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(54) **Title**: ADAPTIVE PHOTOTHERMAL LENS

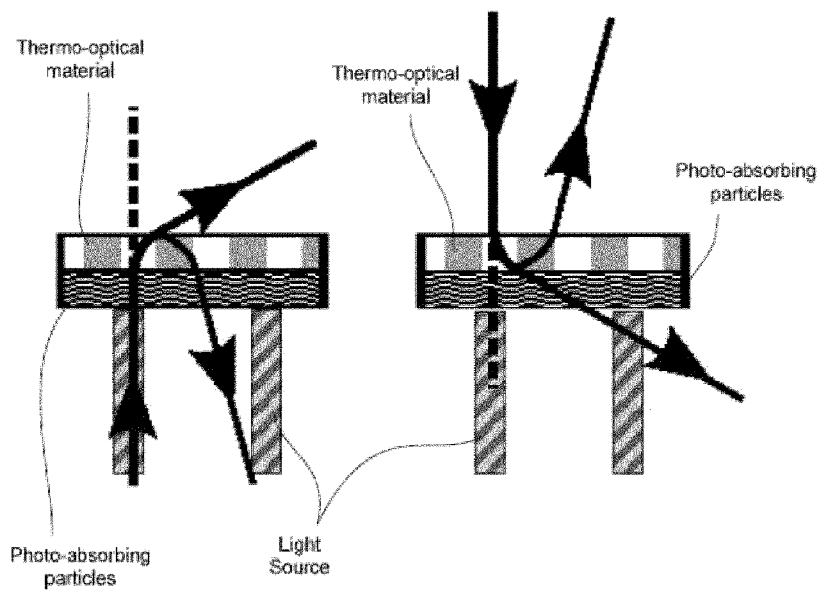

Fig. 1

(57) **Abstract**: An adaptive photo thermal lens comprising at least one cell, each cell provided with at least one photo absorbing particle, a thermo-optical material in thermal contact with the cells and at least one controllable light source for illuminating the photo absorbing particles, the light source having at least one spectral component which can be absorbed by the photo-absorbing particles and being controllable in wavelength and/or power and/or polarisation.

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ADAPTIVE PHOTOTHERMAL LENS

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to photothermal lenses, that is, lenses which have the ability of changing their properties by an induced temperature change and thus exhibit tunable properties.

Description of the Related Art

In the current general trend towards miniaturization, integrated micro-optical elements have played a central role in data storage, optical displays and imaging systems. Fine alignment and focus adjustment in these systems is usually performed by means of mechanical parts that are often expensive, fragile and slow. To overcome limitations introduced by mechanical adjustment, different electrical based inventions have been proposed.

A first strategy relies on reshaping the surface of a liquid using an electrical signal without altering the thermo-optical properties of the material. For instance, the electro wetting lens described in patent US 20130194323 A1 demonstrates that the shape of a liquid drop can be modified by applying a voltage. The local voltage applied to the surface changes the contact angle between the drop and the surface, thus modifying the shape of the drop, which results in a change of the focal point associated to the liquid based micro lens. Nevertheless, such an approach suffers from drawbacks, which include (but are not restricted to) difficulties of integration, slow time response (in some applications, acceleration of the system could alter the shape of the drop and introduce imperfections in the lens) and inability to simultaneously image multiple planes with a single lens.

A second strategy uses an electrical excitation to deliver energy which alters the lensing material, placed between two electrodes, and tunes its properties. Following this strategy, an electrically excited thermo-optical lens as disclosed in patent

US2005/0117195 has been invented. In this patent, a thermo-optical polymer is enclosed between two optically transparent surfaces, one of them curved, and a temperature controller is coupled to the thermo-optical material. This invention allows for the change of focal property of the such formed lens by changing the temperature. Although the entire focal plane of a single lens can be changed this invention does not allow for finer control such as local adjustment of the focal point, resulting in different focal planes induced by a single element. Furthermore, when considering this invention in a matrix configuration, there is a need to electrically address each lens, which could result in a complex engineering of the lens system, prohibiting its use in some applications.

Generally, electrical excitation can be limiting for some applications. To overcome the obstacles posed by mechanical and electrical induced lensing, inventions of optically controlled lenses appear to be relevant. Indeed, optical control eliminates the need to electrically wire each lensing element, and allows for remote control over the lens properties. Furthermore, eliminating the electric wiring or mechanical elements can help improve the transparency of the optical element. Along this line, a first strategy relies on reshaping the surface of a liquid using an optical signal without altering the thermo-optical properties of the material, where light energy is used to modify the surface energy of liquid droplets, which enables to control their shape. For example, liquid drops can be placed on a photo responsive layer, which is placed between a support layer and the droplet. As described in patent EP1304591A1, the droplet can be selectively irradiated with a light source which modifies the surface energy and thus the contact angle between the droplet and the layer, resulting in a variation of the focal length and the lateral position of the focal spot of the micro-lens. This lens still presents most of the drawbacks associated to electro wetting lenses including the ones described previously (difficulty of integration, slow time response and inability to simultaneously image multiple planes with a single lens).

SUMMARY OF THE INVENTION

The invention uses an optical excitation to deliver energy which alters the thermo-optical properties of the lensing material and enables a fine tuning of its optical properties. The above mentioned drawbacks are thus solved by providing an adaptive lens that is easy to integrate in any optical device for both a single and a matrix of lenses. Also, it is fast, robust and can be cheap. Furthermore it permits local adjustment of the focal point resulting in different focal planes induced by a single element. Note that by “light source” it is meant electromagnetic radiation, including but not limited to X-Rays, ultraviolet, visible, infrared, near infrared, short wavelength infrared, mid wavelength infrared, long wavelength infrared, far infrared, radiowave and radar sources. In this way, a predetermined distribution of temperature is created within the thermo-optical material. Examples of thermo optical materials include various liquids (such as water, octane, alcohols, glycerol, biological medium (blood, plasma, etc)), gases (such as air, helium) and solids (such as glass silica quartz, plastics or polymers). The change in refractive index is driven by the temperature profile, resulting in a local patterning of the refractive index. In this manner the focal length in at least one location may be adjusted, and the focal length throughout the plane can be locally modified. This modification can be performed in a continuous fashion resulting in a continuous control of the focal length or in discrete steps, leading to an array/matrix of individual thermal lenses. In the latter implementation the invention may comprise thermal barriers (materials of different thermal conductivity) between adjacent temperature controlled regions to provide thermal isolation between regions. The barriers can be applied by evaporation or sputtering and using a mask to pattern their location. The same process would be applied for a solid, liquid or gas phase thermo-optical material. In yet another aspect of the invention, a method of modifying an existing lens is proposed, where the photo absorbing particles are patterned onto the existing lens with the same techniques as explained before, which will act as the thermo-optical material, and when shined on with a light source can change the focal depth and lateral position of the original existing lens.

BRIEF DESCRIPTION OF THE DRAWINGS

To complete the description and in order to provide for a better understanding of the invention, a set of drawings is provided. The drawings illustrate a preferred embodiment of the invention, which should not be interpreted as restricting the scope of the invention, but just as an example of how the invention can be embodied.

Figure 1 is a schematic illustration of the principle of a thermal induced lens according to the invention.

Figure 2 displays various morphological photo absorber and light source patterns, which define cells and lensing locations.

Figure 3 shows how the temperature in the vicinity of photo-absorbing particles is increased in presence of a heating laser, which results in the lensing of an incoming light source.

Figure 4 presents experimental results obtained on different configurations using various patterns of photo-absorbing material for different heating light source properties.

Figure 5 characterizes the size and shape of different experimental lenses.

Figure 6 is a schematic illustration of the use of a thermal barrier between adjacent temperature controlled regions to provide thermal isolation between regions.

Figure 7 characterizes the time response required for a cell to adjust the focus while changing the energy absorbed by the photo absorbing material.

DETAILED DESCRIPTION OF THE INVENTION

The invention comprises one or an array of photoabsorbing particles, a thermo-optical material in thermal contact with said photoabsorbing particles, and at least one controllable light source for illuminating them, the light source having at least one spectral component which can be absorbed by the photo-absorbing particles and being controllable in power and/or polarisation and/or wavelength. By thermal contact it is implicit that physical contact is not necessary: the invention can incorporate any material between the absorbers and the thermo optical material as long as the photoabsorbing particles change temperature when illuminated. In this text the term cell is defined as the optical interaction area overlapping between one or an array of photoabsorbing particles and a heating light source (an example: a micrometric gold disk as shown in Figure 4a top left, or also a smaller particle or an array of nanostructures, like gold nano-antennas in Figures 4a right top and bottom or Figure 5b).

The image focal plane of the invention can be dynamically shaped by a control optical signal from the source. The approach relies on the temperature dependence of the refractive index of some materials and the ability of photo absorbing materials to generate heat and create a predetermined distribution of temperature when illuminated with light. A local increase of temperature induces a change in the refractive index that affects the propagation of light. As illustrated in Figure 1, a patterned absorbing material absorbs at least a part of a light source. This energy absorption results in a temperature increase of a thermo-optical material that is in thermal contact with at least a part of the photo-absorbing particles. Therefore, the optical index of the thermo-optical material is modulated in space and time depending on the light absorption. This optical index modulation deviates/refracts a second light source when the latter crosses the thermo-optical material. The second light source lensed by the optical index modulation can arrive to the thermo-optical material either through the absorbing material (left) or directly to the thermo-optical material (right). Also, depending on the reflectivity/transmission of the system, the invention can be used in transmission and/or in reflection (in both left and right Figures, the second light source is transmitted and/or reflected).

The particles are patterned such that the desired temperature distribution is achieved. The interaction areas between the heating light source(s) and absorbing particles define the size and location of the cells which give rise to the lensing effect because of their interactions with the thermo-optical materials. By interaction areas, it is implicit that the size and/or location of the cells is not necessarily exactly the same as the physical overlapping between the absorbing material and the heating light source but rather the optical interaction area. The invention can incorporate any configuration for the interaction areas between the absorbing material and the heating light source, as depicted in Figure 2. In Figure 2a, a scanning electron microscopy (SEM) image of a large and continuous array of gold photoabsorbers, deposited by electron beam lithography, can be seen. Figure 2b shows a SEM image of isolated photo-absorber areas, within each area there are many single photo-absorbing particles. 2c is a sketch of a single photoabsorbing area which is illuminated with a light source that is smaller than the size of the absorbing area. In this case the size and location of the cell is defined by the light source, while 2d shows separated photoabsorbing areas. In the latter, the light source is larger than one isolated area, and covers four areas, there are thus four cells and their locations are defined by the illuminated photo absorbing areas. Figure 2e shows one continuous area of photoabsorbers with four separated light sources, where the size and location of the cells are defined by the beams. In Figure 2f separated photoabsorbing areas can be seen, where four areas are partially illuminated by four light sources. The size and location of the cells are defined by the overlapping region (or interaction area) between the light beams and the photoabsorbers.

In some embodiments, the cells are inside or on a substrate. The substrate can be made of glass, quartz, silica, plastics, or polymers among others. This enables to use the lens in a transmission configuration. Alternatively, the substrate could be made of an opaque material such as silicon, etc. which enables to use the invention in reflection mode. Also, the substrate can have a dependence of the light transmission (for example spectral, angle or polarization dependence), which enables to work in transmission and reflection mode simultaneously. This kind of substrate can be created by different means including a layered media or a dichroic element.

Figure 3 illustrates a cell created on half of the patterned photo-absorber area delimited by a disc shape and made of nano-particles (gold nano-antennas, as in Figure 4a) by shining a heating light source (infra-red laser of wavelength 800nm, for example).

The particles can be positioned on top of a substrate, patterned onto the same. The photo absorbing particles can be made of different materials including metals (for example gold, silver or copper), alloys (for example titanium nitride or silicon carbide) and semiconductor materials (for example silicon or germanium). The pattering can be done by e-beam lithography, photo- lithography, laser writing, evaporation, sputtering, reactive ion etching (RIE) and/or chemical vapor deposition (CVD).

A particularly advantageous embodiment uses electron-beam lithography and evaporation techniques to fabricate gold micro and nano structures (see the scanning electron microscope images in Figure2a-b (patterning of the absorber on a substrate) and Figure4a (size and shape of two different absorbing structures)).

The photo absorbing particles can be structured at any scale, namely: macro, meso, micro and nano scales. This structuration could be used to reduce the size of the lens and/or to enhance the efficiency of light to heat energy conversion of the photo absorbing material. An example of such an enhancement is given by using plasmonic nano structures such as: nano antennas, nanorods, nano holes, nanoparticles, nano stars, nano oligomers, multi branch nano particles amongst others. Figures 4 and 5 show that the use of plasmonic structures enables to enhance the lensing effect (Figure4) and to control the size and shape of the cells (Figure5) by taking advantage of the resonances supported by these nanostructures. Plasmonic nano particles are thus preferred, as they provide better results, but the invention is not limited to such particles.

Figure 4 shows an efficient plasmonic heating for a thermal lens and lens transfer function characterization. Figure 4a are SEM images of a full 5 µm radius gold disc (left), and a 5 µm radius disc made of Nano-Rods (NR) (right). A higher magnification image of the 120X80X50 nm nano rods is presented. The corresponding absorption spectrum displays a Surface Plasmon Resonance (SPR) at 800nm. Figure 4b shows a focus shift and optical index variation in dependence of a 800nm laser power shined on a NR disc (from a) excited at the SPR with a parallel polarization (black crosses +), a NR disc excited off resonance using a perpendicular polarized configuration (black crosses X), a full gold disc (black dots) and in absence of any structure (black squares). Figure 4c shows the linear dependence of the focus shift for the disc made of nano-rods excited at the SPR (similar to + in b.) as a function of the 800 nm heating laser power until a power of 30 mW. In Figure 4d, absorption spectra can be seen, recorded on two different arrays made of gold nano-rods having slightly different sizes (100X80 nm and 120X80 nm). The morphology change results in a shift of the SPR spectral position. The absorption of these two different morphologies of photoabsorbing particles is different for the considered heating light source. In Figure 4e, a focus shift and optical index variation in dependence of a 800nm laser power shined on the two different areas are described.

Figure 5a shows the contrast improvement of a 2.5 µm grating (as a function of the location X) due to thermal lensing. From the contrast improvement we determined the in-plane lateral size of the region where the refractive index of the thermo-optical material is modified. This was done by imaging a grating in absence and in presence of a heating light source (infra-red laser beam of wavelength 800 nm in this case, images are presented in the inset of Figure 5a) acting on a patterned photo-absorber area (as in Figure 2c for one laser beam, radius of the beam is 5µm).

Figures 5b-d show the possibility to locally and dynamically change the focal points within a single element by modifying the heating light source properties (polarizations in Figure 5c-d) while keeping the same patterned absorbing material. The heating light source is focused to an area larger than the considered photo-absorbing particles array presented in Figure 5b. In this case, the interaction area between the heating light source and the considered photoabsorbing particles array defines the size and shape of the induced thermal lens (as sketched in Figure 2d). More precisely, Figure 5b is a SEM image of a cross shape structure made of nanorods (NR) by electron beam lithography. The NR are similar to the ones displayed in Figure 4a (top and bottom right) and present a resonance in the near infrared at 800 nm. The two insets correspond to a zoom of each arm of the cross and show that the nano-rods are oriented perpendicularly in each arm. Figure 5c shows a local focus shift for a light polarization oriented along the vertical direction of Figure 5b so that the nanorods of the vertical axis of the cross are resonant with the excitation and therefore absorbs efficiently the light. Figure 5d is the same as 5c, but with the incident light polarization oriented along the horizontal direction.

All these embodiments can be considered for a uniform thermo-optical material or a thermo-optical material patterned with thermal barriers as shown in Figure 6.

In Figure 7, the time response of the thermal lens in dependence on the size of the interaction area is shown. Figures 7 a-c, show the rise time of the thermal lens made of a 10,5 and 2 µm diameter disc in a,b and c, respectively. The discs are made of gold nano rods (as in Figure 4a on the top right). Experimental results of the rise time are plotted as function of the disc diameter in Figure 7d.

Particular example:

We fabricated an array made of gold nanorods (120 x 80 x 50 nm3) positioned with a pitch of 300nm (fig4a right top and bottom), that lead to a maximum of absorption at 800nm (Figure 4a, bottom left) at their longitudinal plasmon mode; *i. e.* for the incident field linearly polarized along the nanorods long axis. The gold nanorods are pattered in an area of a disc having a radius of 5 micrometers (Figure 4a top right). We also fabricated a full gold disc with a 5 micron radius (Figure 4a top left). To heat the structures, we used a laser light source with a wavelength of 800 nm linearly polarized along the principle axis of the nanorods.

We first measured the relationship (transfer function) between the incoming heating laser power and the resulting focus shift of an incident light source (blue laser diode of wavelength 473 nm) (Figure 4c). The heating beam was set to a radius of 5 µm. We obtained a linear dependence of the focus shift for the gold disc made of nano-rods as a function of laser power for the range of 0 - 30 mW.

Consequently, we measured the focus shift of a NR disc (as before) as illuminated with the same 800 nm laser, in the power range of 0-15 mW both for parallel and perpendicular polarization. The resulting linear dependence is presented in Figure 4b. This result is again given for a focus shift of a 473nm diode laser. Also, the focus shift as function of incoming heating laser (800 nm) power was recorded for a full gold disc with radius of 5 µm (a single particle), for powers spanning the range of 0-15 mW (Figure 4b). Finally, the focus shift when there is no absorbing structure was measured for different heating powers (Figure 4b). For all these experiments the resulting temperature was measured (using a method called fluorescence polarization anisotropy), from which the change in refractive index was extracted for each case (Figure 4b).

In yet another experiment, we measured the absorption spectra on two different arrays made of gold nano-rods having slightly different sizes (100X80 nm and 120X80 nm in both pitch of the NRs is 300 nm), Figure 4d. The morphology change causes a shift of the SPR spectral position. The absorption of these two absorbing structures is therefore different for a considered heating light source.

Consequently, the focus shift and optical index variation in dependence of a 800nm laser power (0-10 mW) shined on these two different areas made of gold NRs and delimited by the same disc shape (radius of 5 µm) are different as shown in Figure 4e.

To characterize the size and shape of a cell, the contrast of a 2.5 µm grating is calculated with thermal lensing normalized by the contrast without a thermal lens as a function of the location X (Figure 5a). To this end the grating is placed above a thermal lens made of: an array of photo absorbing particles as described above and in Figure 4a, water as the thermo-optical material, and a 800 nm heating laser beam focused to a radius of 5 µm. We determined the in-plane lateral size of the region where the refractive index of the thermo-optical material is modified to be 6.5 µm (by measuring the FWHM of the contrast ratio graph).

Figure 5b-d show the possibility to dynamically change the size and shape of a cell by modifying the heating light source properties and specifically here (Figure5c-d) we changed the polarization while keeping the same patterned absorbing material. Figure 5b presents a SEM image of a cross shape structure made of nanorods (NR) by electron beam lithography followed by gold evaporation. The NR are similar to the ones displayed in the Figure 4a botom right and present a resonance in the near infrared at 800 nm. The two insets of Figure 5b correspond to a zoom of each arm of the cross and show that the nano-rods are oriented perpendicularly in each arm. Figure 5c shows local focus shift for a heating laser light source of 800 nm with a polarization oriented along the vertical direction of Figure 5b so that the nanorods of the vertical axis of the cross are resonant with the excitation and therefore efficiently absorbs the light. In Figure 5d the incident heating light polarization is oriented along the horizontal direction. In both 5c and 5d the asymmetric nature of the thermal lens can be evidenced, as well as the local control of the focus shift by changing the incoming polarization while keeping the same patterned absorbing material and heating light source size and power.

In this text, the term “comprises” and its derivations (such as “comprising”, etc.) should not be understood in an excluding sense, that is, these terms should not be interpreted as excluding the possibility that what is described and defined may include further elements, steps, etc.

On the other hand, the invention is obviously not limited to the specific embodiment(s) described herein, but also encompasses any variations that may be considered by any person skilled in the art (for example, as regards the choice of materials, dimensions, components, configuration, etc.), within the general scope of the invention as defined in the claims.

CLAIMS

1. An adaptive photo thermal lens comprising at least one cell, each cell provided with at least one photo absorbing particle, a thermo-optical material in thermal contact with the cells and at least one controllable light source for illuminating the photo absorbing particles, the light source having at least one spectral component which can be absorbed by the photo-absorbing particles and being controllable in wavelength and/or power and/or polarisation, each cell being defined by the optical interaction area between the particle or particles and the light source or light sources.

2. An adaptive photo thermal lens according to claim 1 wherein the photo absorbing particles are patterned on a substrate.

3. An adaptive photo thermal lens according to any of the previous claims wherein the photo absorbing particles are plasmonic particles and the source is adapted to emit at their plasmonic resonance.

4. An adaptive photo thermal lens according to claim 3 wherein the plasmonic particles are one or a combination of nano antennas, nanorods, nano holes, nanoparticles, nano stars, nano oligomers and/or multi branch nano particles.

5. An adaptive photo thermal lens according to claim 4 wherein the plasmonic particles are Au nano particles.

6. An adaptive photo thermal lens according to any of the previous claims wherein the thermo-optical material is water, glycerol or octane.

7. An adaptive photo thermal lens according to any of the previous claims provided with an array of cells, each cell being defined by the spot size of the source or sources.

8. An adaptive photo thermal lens according to any of the previous claims wherein the cells are defined by the physical location of the photo absorbing particles.

9. An adaptive photo thermal lens according to any of the previous claims provided with one source and a galvanometric mirror for providing different positions of a spot of the source.

10. An adaptive photo thermal lens according to any of claims 1-8 provided with a plurality of light sources.

11. A micro lens array comprising a plurality of lenses as in any of the previous claims.

12. Use of any of the adaptive photo-thermal lenses of claims 1-10 in transmission or reflection mode.

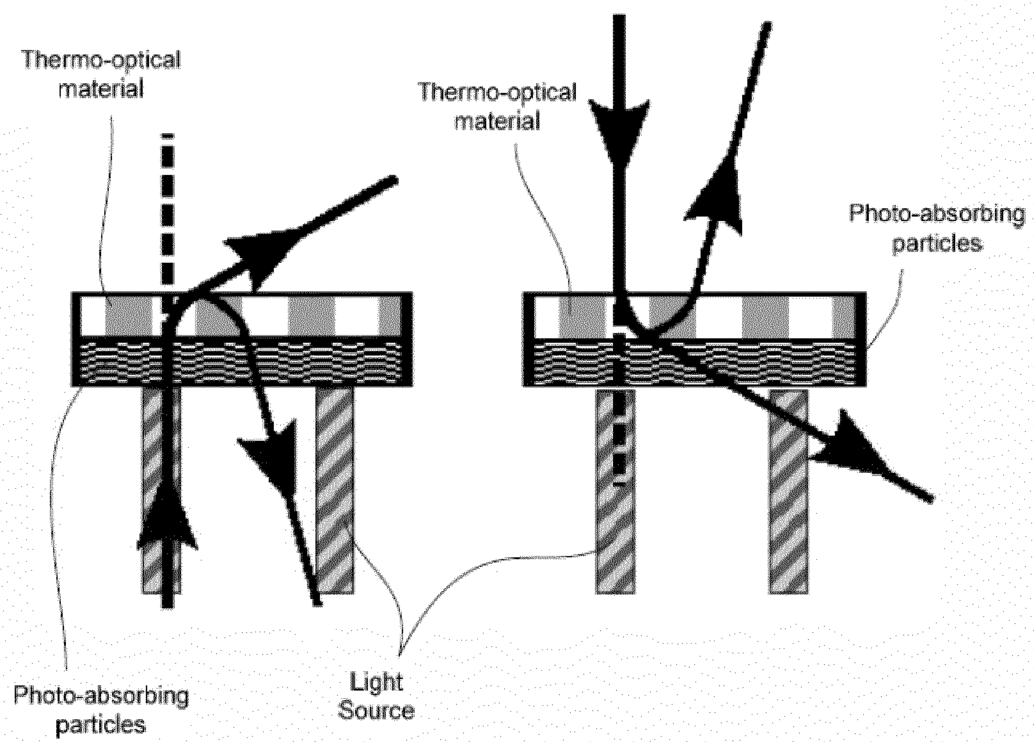

Thermo-optical material
Thermo-optical material
Photo-absorbing particles
Photo-absorbing particles
Light Source

Fig. 1

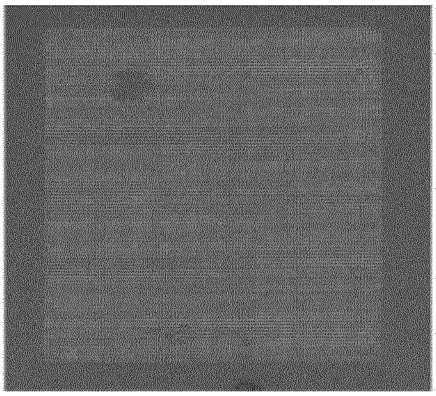


Fig. 2A

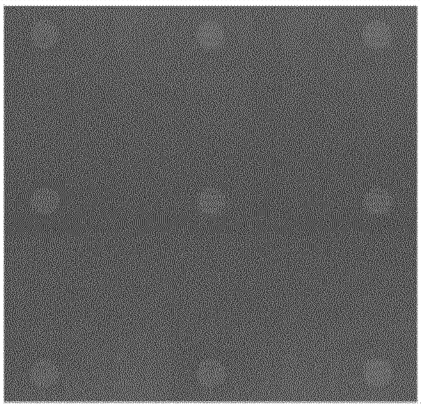
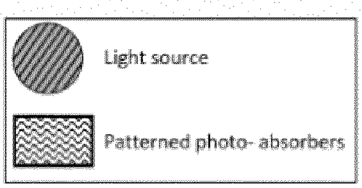


Fig. 2B



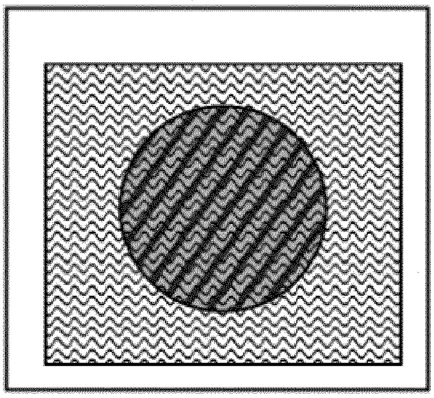


Fig. 2C

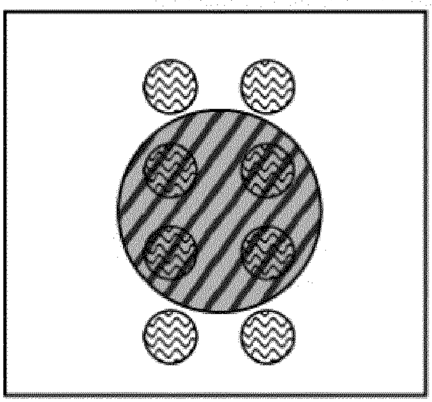


Fig. 2D

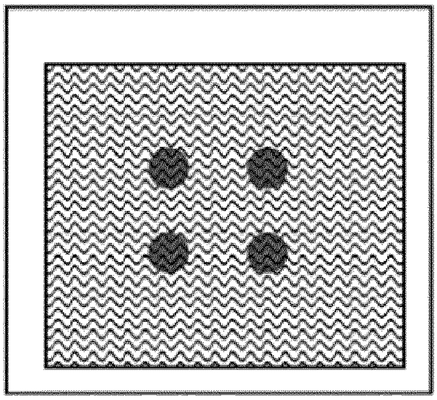


Fig. 2E

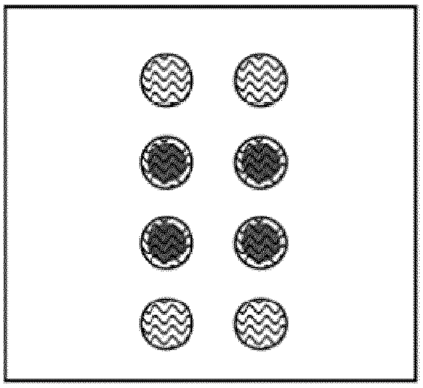
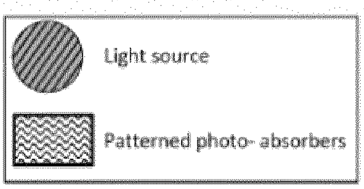


Fig. 2F



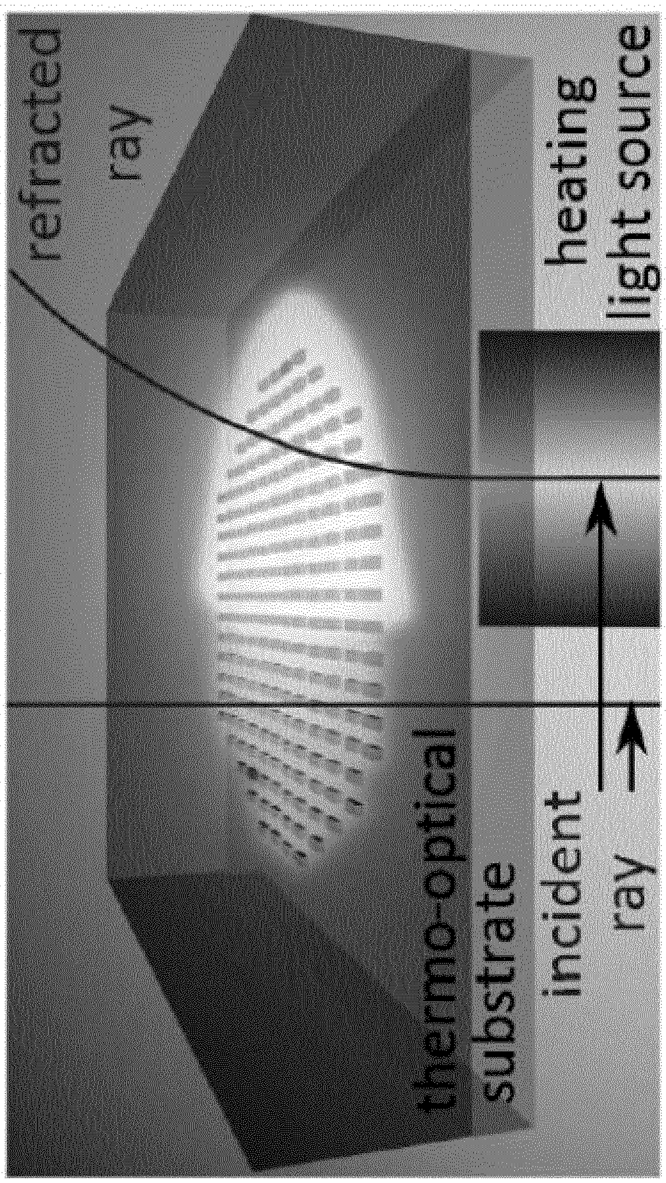

refracted ray
heating light source
thermo-optical substrate
incident ray

Fig. 3

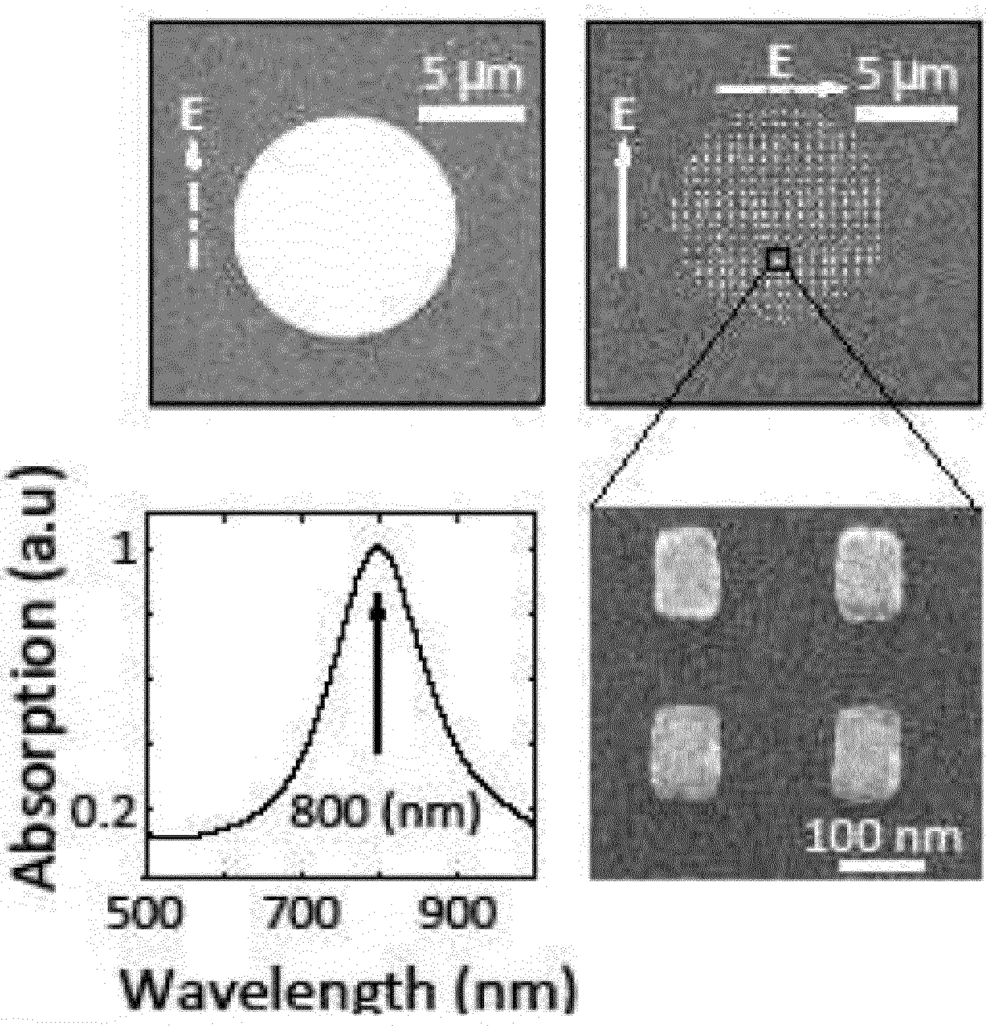

5 µm
E
E
5 µm
Absorption (a.u)
1
0.2
800 (nm)
500
700
900
Wavelength (nm)
100 nm

Fig. 4A

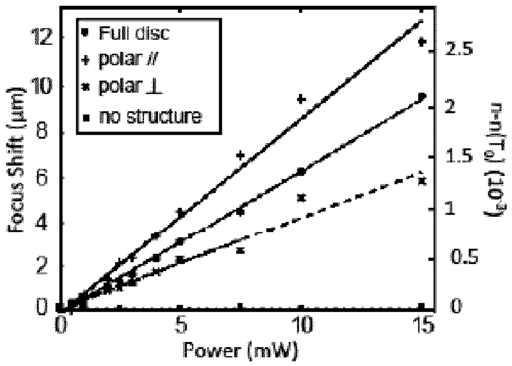


Fig. 4B

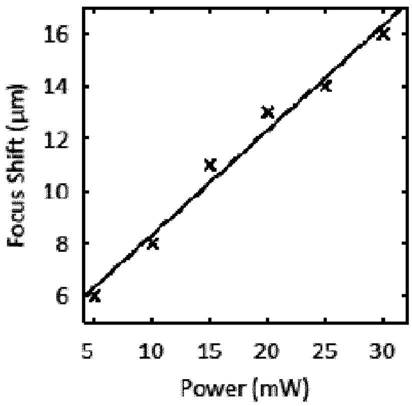


Fig. 4C

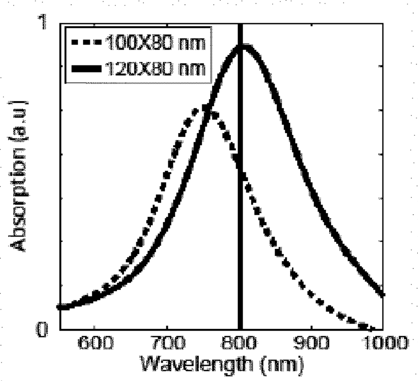


Fig. 4D

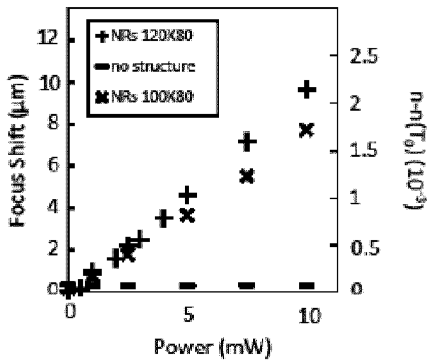


Fig. 4E

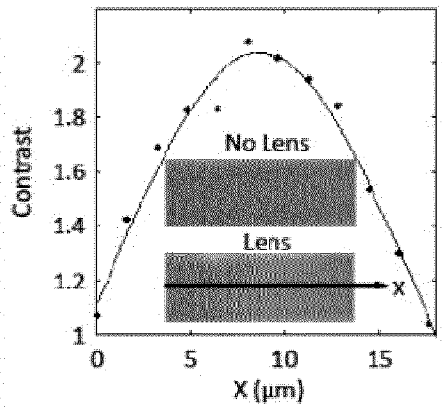


Fig. 5A

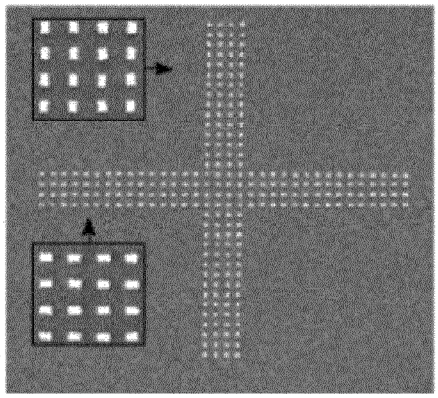


Fig. 5B

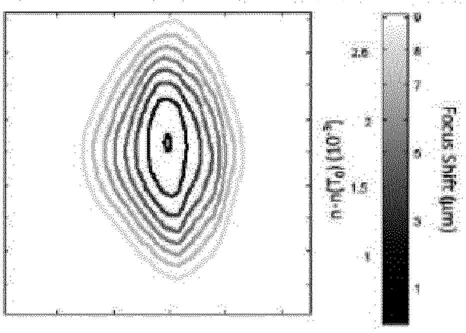


Fig. 5C

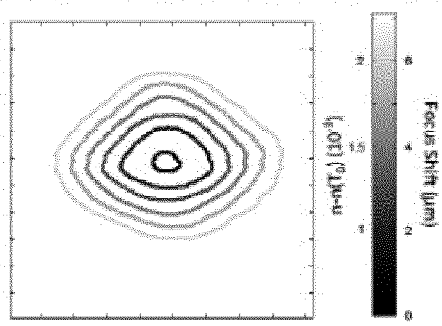


Fig. 5D

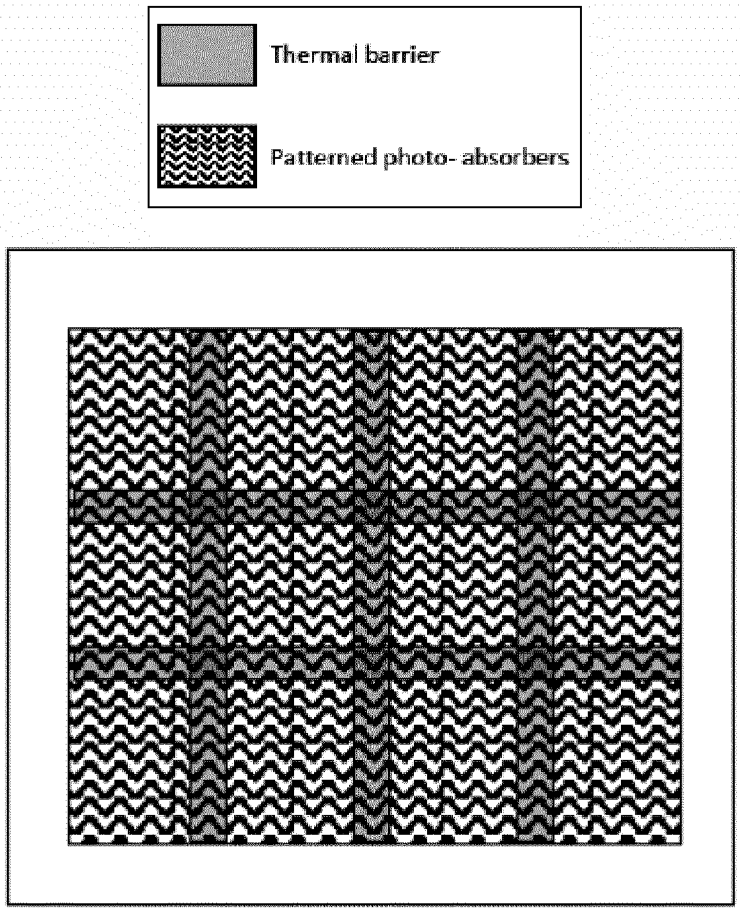


Fig. 6

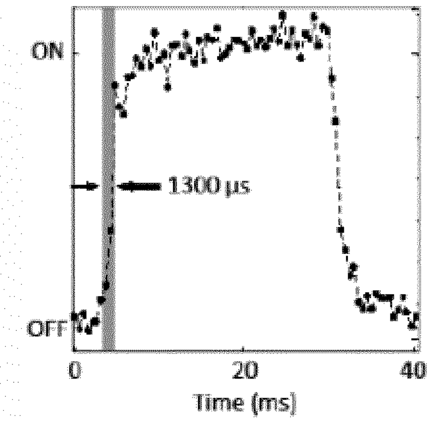


Fig. 7A

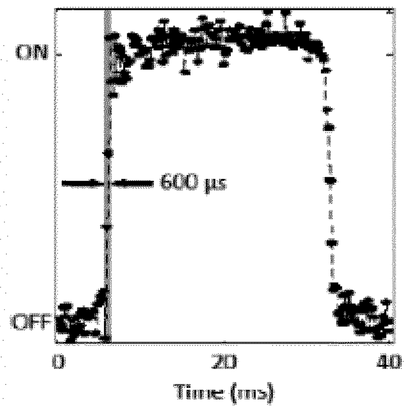


Fig. 7B

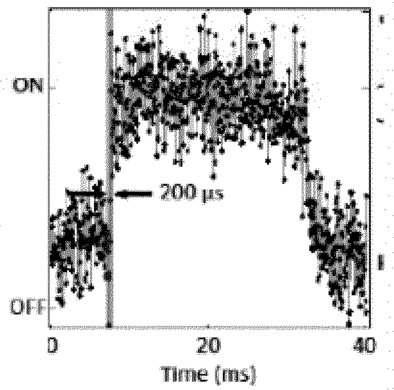


Fig. 7C

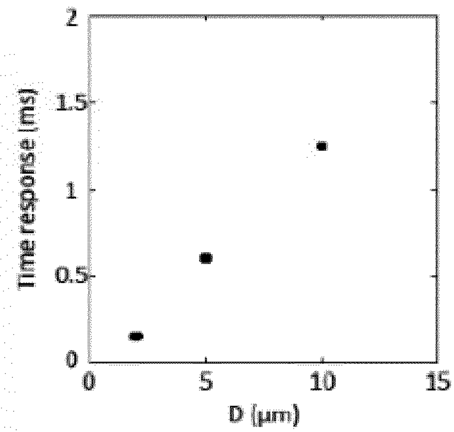


Fig. 7D

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2015/056069

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02F1/01 G02B3/00 G02B3/12 G02B3/14
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)
G02F G02B

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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X	US 2013/137054 A1 (JIANG HONGRUI [US] ET AL) 30 May 2013 (2013-05-30) paragraphs [0021], [0033], [0055] - paragraph [0059]; figures 3(a),(b),9(a),(b),10	1,2,7,8, 10-12
X	WO 2009/156816 A1 (KILOLAMBDA TECH LTD [IL]; DONVAL ARIELA [IL]; NEMET BOAZ [IL]; NEVO DO) 30 December 2009 (2009-12-30) page 5 - page 6; figure 1	1-5,9,12
X	WO 2004/027508 A1 (NAT INST OF ADVANCED IND SCIEN [JP]; DAINICHISEIKA COLOR CHEM [JP]; UE) 1 April 2004 (2004-04-01) Pages 4,5,11,20,25-26; pages 41-47; figures 1-6	1,3-8, 10,12

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
15 July 2015	24/07/2015

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Feeney, Orla

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	US 4 585 301 A (BIALKOWSKI STEPHEN E [US]) 29 April 1986 (1986-04-29) column 6 - column 8; figures 3,4,5	1,12

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Information on patent family members

International application No

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