Figure 1.

Problems can arise when the incident image has both dark areas of low light  
intensity and bright areas of high light intensity, as shown in Figure 1. If the  
25 integration time of the imaging device is too long, it is possible for it to become  
saturated, i.e. for the area of high light intensity 12, the imaging device loses its  
(linear) responsiveness to the incident light and the intensity samples values associated  
with the area of high light intensity 12 assume a maximal value. Figure 3 of the  
accompanying drawings is an example plot of intensity values when saturation occurs.  
30 The line 20 is a plot of the (integrated) intensity of the light incident on the imaging  
device over the exposure period. The value  $I_{\max}$  is the maximum (integrated) intensity

value that the imaging device can faithfully record. The line 22 therefore represents the resultant captured incident light (integrated) intensity, with (integrated) intensity values constrained to being at most  $I_{\max}$ , causing a loss of detail.

5 Further problems can occur when the integration time is set to be too long. For some imaging devices, such as CCD cameras, an effect known as “blooming” may occur in which, once a saturation level has been reached for some of the sampled intensity values, erroneously high values are given to samples surrounding the area of saturation.

10

It is therefore important to ensure that the integration time of the imaging device is correctly set, dependent on the incident light image. Figure 4 of the accompanying drawings is an example plot of (integrated) intensity values similar to those of Figure 3, but in which the integration time has been reduced. The line 24  
15 represents the (integrated) intensity values captured by the imaging device over the reduced integration period. As the integration time has been reduced, the maximum captured (integrated) intensity is now close to the maximum possible captured (integrated) intensity,  $I_{\max}$ .

20 Figure 4 also represents an example plot of (integrated) intensity values when the imaging device makes use of a controllable gain setting, the gain setting acting as an intensity multiplier. Instead of adjusting the integration time, the gain setting can be adjusted to reduce the captured (integrated) intensity values, resulting in captured (integrated) intensity values according to the line 24.

25

Whilst reducing the integration time or the gain setting of the imaging device is useful for faithfully capturing areas of the incident image that have high intensity values, such adjustments can have a negative impact on the capture of areas of the incident image that have low intensity values. Figure 5 of the accompanying drawings  
30 is a close-up plot of the intensity values from a range 26 of intensity values from Figure 4, the range 26 corresponding to a less bright section of the incident image with low (integrated) intensity values. The signal level of the (integrated) intensity of the

incident light 20 is much larger than the signal level of the intensity of the captured light 24 when the imaging device has been set to use a reduced integration time or a reduced gain setting. This may result in a significant loss of detail. For example, if the captured intensities are digitised, then the effective number of bits being used to describe the area of low intensity is less than would be used if a longer integration time or higher gain setting had been selected for the imaging device. Further, the low level signals may be swamped by noise such that the intensity information is degraded.

There is therefore a difficulty with capturing incident images that have areas of both high and low light intensity. Adjusting the gain setting or integration time of the imaging device to accommodate high light intensities can have an adverse effect on the quality/resolution of captured intensities corresponding to the areas of low light intensity.

The ability of an imaging detector to faithfully record information of both high intensity and low intensity signals within an image is described by its dynamic range.

This problem of limited dynamic range can be exacerbated when a series of electronic recorded images is to be processed to produce a final image. Invariably, processing a series of images will further reduce the dynamic range of the final image, as intensities often need to be normalised to account for variations across the series of images. This can occur, for example, in fluorescence lifetime imaging, in which fluorescent molecules, such as marker dyes, are used to identify areas with certain characteristics and optical imaging techniques are used to produce maps of the localisation of the fluorophore over time.

Another problem resulting from the limited dynamic range can occur during processing in which, for example, the background is to be removed from the image. It may be the case that the background has a larger magnitude than the regions of interest. Consequently, when the background is removed, the resulting image has a dynamic range that is a small fraction of the dynamic range of the original imaging device.

A known approach to solving this problem is to use imaging devices with as large a dynamic range as possible, thereby allowing bright areas to be reproduced whilst at the same time allowing the faint or dark areas to be reproduced with sufficient detail. CCD cameras typically are limited to a pixel bit-depth of 16 bits. In  
5 general, imaging devices of higher dynamic range are more expensive and are slower.

There is, therefore, a need for an imaging system that can reproduce, with sufficient dynamic range, an incident image that has a wide range of intensity values,  
10 such as an image in which faint or dark objects are close to bright objects.

According to one aspect this invention provides an imaging apparatus comprising:

a spatial light modulator operable to receive incident light representing an  
15 incident light image and to intensity modulate said incident light to form modulated light; and

an image capture device operable to receive said spatially modulated light and to detect an intensity value for different portions of said modulated light to form a modulated light image therefrom; wherein

20 said spatial light modulator attenuates different parts of said incident light by different proportions such that intensity values of said incident light image are given by a combination of intensity values of said modulated light image captured by said image capture device and data representing proportions of attenuation applied to corresponding parts of said incident light image by said light modulator.

25

The invention recognises that by intensity modulating an incident image into a modulated image of reduced dynamic range, an imaging device of a lower dynamic range may be used to record the image. This allows the use of cheaper and faster imaging devices of lower dynamic range. The dynamic range of the light modulator  
30 effectively augments the dynamic range of the image capture device. Settings used during the modulation process may be recorded for later interpretation of the captured image.

In preferred embodiments, the spatial light modulator is used to produce modulated light that has a reduced range of intensity values in comparison to the range of intensity values of the incident light. Such embodiments allow an image capture device with a dynamic range less than the range of intensity values of the incident light to be used to capture the modulated light. As capture devices, such as CCD cameras, with a large dynamic range are both expensive and slow, embodiments of the invention that make use of a light modulator in this way are both cheaper and faster than an imaging apparatus that uses an image capture device with a dynamic range large enough to faithfully capture the full range of the un-modulated incident light.

Furthermore, whilst embodiments of the invention may use light modulators to produce modulated light with an arbitrary dynamic range of intensity values, preferred embodiments of the invention use light modulators to produce modulated light with a dynamic range of intensity values that matches the dynamic range of the capture device. In doing so, the capture device is used to greatest effect. If the range of intensity values of the modulated light is less than the dynamic range of the capture device, then bandwidth associated with the captured image is wasted and the captured image may be less detailed than would otherwise have been possible. If the range of intensity values of the modulated light is greater than the dynamic range of the capture device, then it is possible that the same problem of being able to faithfully capture an image that has a large range of intensity values still exists.

Further preferred embodiments of the invention comprise a feedback controller responsive to the intensity values of the modulated light image captured by the image capture device and operable to control the attenuation effected by the light modulator. The feedback controller provides additional advantage in that it is able to control how the light modulator attenuates different parts of the incident light image in dependence upon the incident light image. It is therefore able to control the light modulator in an attempt to produce a modulated light image that is most suitable for the image capture device. For example, the feedback controller may control the light modulator so that the dynamic range of intensity values of the modulated light matches the dynamic

range of the image capture device. The feedback controller is operable to control the light modulator on a per-image basis, thereby allowing the imaging apparatus to adapt appropriately for any given incident light.

5 In preferred embodiments, the image capture device is a 2-dimensional array detector such as a CCD array or a CMOS detector array. For imaging with coherent light preferred embodiments include (a) a single or few channel detector such as a photodiode or a photo multiplier tube, or (b) a two photon detector, employed to sample an optical signal that indicates the degree to which the incident light intensity  
10 distribution is uniform. Preferred coherent imaging embodiments would utilize a single or few channel one-photon detector behind an aperture or a two-photon (intensity-dependent) detector located in a Fourier plane of the spatially modulated light image. The use of the single or few channel detector providing feedback to the modulator such that it produces a uniform output image opens the possibility of being  
15 able to detect wavelengths not normally possible in wide field imaging, for example at wavelengths for which only single or few channel detectors are available.

Viewed from another aspect the invention provides a method of imaging comprising the steps of:

20 receiving incident light representing an incident light image;  
intensity spatially modulating said incident light to form modulated light;  
capturing said modulated light; and  
detecting an intensity value for different portions of said captured modulated  
light to form a modulated light image therefrom; wherein  
25 said intensity spatial modulation attenuates different parts of said incident light by different proportions such that intensity values of said incident light image are given by a combination of intensity values of said captured modulated light image and data representing proportions of attenuation applied to corresponding parts of said incident light image.

30

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:



Figure 1 is an example plot of light intensities for an incident image that is to be captured by an imaging device;

5        Figure 2 is an example cross-section through the plot of Figure 1;

Figure 3 an example plot of intensity values when saturation occurs;

Figure 4 is an example plot of intensity values similar to those of Figure 3, but  
10    in which the integration time has been reduced;

Figure 5 is a close-up plot of the intensity values from a range of intensity values from Figure 4;

15        Figure 6 schematically illustrates a capture device connected to a light modulator;

Figure 7 is an example plot of how incident light can be modulated by a spatial light modulator;

20

Figure 8 schematically illustrates an imaging apparatus using a single channel detector located behind an aperture in a Fourier plane of the modulated light image; and

25        Figure 9 schematically illustrates an imaging apparatus using a two-photon detector in a Fourier plane of the modulated light image .

Figure 6 schematically illustrates a capture device 42 arranged to receive light from a spatial light modulator (SLM) 30. The SLM 30 receives incident light 34, modulates this (reduces in intensity) and outputs modulated light 38. Essentially  
30    (some of) the burden of dynamic range is transferred from the capture device 42 to the SLM 30. One example application might be imaging in a building on fire. There are

also many biomedical applications, such as fluorescence imaging when there is more than one fluorescent species in the field of view and one species fluoresces much more brightly than another. Specific applications include spectrally-resolved imaging and fluorescence lifetime imaging, for which there is a minimum dynamic range requirement to permit accurate fitting of the recorded fluorescence profiles. This is extremely challenging when one fluorescent species may be weak while another is saturating the imaging detector.

It will be appreciated that many different types of light modulator exist and may be used with the capture device 42. In this example embodiment, an SLM 30 is being used. SLMs are well known in this field of technology and shall not be described in great detail here. In brief though, the SLM 30 is operable to modulate a value of incident light intensity in dependence on the spatial location of the incident light sample in the incident image. For example, the SLM 30 may be configured to modulate the left half of the incident light 34 to a greater extent than the right half of the incident light 34. The SLM 30 is also able to selectively modulate light on a pixel-by-pixel basis.

Figure 7 is an example plot of how the incident light 34 can be modulated by the SLM 30. The plot 7a is the same plot of intensity values of an incident image as in Figure 1. As in Figure 1, there are areas 10 in the incident image of low intensity value and there is an area 12 in the incident image of high intensity value.

The plot 7b is a plot of the degree of modulation that is to be applied by the SLM 30. Note that the SLM 30 has been set to apply a higher level of modulation to the area 12 of higher incident light intensity. However, the modulation level does not necessarily exactly match the incident light intensities and it is possible for a low intensity level to be modulated to a greater extent than a higher intensity level as the modulation level is dependent on a spatial position.

30

With the modulation level of the SLM 30 set according to the plot 7b, the intensity levels of the modulated light 38 are illustrated in the plot 7c. As can be seen,

the dynamic range of the modulated light 38 is considerable lower than the dynamic range of the incident light 34.

The SLM 30 can therefore be set to produce modulated light 38 of a lower  
5 dynamic range than the incident light 34, thereby allowing a capture device 42 of reduced dynamic range to be used. Such capture devices 42 of reduced dynamic range are, in general, cheaper and faster than similar devices of higher dynamic range. Naturally, in order to interpret the captured modulated light, it is necessary to know the degree of modulation applied to the incident light 34. The SLM 30 therefore has its  
10 own inherent dynamic range and the arrangement of Figure 6 can be viewed as transferring some of the dynamic range "burden" from the capture device 42 to the SLM 30. For example, a 32 bit captured image could correspond to 16 bits of dynamic range from the capture device 42 and 16 bits of dynamic range from the SLM 30.

15 It is preferable if the dynamic range of the modulated light 38 matches the dynamic range of the capture device 42. If the SLM 30 modulates the incident light 34 too much, then the dynamic range of the capture device 42 is not being used to its greatest effect. However, if the SLM 30 does not modulate the incident light 34 sufficiently, then it is possible that the capture device 42 will still have difficulty in  
20 faithfully capturing an incident image with a wide range of intensity levels.

Also illustrated in Figure 6 is a feedback channel 43. The capture device 42 is connected to a computer 44 via a connection 46. The computer 44 analyses the modulated light 38 captured by the capture device 42 and sends a control signal to the  
25 SLM 30 via the feedback channel 43. The computer 44 operates to improve the resultant captured image by adjusting how the SLM 30 modulates the incident light 34. These adjustments aim to create modulated light 38 that is best suited to the capture device 42. The computer 44 could, for example, iteratively control the modulation applied by the SLM 30 until the dynamic range of the intensity values of the  
30 modulated light 38 matches the dynamic range of the capture device 42.

The example embodiment of Figure 8 uses one or more single channel detectors 50 to record the signal output from the SLM 30 and provide appropriate feedback to achieve a quasi-uniform detected intensity as the SLM 30 selectively passes the light corresponding to individual pixels one after another in a sequence.

5 Thus one can achieve coherent light imaging with a single or few channel detector 50. This permits imaging with exotic single or few channel detectors 50 in situations where there is no available wide-field imaging detector. Note that the incident image 34 is assumed to be coherent. Generation of the coherent image can be a natural result of the imaging system used or an incoherent image can be converted to a coherent one

10 by using an optically addressed spatial light modulator or a photo-refractive device.

The single channel detector 50 may be a detector located after a spatial filter through which a plane wave (quasi-uniform image) would be coupled most efficiently. This could be, for example, an optical fibre coupled detector. The spatial filter is

15 simply a lens 51 with an aperture (pinhole) 53 in the focal (Fourier) plane. A second detector may be used to detect the light rejected by the pinhole to provide a second signal which may be used in comparison with the first signal (collected through the pinhole) to give a better measure of the uniformity of the modulated image that is independent of the total attenuation of the spatial light modulator.

20

Alternatively, the modulated light 38 could be focused through the lens 51 onto a 2-photon detector 52 in the Fourier plane, as illustrated in Figure 9. The output of a 2-photon detector 52 is a nonlinear function of the incident intensity and so this would give a maximum signal when an incident image is a plane wave or a uniform image.

25 Such an approach has been used to provide an effective "pinhole detector" in a confocal microscope experiment (for example, see "Transmission confocal laser scanning microscopy with a virtual pinhole based on nonlinear detection", C.Yang and J.Mertz, OPTICS LETTERS / Vol. 28 (2003) 224-6).

30 This approach also has the useful feature that the detector would be sensitive to half the incident radiation wavelength. Thus it could be used, for example, for near-mid-infrared imaging applications.

The main application of the example embodiments of Figure 8 and 9 would be to achieve full-field imaging using a single channel detector or 2-photon detector in situations where there are no appropriate imaging detectors available, or where they are very expensive or not very sensitive. One application would be mid-infrared imaging (longer than 1.8 $\mu$ m) for which there are very few detectors available, those detectors that do exist tending to be very expensive.

In the case where no imaging detector is available, the two-photon detector may permit the use of appropriate detectors at half the wavelength.

One could also use a nonlinear sum-frequency generation scheme in which a power local oscillator is mixed with incoming radiation to generate a detectable signal. It would be much easier to implement this in a single channel detector than in an imaging detector.

CLAIMS

1. An imaging apparatus comprising:  
a spatial light modulator operable to receive incident light representing an incident light image and to intensity modulate said incident light to form spatially  
5 modulated light; and  
an image capture device operable to receive said spatially modulated light and to detect an intensity value for different portions of said spatially modulated light to form a modulated light image therefrom; wherein  
said spatial light modulator attenuates different parts of said incident light by  
10 different proportions such that intensity values of said incident light image are given by a combination of intensity values of said modulated light image captured by said image capture device and data representing proportions of attenuation applied to corresponding parts of said incident light image by said spatial light modulator.
- 15 2. An imaging apparatus as claimed in claim 1, wherein said spatial light modulator is controlled so as to reduce a dynamic range of intensity values of said modulated light image.
3. An imaging apparatus as claimed in any one of claims 1 and 2, wherein said  
20 spatial light modulator is controlled so as to match a dynamic range of intensity values of said modulated light image with a dynamic range of said image capture device.
4. An imaging apparatus as claimed in any one of the preceding claims, comprising a feedback controller responsive to intensity values of said modulated light  
25 image captured by said image capture device to control a proportion of attenuation applied by said spatial light modulator to respective different parts of said incident light image.
5. An imaging apparatus as claimed in any one of the preceding claims, wherein  
30 said image capture device comprises a CCD array.

6. An imaging apparatus as claimed in any one of claims 1 to 4, wherein said image capture device is a single or few channel detector and said light modulator selects a portion of said incident light to be detected.
- 5 7. An imaging apparatus as claimed in claim 6, wherein said single channel detector is one of:  
a photodiode; and  
a photo multiplier tube.
- 10 8. An imaging apparatus as claimed in any one of claims 1 to 4, wherein said image capture device is a two photon detector and said light modulator selects a portion of said incident light to be detected.
- 15 9. An imaging apparatus as claimed in any one of the preceding claims, wherein an incident incoherent light image is converted to a coherent light image incident on the spatial light modulator.
10. An imaging apparatus as claimed in any one of the preceding claims, wherein an incident incoherent light image is converted to a coherent light image incident on the spatial light modulator using one of:  
20 (i) an optically addressed spatial light modulator; or  
(ii) a photorefractive device.
11. A method of imaging comprising the steps of:  
25 receiving incident light representing an incident light image;  
intensity spatially modulating said incident light to form spatially modulated light;  
capturing said spatially modulated light; and  
detecting an intensity value for different portions of said captured modulated  
30 light to form a modulated light image therefrom; wherein  
said intensity spatial modulation attenuates different parts of said incident light by different proportions such that intensity values of said incident light image are

given by a combination of intensity values of said captured modulated light image and data representing proportions of attenuation applied to corresponding parts of said incident light image.

5 12. A method of imaging as claimed in claim 11, wherein said intensity spatial modulation is performed by a spatial light modulator.

13. A method of imaging as claimed in any one of claims 11 and 12, wherein said intensity spatial modulation is controlled so as to reduce a dynamic range of intensity  
10 values of said modulated light image.

14. A method of imaging as claimed in any one of claims 11, 12 and 13, wherein said intensity spatial modulation is controlled so as to match a dynamic range of intensity values of said modulated light image with a dynamic range associated with  
15 said step of capturing said modulated light.

15. A method of imaging as claimed in any one of claims 11 to 14, comprising a further step of controlling a proportion of attenuation applied by said intensity spatial modulation to respective different parts of said incident light image in dependence on  
20 intensity values of said modulated light image.

16. A method of imaging as claimed in any one of claims 11 to 15, wherein said step of capturing said modulated light is performed by a CCD array.

25 17. A method of imaging as claimed in any one of claims 11 to 15, wherein said step of capturing said modulated light is performed by a single or few channel detector and said intensity modulation additionally involves selecting a portion of said incident light to be detected.

30 18. A method of imaging as claimed in claim 17, wherein said single channel detector is one of:  
a photodiode; and



a photo multiplier tube.

19. A method of imaging as claimed in any one of claims 11 to 15, wherein said  
step of capturing said modulated light is performed by a two photon detector and said  
5 intensity modulation additionally involves selecting a portion of said incident light to  
be detected.

20. A method of imaging as claimed in any one of claims 11 to 19, wherein an  
incident incoherent light image is converted to a coherent light image incident on the  
10 spatial light modulator.

21. A method of imaging as claimed in any one of claims 11 to 20, wherein an incident  
incoherent light image is converted to a coherent light image incident on the spatial  
light modulator using one of:  
15 (i) an optically addressed spatial light modulator; or  
(ii) a photorefractive device.

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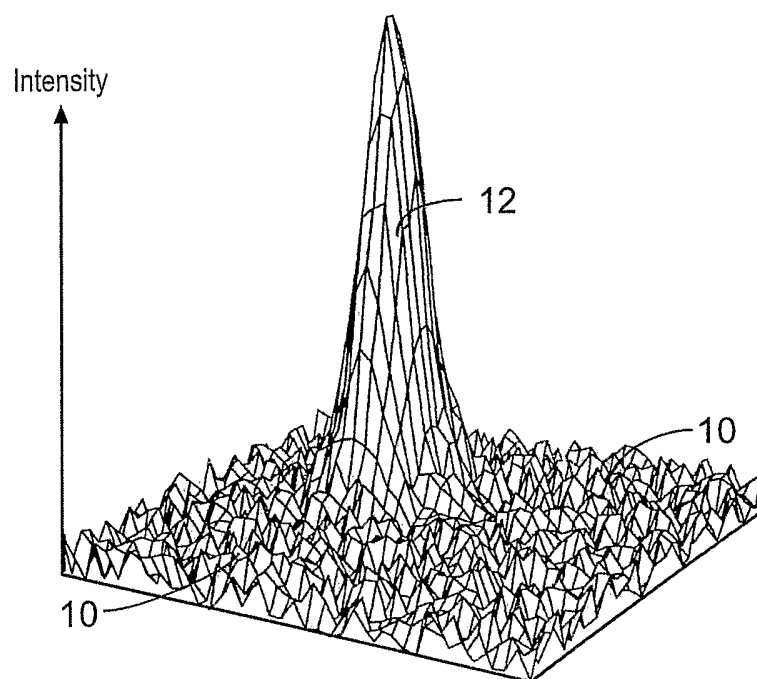


Fig. 1

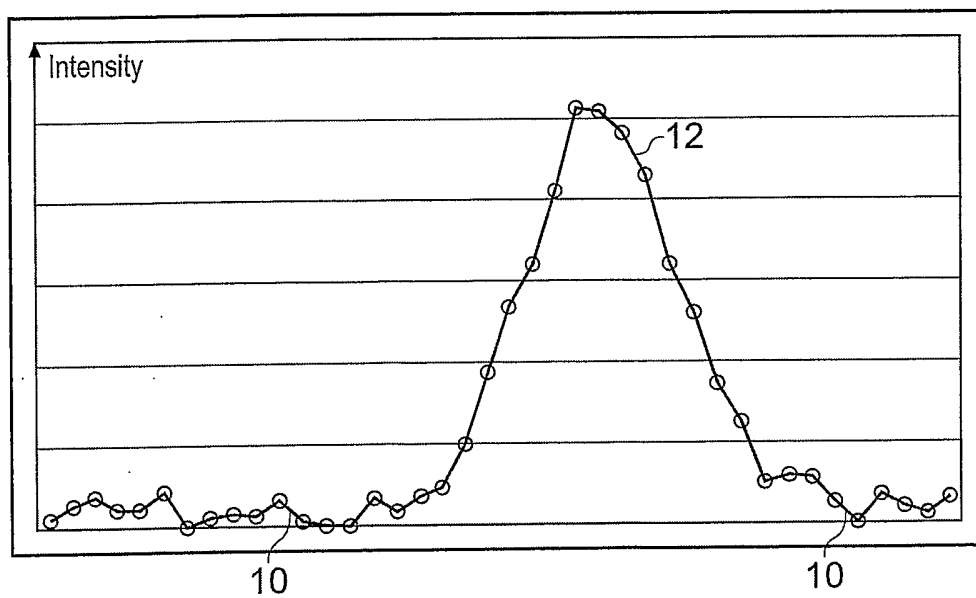


Fig. 2

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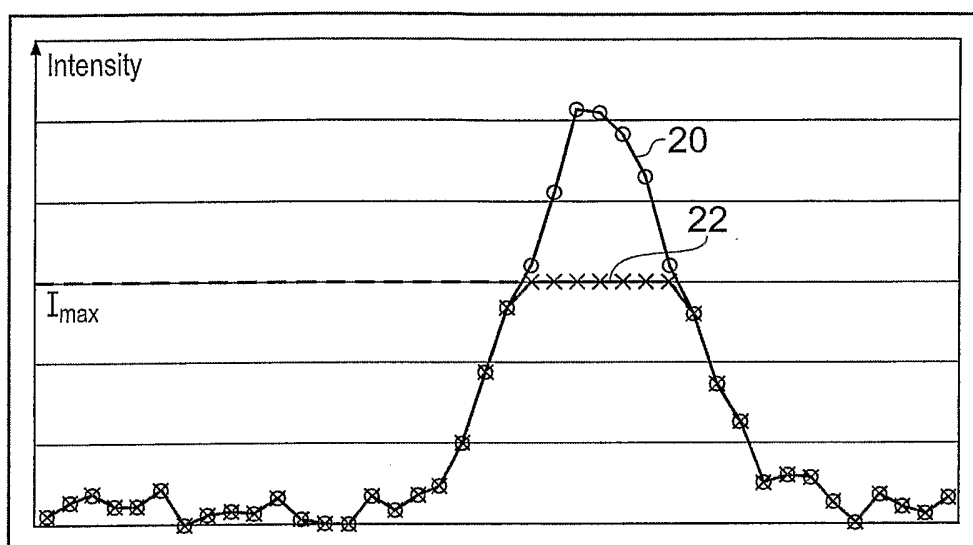


Fig. 3

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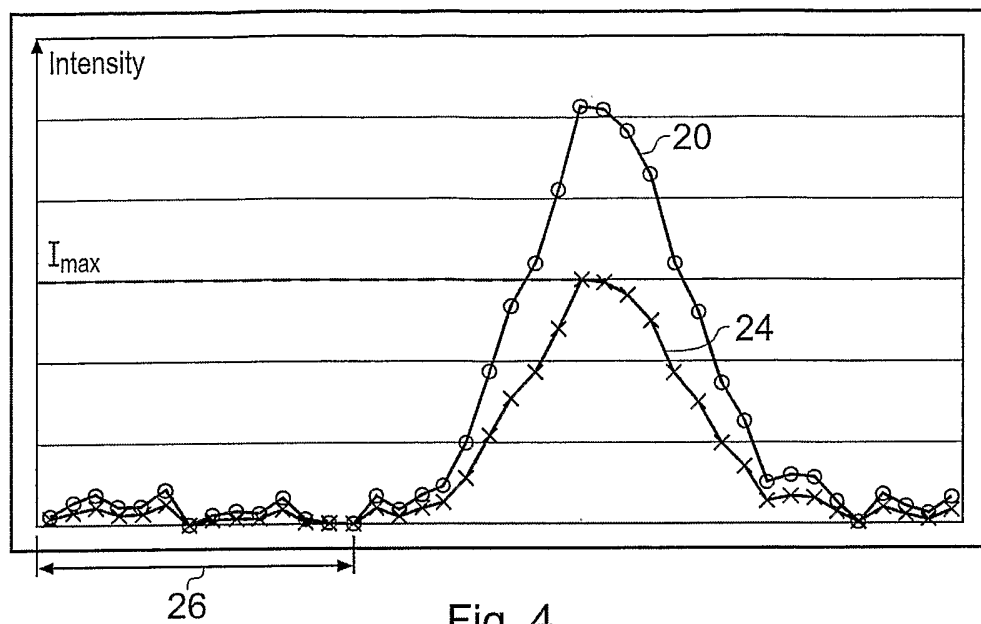


Fig. 4

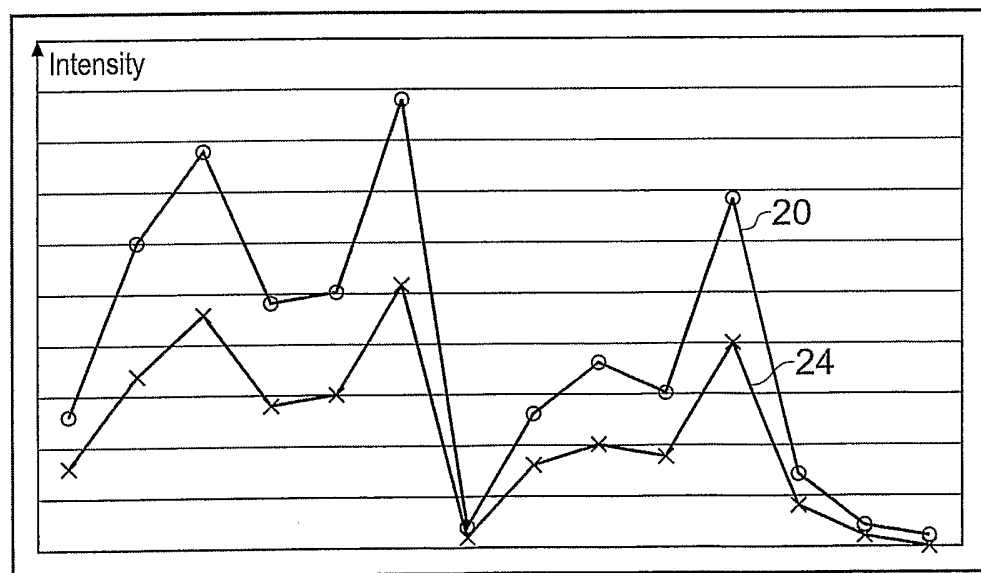


Fig. 5

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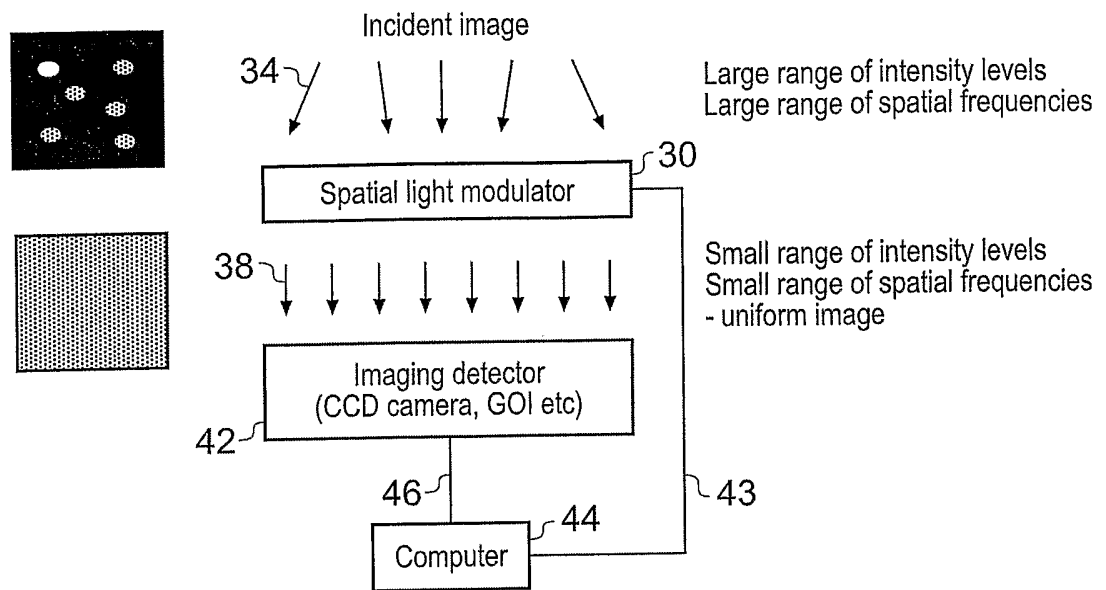


Fig. 6

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Fig. 7a

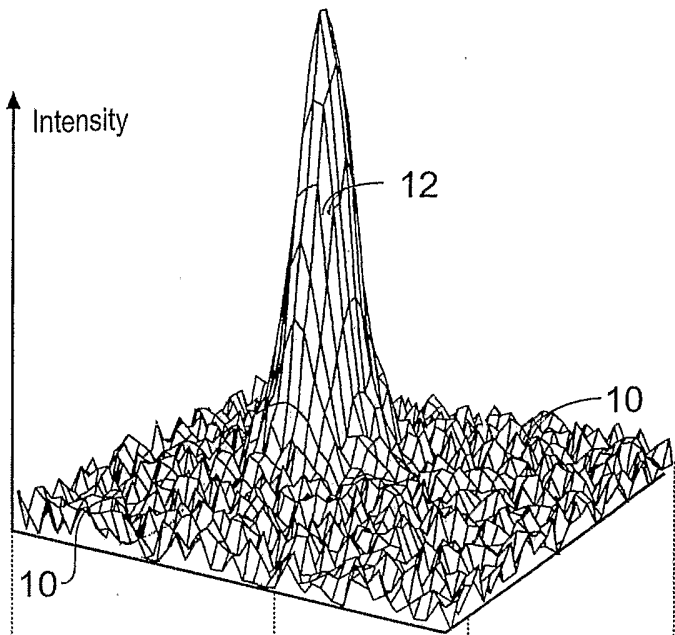


Fig. 7b

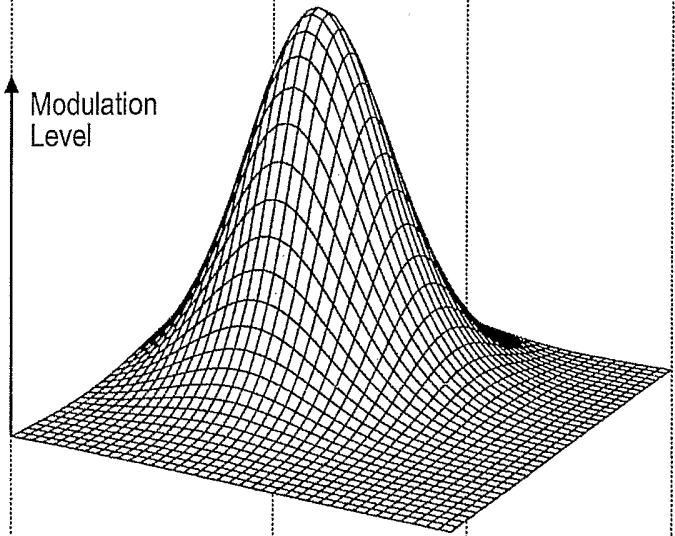
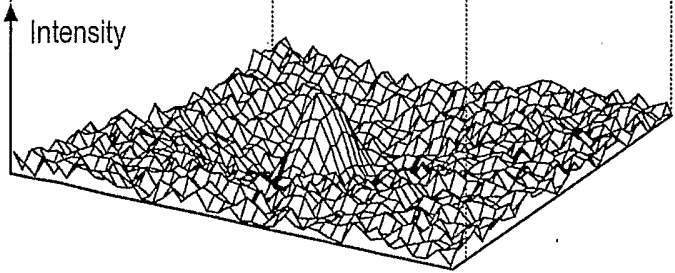


Fig. 7c



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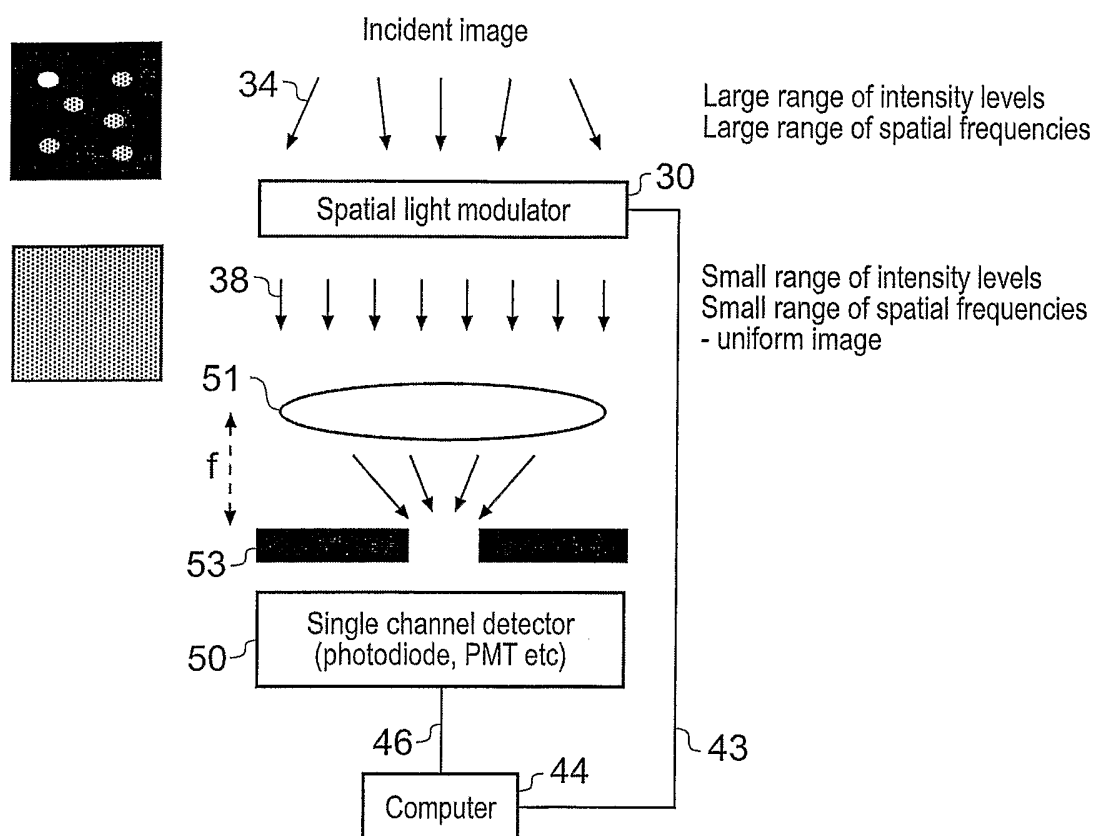


Fig. 8

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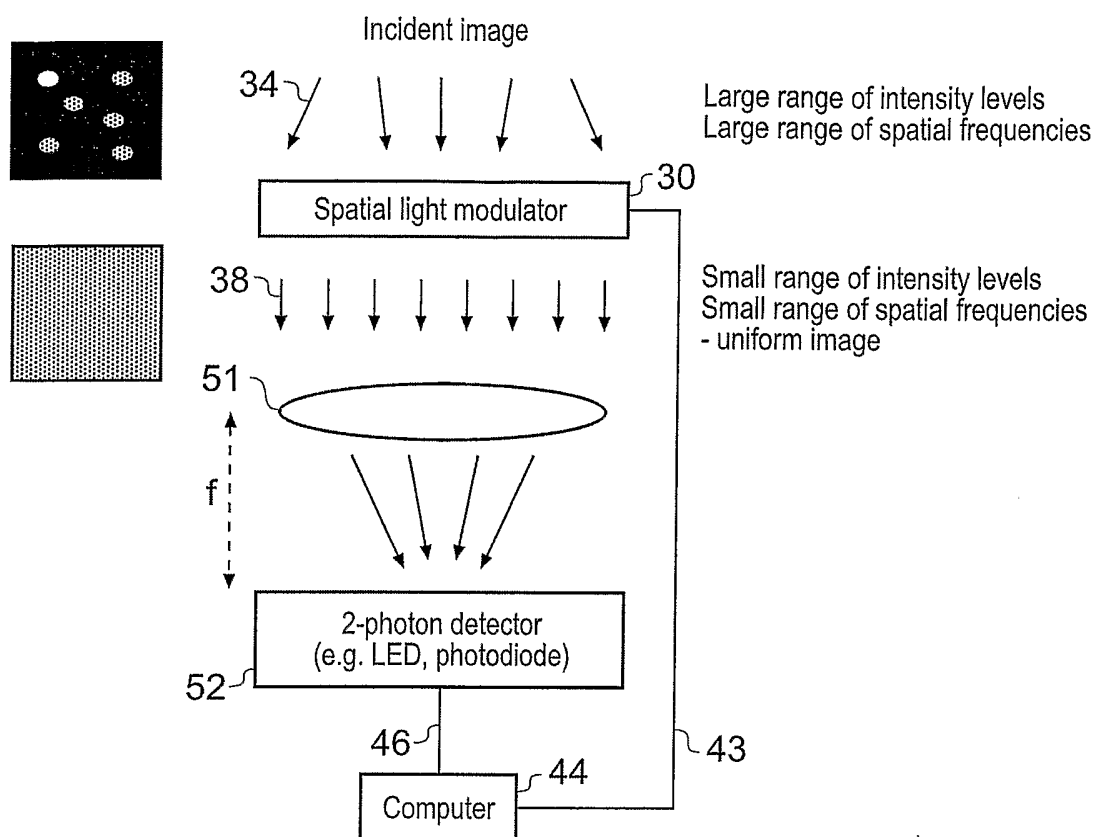


Fig. 9



# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/GB2005/001775

## A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 H04N5/238

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)

IPC 7 H04N

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 practical, search terms used)

EPO-Internal, WPI Data, PAJ

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	-/--	

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax: (+31-70) 340-3016

Authorized officer

Schreib, F

# INTERNATIONAL SEARCH REPORT

Int'l Application No  
PCT/GB2005/001775

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
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