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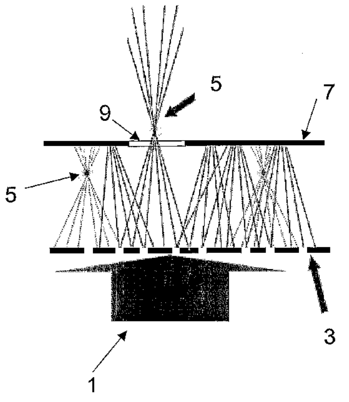
(54) Title: AN OPTICAL SYSTEM AND METHOD FOR SUB-WAVELENGTH ENERGY CONCENTRATION



(57) Abstract: An optical system configured to direct radiation onto an object, said system comprising a source of radiation and a lens (3), said lens comprising an arrangement of features (13) configured to allow transmission of radiation from said source, the object being located at a distance from the lens (3) such that at least one caustic (5) due to diffraction of radiation through the features (13) is in focus on said object, said caustic (5) having at least one dimension which is smaller than the wavelength of the radiation from the source.

AN OPTICAL SYSTEM AND METHOD FOR SUB-WAVELENGTH ENERGY CONCENTRATION

The present invention relates to the field of optical systems and methods which may be used for imaging, investigating, writing etc. More specifically, the present invention relates to an optical system which can be used to image or produce features smaller than the radiation wavelength used in the system.

Spatial resolution of conventional optical instruments is fundamentally limited by the wavelength of light. Use of shorter wavelength light increases resolution, but is limited by the deleterious effect of such wavelengths on the irradiated materials and availability of short-wavelength optical sources and lasers.

The introduction of negative index materials and the "superlens" concept based on their uses has created an incredible opportunity to break the wavelength barrier. The superlens, however, requires the development of optical negative index media. Substantial progress has been possible here, however, a practically acceptable solution is still far away, particularly in the visible and NIR regimes.

Other methods of trying to overcome the diffraction limit include scanning near field optical microscopy where a probe with a sub-wavelength diameter aperture is employed either to illuminate (or collect light from) a sample that is placed within its near field, at a distance much less than the wavelength of the light, e.g. 2-20 nm. The probe is scanned over the surface, and the optical signal from the surface is collected and detected. The primary limitation of this system is that an exact and very small distance between the light source and sample surface must be maintained throughout scanning. This requires precise feedback directed control of the probe (or sample) position during scanning, resulting in very slow scan times of minutes-hours. The up-down movement of a probe following the topography of the sample surface often results in topography-related artefacts in measured optical results, which harms its credibility of working at close distances proximity to the sample surface, while on that its high resolution capability relies. Furthermore, the small high resolution working distance, e.g. 2-20 nm, prohibits applications of this technique on wet biological samples, e.g., investigating the inner structure of a cell.

Another proposed method is of the type described in US2006/0153045 which uses a metal element with subwavelength structures which is believed to operate using the coupling resonance of the surface plasmon waves and light to deliver energy through the metal element such that a sub wavelength “funnel” of light is produced.

Applications where optical resolution is known to be limiting capability are microscopy; photolithography; optical data storage devices; laser surgery and other areas of nanophotonics.

Most ideas (like the mentioned methods above) for achieving super-resolution in optics are based on the recovery of evanescent fields which contain field components with spatial frequency higher than the wavevector of light. Evanescent fields are commonly believed to be the necessary components to form subwavelength field concentrations. However, a recent remarkable theoretical discovery suggests that evanescent fields may not be needed to achieve subwavelength concentration of light in the far field: Berry and Popescu (J.Phys.A: Math.Gen. 39 (2006) 6965-6977) predicted that diffraction on a grating structure could create subwavelength localizations of light that propagate further into the far field than more familiar evanescent waves. They relate this effect to the fact that band-limited functions are able to oscillate arbitrarily faster than the highest Fourier components they contain, a phenomenon called superoscillations.

The present invention provides a sub-wavelength technique which at least partially addresses the above problems by exploiting the superoscillation effect and in a first aspect provides an optical system configured to direct radiation onto an object, said system comprising a source of radiation and a lens, said lens comprising an arrangement of features configured to allow transmission of radiation from said source, the object being located at a distance from the lens such that at least one caustic due to diffraction of radiation through the features is in focus on said object, said caustic having at least one dimension which is smaller than the wavelength of the radiation from the source.

Thus, the object is placed at a subwavelength focal point or other focus. Here a caustic is formed from the superposition of partial waves from a plurality of features in the arrangement.

The arrangement of features which may be a quasi-crystal array of holes in metal film creates well isolated sub-wavelength hot-spots or caustics of electromagnetic energy concentration when the array is illuminated with a coherent beam of light or even non-coherent white light. Importantly, the hot spots or caustics appear at a distance of a few microns to tens of microns from the film which is a convenient distance for lithography and microscopy.

Thus, the present invention allows:

- the ability to produce light spots of sub-wavelength diameter;
- the high light intensity of these spots (relative to light spots generated by aperture constriction only);
- the long focal distance at which the spots are produced (2-50 micrometers) and
- the depth of this focal field is up to a few hundred nanometers.

The underlying reason for sub-wavelength energy concentration is in the cooperative interference of multiple beams diffracted from the individual small holes. This is a process similar to the self-imaging of periodic structures in the Talbot effect. The peculiarity of the near-field diffraction on the quasi-crystal array is that it can provide high intensity, clearly isolated hot spots of optical energy concentration. The ultimate resolution achievable with this arrangement is determined not by the wavelength, but by the diameter of individual hole of the array, type of the pattern and the number of holes cooperatively interfering at the given distance from the array. Although the Talbot effect has been known for a considerable time and the formation of field caustics has been theoretically investigated, its use for achieving a sub-wavelength resolution has never been discussed.

For example, a quasi-crystal array of holes in metal screen creates well isolated sub-wavelength hot-spots of electromagnetic energy concentration when the array is illuminated with a coherent beam of light. This lends to applications in light-pen nanolithography and optical imaging of small objects like cells, structures on semiconductor microchips and nano-particulates.

The arrangement may comprise quasi-crystal array of holes, a regular array of holes, a quasi-periodic arrangement of holes, a fractal arrangement of holes or rings.

The size and intensity of the spots can be modified through modifying the array structures and conditions used, in particular by modifying the size of the holes, the pattern of holes, the characteristics of the incident light and depth of illuminated surface. Specifically smaller light spots and more intense light spots may be generated. Different arrangements of holes may be used, including regular, quasi-crystal and quasi-periodic arrangements of holes. As mentioned above, sub-wavelength rings may also be used.

The lens may comprise a metal film and said arrangement of features is provided through said metal film. However, the arrangement may be provided in any type of material which blocks the radiation from the source, or transparent materials with featured phase contrast.

Preferably, the object is placed at a distance from 2 μm to 50 μm, preferably from 10 μm to 25 μm from said lens.

With such high localization of light, imaging with subwavelength resolution can be achieved by scanning the investigated object against the focal spot. Similarly, a single hot spot appropriately isolated by a mask may be used as a "light pen" in high resolution photo-lithography.

Thus, the present invention may comprise a means to isolate a single caustic. For example, a mask may be provided.

In a further embodiment, the system further comprises an optical fibre, said source being configured to direct radiation into a first end of said fibre and said lens being provided at the other end of said fibre.

The system may also further comprise means to scan the lens such that the caustic is scanned relative to said object.

In a preferred embodiment, the present invention also comprises a detector. The detector may be provided on the same side of the object as the source or the opposing side of said object to said source.

It is also possible to use the system to image sub-wavelength features by using the lens to focus the radiation after it has impinged on the object to be studied.

Thus, in a second aspect, the present invention provides an optical system for examining an object, the system comprising a source, configured to direct radiation onto an object, a lens configured to collect radiation from said object and a detector configured to receive radiation from said lens, said lens comprising an arrangement of features configured to allow transmission of radiation from said source, the object being located at a distance from the lens such that at least one caustic due to diffraction of radiation through the features formed, said caustic having at least one dimension which is smaller than the wavelength of the radiation from the source.

Thus, the lens is capable of creating at least one subwavelength caustic in space when illuminated by the radiation from said source.

The present invention may also be used for imaging, thus in a third aspect, the present invention provides an imaging system for imaging an object, said system comprising a source, configured to direct radiation onto an object and a lens configured to collect radiation from said object and project it onto an image plane, said lens comprising an arrangement of features configured to allow transmission of radiation from said source and to produce a super-oscillating optical field, where at least one focus of the field has a dimension smaller than the wavelength of the radiation from the source.

The present invention may be configured for many uses, one particular use is in microscopy. The resolution of a conventional optical microscope such as a confocal microscope is limited by the diffraction limit of light, which is about half the wavelength of the illumination light. Resolution below the diffraction limit is currently only achievable through a system called Scanning Near-field Optical Microscopy (SNOM/NSOM). Advantages of the present invention over SNOM/NSOM derive principally from the increased operating depth (a few microns to tens of microns), enabling very fast scan speed without the need of employing a feedback control system, which will greatly save times in applications and have key advantages in particular areas, e.g., in bioscience research, where *in-situ* observation is key in many processes. The long focal distances (a few microns to tens of microns) of the present invention also allow them to probe the inner structure of cells, a job forbidden for SNOM/NSOM due to their extremely short working distances. Currently, investigation of inner structures of cells are usually conducted by nonlinear optical effects, such as two-photon fluorescence, Coherent anti-stokes Raman scattering (CARS) etc. However, these performances require expensive pulsed laser sources, which may not be accessible by many research labs. Furthermore, the response of nonlinear optical processes is low, requiring high power illumination, which may cause damages to delicate samples.

The advantages of the present invention over conventional optical microscopes are many. First, its subwavelength focusing capability is not achievable by the conventional optical microscopes due to the diffraction limit; Secondly, the size of the subwavelength light concentrator is small (from tens to hundreds of microns), which allows them to be integrated in microchips. Thirdly, the subwavelength light concentrator can work not only as a single “writing pens”, it also can be patterned in an array and thousands of them work simultaneously, which may find great applications in industry, e.g, photolithography.

Optical microscopy based on the new technique combines the advantages of the conventional optical microscopy (fast, non-contact, deep focal depth) and the scanning near–field optical microscopy (subwavelength resolution), and short of their drawbacks, such as diffraction limited resolution of conventional optical microscopy; slow scan speed, short working distance of SNOM/NSOM.

Applications of this invention include optical imaging of small objects like cells, structures on semiconductor microchips and nano-particulates, nanoscale optical writing including photolithography and data recording, and other nano optical applications such as microlaser surgery, and security markings.

The present invention may be applied to photolithography. Photolithography resolution limits chip detailing & processor speed. Thus, it is possible to enable creation of smaller detail in chip manufacture with consequent increases in processor speed. Thus, said object may be a photosensitive material.

The present invention may also be applied to optical storage technologies, for example in DVD and RW-DVD like technologies for improved storage capacity. Thus, said object may be an optical storage medium.

Previously, the present invention has been discussed mainly for imaging etc. However, it may be used as a cutting tool since the radiation is concentrated.

Thus, in a fourth aspect, the present invention provides a cutting tool comprising a source of radiation, an optical fibre and a lens, said source configured to direct radiation into an input end of said optical fibre and said lens being provided at the output end of said optical fibre, said lens comprising an arrangement of features configured to allow transmission of radiation from said source.

The lens is configured to allow the formation of subwavelength caustics in space

The lens comprises an arrangement of features configured to allow transmission of radiation from said source and to produce a super-oscillating optical field, where at least one focus of the field has a dimension smaller than the wavelength of the radiation used to illuminate the lens.

The present invention will be now described in more detail with reference to the following non-limiting embodiments in which:

Figure 1a shows an example of a function composed of simple harmonics, which is superoscillating at x=0, figure 1b is a schematic of an apparatus in accordance with an embodiment of the present invention, figure 1c is a diagram showing the construction of a caustic from a superposition of partial waves from features within the arrangment of the lens;

Figure 2a is a picture of the optical field distribution on an object placed at a distance of 200nm from a lens having a quasi-crystal array of holes in accordance with an embodiment of the present invention, Figure 2b shows the optical field obtained in the manner described in figure 1b at a distance of 10μm from the lens, figure 2c shows the field distribution achieved at a distance of 25μm from the lens and figure 2d shows a scan through an individual spot shown in figure 2c and the de-convoluted energy distribution assuming a near-field probe aperture of 200nm;

Figure 3a is a picture of the optical field distribution measured at a distance of 5 μm from a lens having a quasi-crystal array of holes in accordance with an embodiment of the present invention, figure 3b shows a selected subwavelength spot from figure 3a, figure 3c shows the intensity profile across the scanned spot of figure 3b, figure 3d is a picture of the optical field distribution measured at a distance of 12.5 μm from the lens, figure 3e shows a selected subwavelength hot spot from figure 3e and figure 3f shows the intensity profile of the spot of figure 3e; figure 3g is an image of the pattern provided on the lens used to produce the data shown in figures 3a to 3f and figure 3h is an SEM photo of part of the pattern of figure 3g, figure 3i shows pictures of the caustic or “hot-spot” formed at distances of 6.4 μm, 6.6 μm, 6.8 μm, 7.0 μm, 7.1 μm, 7.2 μm, 7.4 μm and 7.6 μm from the lens and figure 3j is a plot showing how the intensity of the spot and the width of the spots shown in figure 3i vary with the distance (h) from the lens;

Figure 4a is a schematic of a further apparatus in accordance with an embodiment of the present invention used for detection, figures 4b and 4c show a further system in accordance with an embodiment of the present invention used for imaging;

Figure 5a shows an apparatus in accordance with an embodiment of the present invention where an aperture is used to isolate a single focus spot to irradiate a small object, and figure 5b is an apparatus in accordance with an embodiment of the present invention which uses reflection geometry and may be embodied in an optical microscope;

Figure 6 shows an embodiment of the present invention which has an optical fibre;

Figure 7 shows a variation on the embodiment of figure 6 where a detector is provided;

Figure 8 shows an apparatus in accordance with an embodiment of the present invention;

Figure 9 is an apparatus in accordance with an embodiment of the present invention configured for use for examining bio-samples, drugs etc;

Figure 10 shows an apparatus in accordance with an embodiment of the present invention configured for writing to an optical information storage media;

Figure 11 shows a variation on the system of figure 10 which is further configured for reading an optical information storage media in reflection mode;

Figure 12 shows an apparatus in accordance with an embodiment of the present invention used for reading information from an optical information storage media in accordance with an embodiment of the present invention;

Figure 13 schematically shows a quasi-crystal pattern of holes which may be used in accordance with an embodiment of the present invention;

Figure 14 shows a regular array of holes which may be used in accordance with an embodiment of the present invention;

Figure 15 shows a fractal pattern array of holes in accordance with an embodiment of the present invention; and

Figures 16a to 16*l* show various hole arrays which may be used in accordance with an embodiment of the present invention.

Figure 1a shows an example of a function composed of simple harmonics, which is superoscillating at x=0, The dashed line shows the highest Fourier harmonic of the Fourier spectrum of the function. The superoscillating feature changes nearly nine times faster than the highest harmonic.

A simple example of a superoscillating function is a limited series of harmonics such as

$$f(x)=\sum_{k=0}^{5}a_k\cos(2\pi kx) \tag{1}$$

By appropriately choosing the constants a_k of the series, one is able to create features which oscillate much faster than the highest frequency component. Consider, for example, $f(x)$ with a_0= 1, a_1= 13295000, a_2=-30802818, a_3= 26581909, a_4= -10836909, a_5= 1762818. It is plotted on fig. 1a (solid curve). In comparison, plot function $f_{\max}(x)=\cos(2\pi\times 5x)$ is also plotted, which is the highest frequency component of $f(x)$ (dashed curve). One can observe that at x=0 function $f(x)$ has a feature that oscillates much faster than $f_{\max}(x)$. Actually, near x=0 function $f(x)$ can be well approximated by a harmonic function $f_+(x)=0.5(\cos(2\pi\times 43.6x)+1)$ (dotted red curve) oscillating nearly 9 times faster than the highest harmonic of $f(x)$.

The fields diffracted from an array of individual holes are in analogue to the equation (1). According to the diffraction theory of light employing angular spectrum representation of the diffracted fields, the field in space point (x,y,z) diffracted from a structure *S* is given by

$$E(x,y,z)=\int F(u,v)e^{i(ux+vy)}e^{iz\sqrt{k^2-u^2-v^2}}dudv \qquad (2)$$

Wherein $F(u,v)$ is the amplitude of the Fourier transform coefficient of the initial diffracted field from the structure S at Z=0. u, v are the spatial frequency of the Fourier components and k ($k=2\pi/\lambda$) is the wavevector of light. In the far-field ($z \gg \lambda$), only the components of $u^2+v^2 \leq k^2$ make significant contributions. For components of $u^2+v^2 > k^2$, $\sqrt{k^2-u^2-v^2}$ is imaginary, therefore the fields decay exponentially in space and lost in the far-field, which are so-called evanescent fields.

Equation (2) is analogue to equation (1), so according to the phenomenon of superoscillation, an appropriate structure is able to create superoscillating field structures (i.e., subwavelength features) in space without the need of evanescent fields.

In the apparatus of figure 1b, there is provided a source of monochromatic radiation 1. The source impinges on lens 3 which comprises an array of holes. The holes may be subwavelength holes.

The radiation passes through the lens 3 and is diffracted by the lens to form a plurality of "hot-spots" or caustics 5, which are the result of the superposition of diffractive waves from the array of holes. They are formed at different distances from the lens 3. In the apparatus of figure 1b, a member 7 is provided with an aperture 9 which allows the transmission of a plurality of rays which produce a single hot-spot 5.

Figure 1c schematically shows the construction of a hot spot 11 from a plurality of holes 13 in an array. The cross section of the hotspot along the direction parallel to the plane of the array may be presented as a superposition of partial waves emanated from individual holes of the quasi-crystal array:

$$E(x)=\sum a_n \cos(k_n^{\parallel}x+\varphi_n)$$

Such a superposition resembles the structure of superoscillating function (1). For a certain combination of partial amplitudes a_n, spatial frequencies $k_n^{||}$, and phases ϕ_n the superoscillating features of figure 1a are observed.

To produce the data shown in figure 2, a quasi-crystal array was produced containing about 14000 holes of 200nm in diameter. The array had approximately 10-fold symmetry and was manufactured using electron beam lithography in 100nm aluminium film on a silica substrate.

The results shown were measured using a scanning near-field optical microscope (SNOM). The array was illuminated with a laser source from the opposite side of the array to the microscope. In near proximity of the sample, for example at 200nm, the optical field concentrates at the holes and the pattern projected at the distance of 200nm the same as that of the holes. At further distances, from the array the field map changes rapidly and dramatically.

Figure 2b shows the results taken at a distance of 10μm from the lens 3. A diffraction pattern is shown of hot spots. It should be noted that the pattern shown in figure B does not directly correspond to the pattern of holes as shown in figure 2a.

At further distances from the array, for example figure 2c shows the pattern at 25μm, well defined hot spots are seen. In 2c, hot spots are separated from other neighbouring hot spots by distances of a few microns. Further, the measured size of optical hot spots are as small as 340μm.

Figure 2d shows a scan across an individual hot spot shown in figure 2c and a de-convoluted energy distribution assuming a near-field probe aperture of 200nm. This produced a hot spot diameter of about 275nm.

To produce the data shown in figures 3a to 3f, a quasi-crystal array was produced containing about 14000 holes of 200nm in diameter. The structure is shown in figures 3g and 3h. The array had approximately 10-fold symmetry and has a Penrose-like quasi-periodic pattern. Figure 3g is a fragment of a Penrose-like quasi-periodic pattern of holes. Figure 3h is a SEM image of the fragment on the sample similar to the marked area in figure 3g. The holes were drilled by electron beam lithography on 100 nm thick Aluminium film. The diameter of individual hole is 200 nm and the minimum distance between two neighbouring holes is d=1.2 μm. The overall number of holes is about 14, 000.

The results shown were measured using a scanning near-field optical microscope (SNOM). The array was illuminated with a laser source (wavelength 660 nm) from the opposite side of the array to the microscope. In near proximity of the sample, the optical field concentrates at the holes and the pattern resembles that of the holes. At further distances, from the array the field map changes rapidly and dramatically.

Figure 3a shows the results taken at a distance of 5μm from the lens 3. A diffraction pattern is shown of many subwavelength hot spots. One of the subwavelength hot spots is selected and zoomed in figure 3b. The intensity profiles scanned across the spot are shown in figure 3c. The measured size of spot is as small as 235 nm. After deconvolution taking into account the size of the SNOM aperture (assumed to be 100 nm), the hot spot size is about 210 nm.

At further distances from the array, for example figure 3d shows the pattern at 12.5 μm, well defined hot spots are seen. In 3d, hot spots are separated from other neighbouring hot spots by distances of a few microns. One of them is selected and zoomed in figure 3e. The intensity profiles scanned across the spot are shown in figure 3f, indicating that the measured size of optical hot spots are as small as 320 nm. After deconvolution taking into account the size of the SNOM aperture (assumed to be 100 nm), the hot spot size is about 300 nm.

It is believed that the sub wavelength energy concentration is caused due to the cooperative interference of multiple beams diffracted from the individual small holes within the array. This is a process similar to the self-imaging of periodical structures in the Talbot effect. The peculiarity of near-field diffraction on the quasi-crystal array is that it can provide high intensity, clearly isolated hot spots of optical energy concentration.

The ultimate resolution achievable with the arrangement is not determined by the wavelength but by the diameter of the individual hole of the array, the type of the pattern and the number of holes cooperatively interfering at a given distance from the array.

Figure 3i shows pictures of the caustic or "hot-spot" formed at distances of 6.4 μm, 6.6 μm, 6.8 μm, 7.0 μm, 7.1 μm, 7.2 μm, 7.4 μm and 7.6 μm from the lens. Figure 3j is a plot showing how the intensity of the spot and the width of the spots shown in figure 3i vary with the distance (h) from the lens.

Figure 1b schematically illustrates how the apparatus can be used to produce a sub-wavelength focused spot of radiation. However, it is also possible to use the present invention in a "reverse" mode where it is used to detect radiation from a sub-wavelength volume. This is shown schematically in figure 4a.

In figure 4a, radiation of a first wavelength is directed onto a volume with at least one dimension which is smaller than the wavelength of the irradiating radiation. In this particular example, the object is irradiated with coherent radiation. Radiation from sub-wavelength volume 21 is then isolated by optional aperture 23 located in element 25. The radiation which has been scattered by subwavelength volume 21 then impinges on lens 27 which has an array of subwavelength holes 29. The lens 27 is of the type described previously with reference to figure 1. The emitted radiation is then collected by a detector.

The photonic lens 27 is analogue to a conventional lens in terms of focusing light into a small spot, so it may also be used to image objects in a reverse way as conventional lens does. In this reverse configuration, light emitted from an object will form a diffraction pattern at some distance from the photonic lens 27 at the opposite side, which can be imaged by a CCD array. The image may be limited to a very small area which corresponds to a subwavelength area in the object plane and thus provides subwavelength resolution.

Imaging is also possible as schematically illustrated in figure 4b. Here, radiation is directed onto subwavelength volume 201 and directed onto lens 203 which is of the type previously described having an arrangement of features which cause subwavelength caustics to be formed. An image of the subwavelength volume is projected onto image plane 205 from the lens 203.

The system of figure 4b is also illustrated in figure 4c. Again, radiation is directed onto a subwavelength volume 206 and directed onto lens 203. An image 207 of the subwavelength volume 206 is projected onto the image plane (not shown) from the lens 203. The subwavelength volume 206 and image 207 are shown schematically, and not to scale, in figure 4c.

As previously described, the present invention may be used for imaging. Figure 5a shows an arrangement which may be used for imaging a small object. The arrangement may be adapted for use in a transmission optical microscope.

As previously explained, a beam of light 31 impinges on lens 33. The lens is provided with a sub-wavelength pattern which generates hot-spots of sub wavelength features 39 by diffraction.

This sub-wavelength spot 39 can then be used to examine object 41 which may also be sub-wavelength in dimensions. The light scattered by object 41 is then collected by detector 43.

An image may be constructed by scanning the spot 39 across the object 41. This may be achieved by providing lens 33 on an x-y mount so that it can move in the x and y directions and thus scan in the spot 39 across object 41 in the x and y directions.

As can be seen in figure 5a which is not to scale, the object which is to be imaged 41 can be placed at a significant distance (few tens of microns) from lens 33. This means that the system may be used to study liquid or delicate samples since the sample may be provided at a reasonable distance from the lens 33.

Figure 5b shows a variation of apparatus of figure 5a operating in reflection mode. A beam of radiation 51 impinges on lens 53 as previously described with reference to figures 1b and 4. Diffraction of the radiation through lens 53 causes formation of a hot spot 57. In practice, a plurality of hot spots will be produced. Therefore, aperture 55 is used to isolate a single hot spot. This hot spot may then be used to investigate object 59. Radiation which is reflected from object 59 is then reflected back through the aperture in element 55 (see dotted lines) and through lens 53 to a detector (not shown). In figure 5b, the dotted lines show the reflected radiation 61.

As described with reference to figure 5a, the lens 53 may be mounted on an x-y mount to allow it to be scanned in the x and y directions across object 59.

Figure 6 shows a further embodiment of the present invention. Here, the system is configured as a "light pen". Radiation enters a fibre-optic cable 72 at a first end 74. It propagates along fibre 72 in the standard fashion until it reaches end 76. At end 76, there is a lens 73 of the type previously described. The lens may comprise an array of sub-wavelength holes or concentric rings. The lens 73 results in the emitted light being focused to a hot spot 75 which is a sub-wavelength.

This may be used as a light pen for example in photo-lithography. Alternatively, when combined with enhanced transmission, it may produce high enough density laser power which could be used for cutting or high resolution surgery etc.

Figure 7 shows a fibre-lens. The system of figure 7 is similar to that of figure 6. Radiation 81 enters through first end 83 of optical fibre 81. It propagates through optical fibre 85 in the standard manner and eventually reaches second end 87. Second end 87 has a photonic lens 89 provided therein. The lens 89 is the same as described with reference to figures 1b and 4 to 6. This lens generates a spot 91 which may be used to exam object 93. The sub-wavelength spot 91 may be scanned in both the x and y directions or for that matter in any dimension over object 93.

The radiation may be collected by photo detector 95 in transmission mode or radiation which has been reflected from the object may be collected via fibre 85 and transmitted back through the fibre for a detector provided (not shown) of the first end 83 of the fibre 85.

Thus, scanning the sample or the fibre will produce optical images with sub-wavelength resolutions.

Figure 8 shows an embodiment of the present invention optimized for use in photo lithography. As before, a beam of coherent light 101 is incident on lens 103. Lens 103 comprises a plurality of sub-wavelength features which can be used to produce hot spots or other caustics at a certain distance from the lens. In photo lithography, it is usually desirable to write more than one feature at anyone time. Therefore, lens 103 comprises a plurality of hole arrays 105 which in turn generate a plurality of hot spots or caustics.

Since each array 105 will generate more than one hot spot or caustic, element 107 is provided with apertures which isolate (in this particular case) a single caustic or hot spot from each array 105. The system is configured so that there is a light sensitive or photo lithographic material 109 provided where the sub-wavelength hot spots are formed. It is possible to write with this material used by either scanning the material as required. Alternatively, it may be possible to construct 2D lens 103 so that a 2D pattern is formed on the photo sensitive material 109 by changing the angle of incident light while keeping the lens fixed-without scanning.

This system allows photo lithography to occur with sub-wavelength features with a high speed and high throughput.

Figure 9 shows a further variation on the system which is optimized for use in looking at bio-samples or drugs etc.

Previously, to look at such samples, it has been suggested to use near-field microscopy. However, the use of near-field microscopy for such a “messy” sample causes a problem in that the source of radiation must be provided very close to the sample in order to see the required diffraction effects. In figure 9, coherent light beam 121 is incident on lens 123 which is of the type previously described with reference to figure 8. The lens 123 comprises a plurality of arrays of holes or concentric rings 125. These arrays 125 produce hot spots or caustics a few tens of microns away from lens 123.

As each array 125 will produce a plurality of caustics or hot spots, an element 127 may be used with apertures which allow the selection of one or a small number of caustics or hot spots from each array 125.

A bio-sample or drug tray 129 is provided at the position of the hot spots or caustics with samples 131 provided such that they are illuminated by the hot spots or caustics.

The array may be scanned in order to scan the samples 123. Alternatively, the samples themselves may be scanned. In a further variation,; both sample and the lens may be fixed without scanning, while the direction of incident light is scanning.

The present invention may also be used for optical storage, for example for writing to DVD/CDs or the like.

Figure 10 shows an embodiment of the present invention configured for writing to a DVD or CD 151.

Coherent light source 153 is incident on lens 155 which has a pattern of the type previously described.

The lens produces a plurality of caustics or hot spots at a distance of a few tens of microns away from lens 155. An aperture is provided on element 157 which isolates a hot spot or caustic at a distance from the lens 155 where the DVD or CD 151 is placed.

Since the provision of lens 155 produces a sub-wavelength spot 159 on at DVD/CD 151, it is possible to write to the DVD/CD 151 in the conventional manner.

Figure 11 shows a variation on the device of figure 10. To avoid any unnecessary repetition, like reference numerals will be used to denote like features. The device of figure 11 is not only a DVD/CD writer, it can also read DVDs/CDs 151 or any other suitable recording medium.

Photo detector 161 is provided at a location such that radiation which is incident on DVD/CD 151 is reflected to photo detector 161. In the standard manner, the photo detector can determine whether a bit 1 or bit 0 is recorded on the DVD/CD 151 from the intensity of the reflected radiation. Of course, the system could be used for other methods of optical storage where the angle of the reflected light can also be used to determine information stored on the CD/DVD 151.

Figure 12 shows a further embodiment which is optimized for reading data from a DVD which has a feature size smaller than the wavelength of the light used to irradiate the DVD. The DVD 171 comprises features which are smaller than the wavelength of the radiation used to illuminate the DVD. The radiation used to illuminate the DVD 173 is directed at a first surface of the DVD. The feature which is to be read 175 scatters the radiation and radiation which has been scattered by feature 175 is isolated using element 177 and directed towards lens 179. Lens 179 comprises an array of sub-wavelength features as described previously with reference to figure 3. The radiation from lens 179 is then detected by detector 181.

The array or pattern of sub-wavelength features used to produce the hot spots or caustics may take a number of different forms. Figure 13 shows an example of a quasi-crystal array which has ten-fold symmetry

Figure 14 shows a further variation where a regular array is provided. The size and intensity of the spots can be modified through modifying the array structures and conditions used. In particular, by modifying the size of the holes, the pattern of the holes, the characteristics of the incident light and the depth of the illuminated surface.

Specifically, smaller light spots and more intense light spots may be generated.

It is also possible to use fractal arrangements of the type shown in figure 15.

Quasi-crystal, fractal, regular and quasi-periodic arrangements can be used to produce the superoscillating fields. However, it is possible to use an arrangement where there is no mathematical relationship between the features of the pattern.

Figure 16 shows a further variation of the types of patterns which may be used. If figure 16a, there is a single ring of holes. In figure 16b, there are two concentric rings of holes. The holes are equally spaced along the circumference of each ring. In figure 16c, there are three concentric rings, the concentric rings are equally spaced and the holes in each ring are also equally spaced along each ring.

However, there is no need for the actual apertures to be circular. In figure 16d, two concentric rings of holes are seen where the holes are triangular in shape. Similarly, in figure 16e, the holes are square shaped. Also, the squares are not of the same size throughout the structure. In 16f, oblong type holes are seen whose size varies around two concentric rings.

Also, it is not necessary for there to be actual holes. In figure 16g, concentric rings are seen where the rings are continuous. In figure 16f, the pattern is seen comprises essentially two concentric rings. In the inner ring, the holes are of a triangular shape. In the outer ring, the holes have a diamond shape. In figure 16i, the holes are generally circular. However, they are arranged in three concentric rings and their size varies considerable between the rings and also within individual rings.

In figure 16j, an arrangement of three concentric rings is seen. In the inner ring, the ring is defined by a plurality of holes with a triangular shape. In the middle ring, the ring is defined by a plurality of holes with a roughly circular cross-section. The holes in the middle ring are roughly of the same size. In the outer ring, the holes alternate between a large size and a small size. Both sizes of holes in the outer ring are larger than the holes in the inner ring.

In figure 16k, an arrangement of three concentric rings is seen but with also a single central hole. Finally, in figure 16*l*, an arrangement is seen with two concentric rings which are made of holes having a triangular cross-section. A single central hole which has a roughly circular cross-section is also seen.

Although a central hole is shown in figures 16k and 16l, there is no need for a central hole in the arrangement.

CLAIMS:

1. An optical system configured to direct radiation onto an object, said system comprising a source of radiation and a lens, said lens comprising an arrangement of features configured to allow transmission of radiation from said source, the object being located at a distance from the lens such that at least one caustic due to diffraction of radiation through the features is in focus on said object, said caustic having at least one dimension which is smaller than the wavelength of the radiation from the source.

2. An optical system according to claim 1, wherein said arrangement comprises a grating configured to produce a super-oscillating optical field, where at least one focus of the field has a dimension smaller than the wavelength of the radiation from the source.

3. An optical system according to any preceding claim, wherein said features have dimensions smaller than the wavelength of the radiation from the source.

4. An optical system according to claim 1, wherein said arrangement comprises quasi-crystal array of holes, a regular array of holes, a quasiperiodic arrangement of holes, a fractal arrangement of holes or rings.

5. An optical system according to any preceding claim, wherein said lens comprises a metal film and said arrangement of features is provided through said metal film.

6. An optical system according to any preceding claim, wherein said object is placed at a distance from 2 μm to 50 μm from said lens.

7. An optical system according to claim 6, wherein said object is placed at a distance from 10 μm to 25 μm from said lens.

8. An optical system according to any preceding claim, further comprising a means to isolate a single caustic.

9. An optical system according to any preceding claim, further comprising a detector provided on the same side of the object as the source.

10. An optical system according to any preceding claim, further comprising a detector provided on the opposing side of said object to said source.

11. An optical system according to any preceding claim, further comprising means to scan the lens such that the caustic is scanned relative to said object.

12. An optical system according to any preceding claim, further comprising an optical fibre, said source being configured to direct radiation into a first end of said fibre and said lens being provided at the other end of said fibre.

13. An optical system according to any preceding claim, wherein said object is a photosensitive material.

14. An optical system according to any preceding claim, wherein said object is a biological or chemical sample.

15. An optical system according to any preceding claim, wherein said object is an optical storage medium.

16. An optical system for examining an object, the system comprising a source, configured to direct radiation onto an object, a lens configured to collect radiation from said object and a detector configured to receive radiation from said lens, said lens comprising an arrangement of features configured to allow transmission of radiation from said source, the object being located at a distance from the lens such that at least one caustic due to diffraction of radiation through the features formed, said caustic having at least one dimension which is smaller than the wavelength of the radiation from the source.

17. An imaging system for imaging an object, said system comprising a source, configured to direct radiation onto an object and a lens configured to collect radiation from said object and project it onto an image plane, said lens comprising an arrangement of features configured to allow transmission of radiation from said source and to produce a super-oscillating optical field, where at least one focus of the field has a dimension smaller than the wavelength of the radiation from the source.

18. A cutting tool comprising a source of radiation, an optical fibre and a lens, said source configured to direct radiation into an input end of said optical fibre and said lens being provided at the output end of said optical fibre, said lens comprising an arrangement of features configured to allow transmission of radiation from said source.

19. An optical method configured to direct radiation onto an object, said method comprising:
irradiating a lens with radiation, said lens comprising an arrangement of features configured to allow transmission of radiation from said source; and
placing said object at a distance from the lens such that at least one caustic due to diffraction of radiation through the features is in focus on said object, said caustic having at least one dimension which is smaller than the wavelength of the radiation from the source.

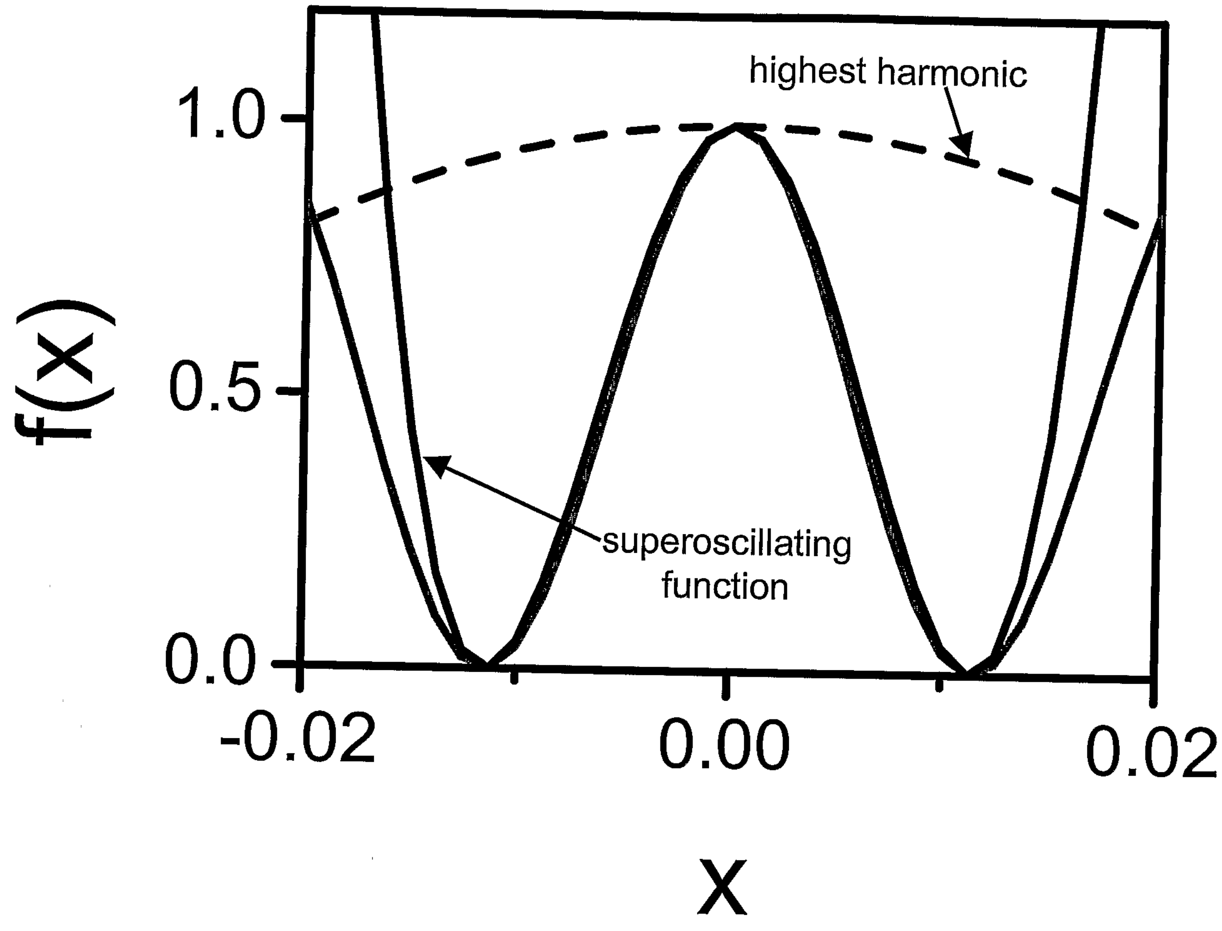

highest harmonic
superoscillating function
f(x)
1.0
0.5
0.0
-0.02
0.00
0.02
x

Figure 1a

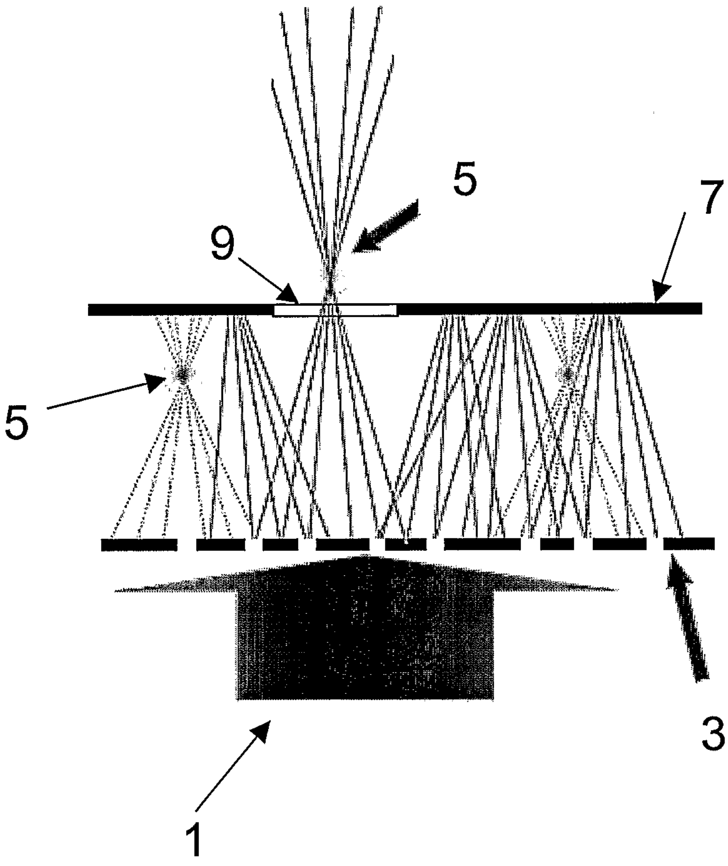


Figure 1b

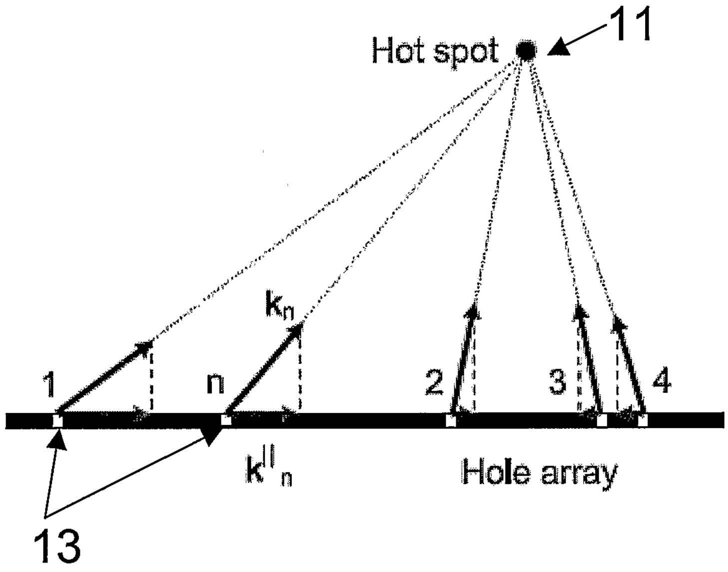


Figure 1c

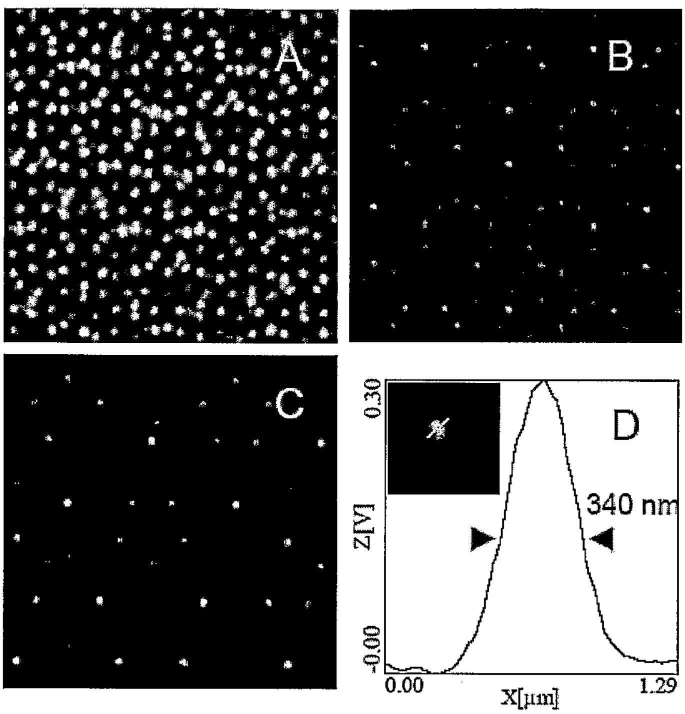
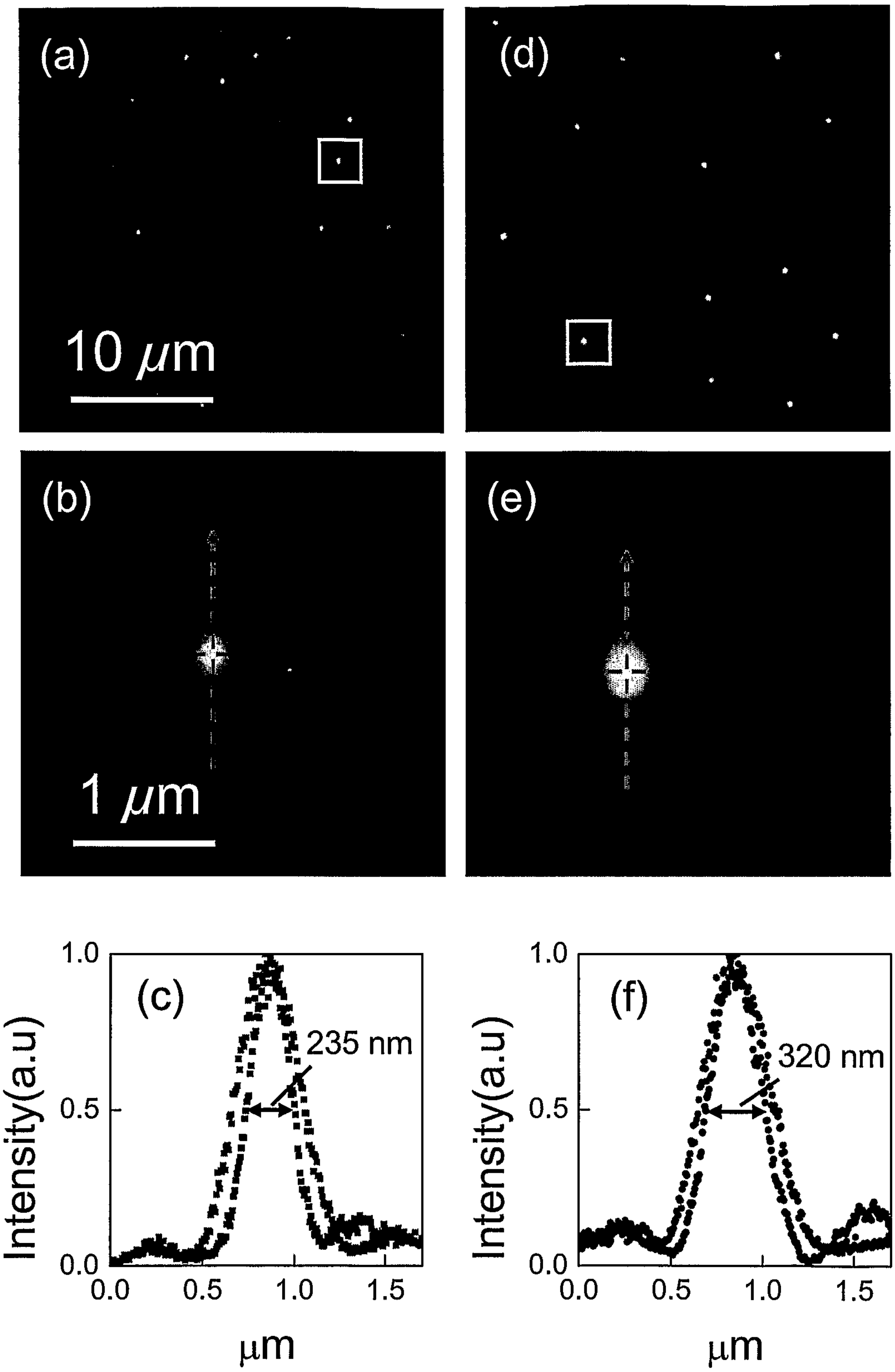


Figure 2


(a)
10 μm
(d)
(b)
1 μm
(e)
(c)
235 nm
Intensity(a.u)
1.0
0.5
0.0
0.0
0.5
1.0
1.5
µm
(f)
320 nm
Intensity(a.u)
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0.5
0.0
0.0
0.5
1.0
1.5
µm

Figure 3

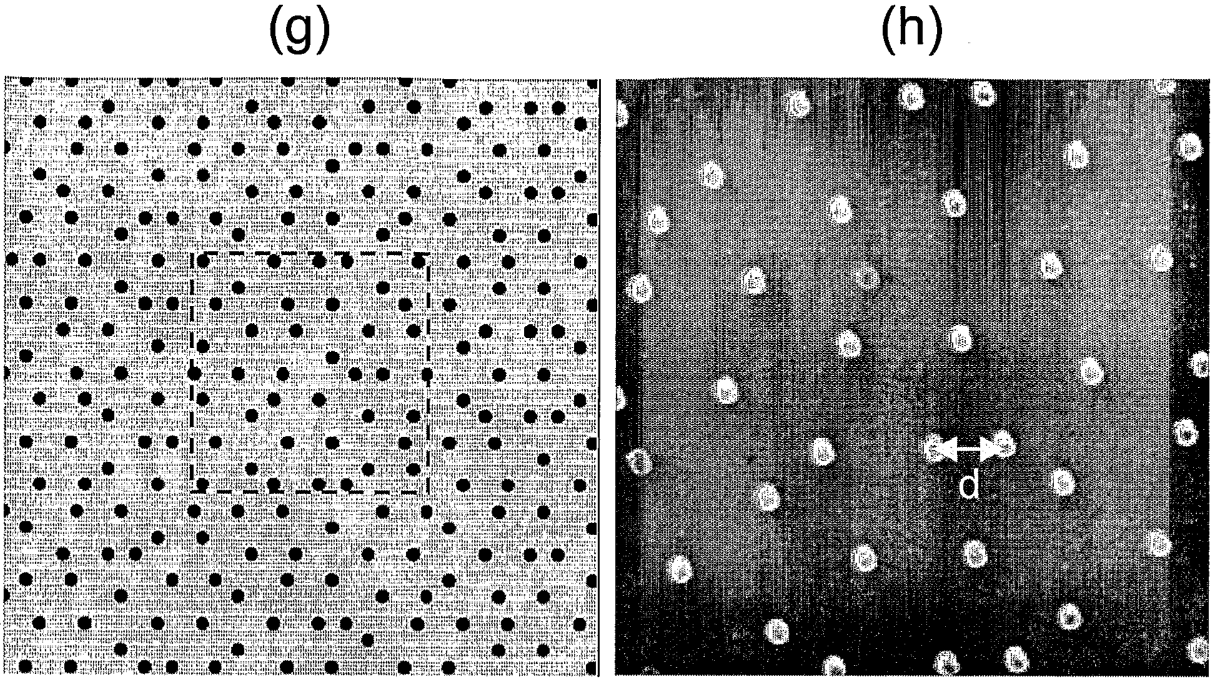

Figure 3

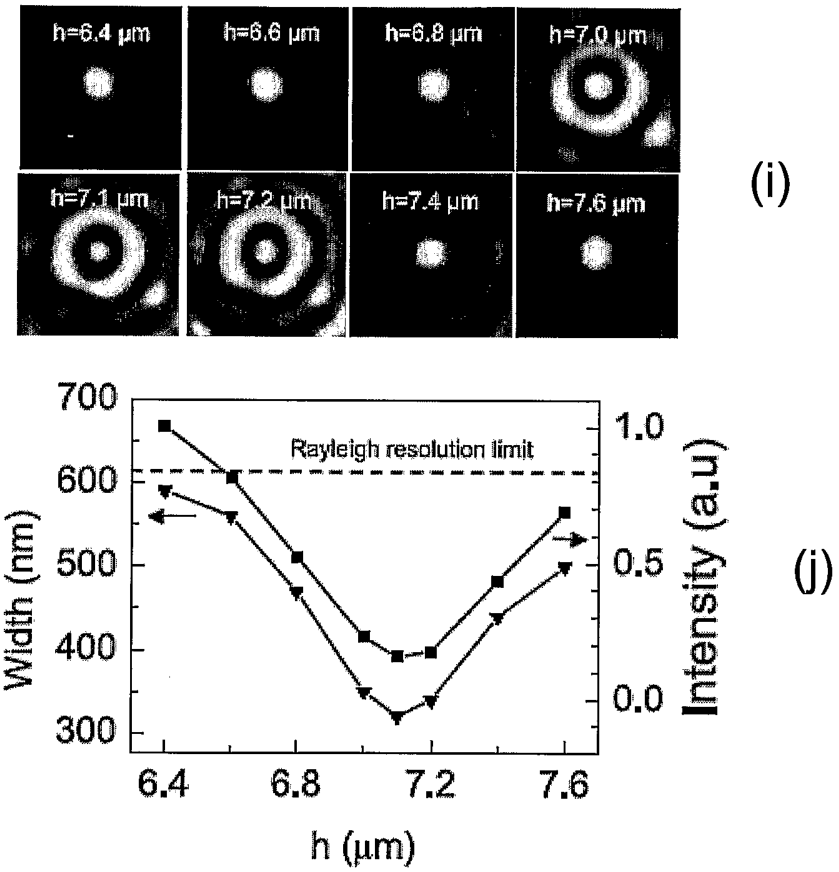
h=6.4 µm
h=6.6 µm
h=6.8 µm
h=7.0 µm
h=7.1 µm
h=7.2 µm
h=7.4 µm
h=7.6 µm
(i)
700
600
500
400
300
Width (nm)
Rayleigh resolution limit
1.0
0.5
0.0
Intensity (a.u)
6.4
6.8
7.2
7.6
h (µm)
(j)

Figure 3

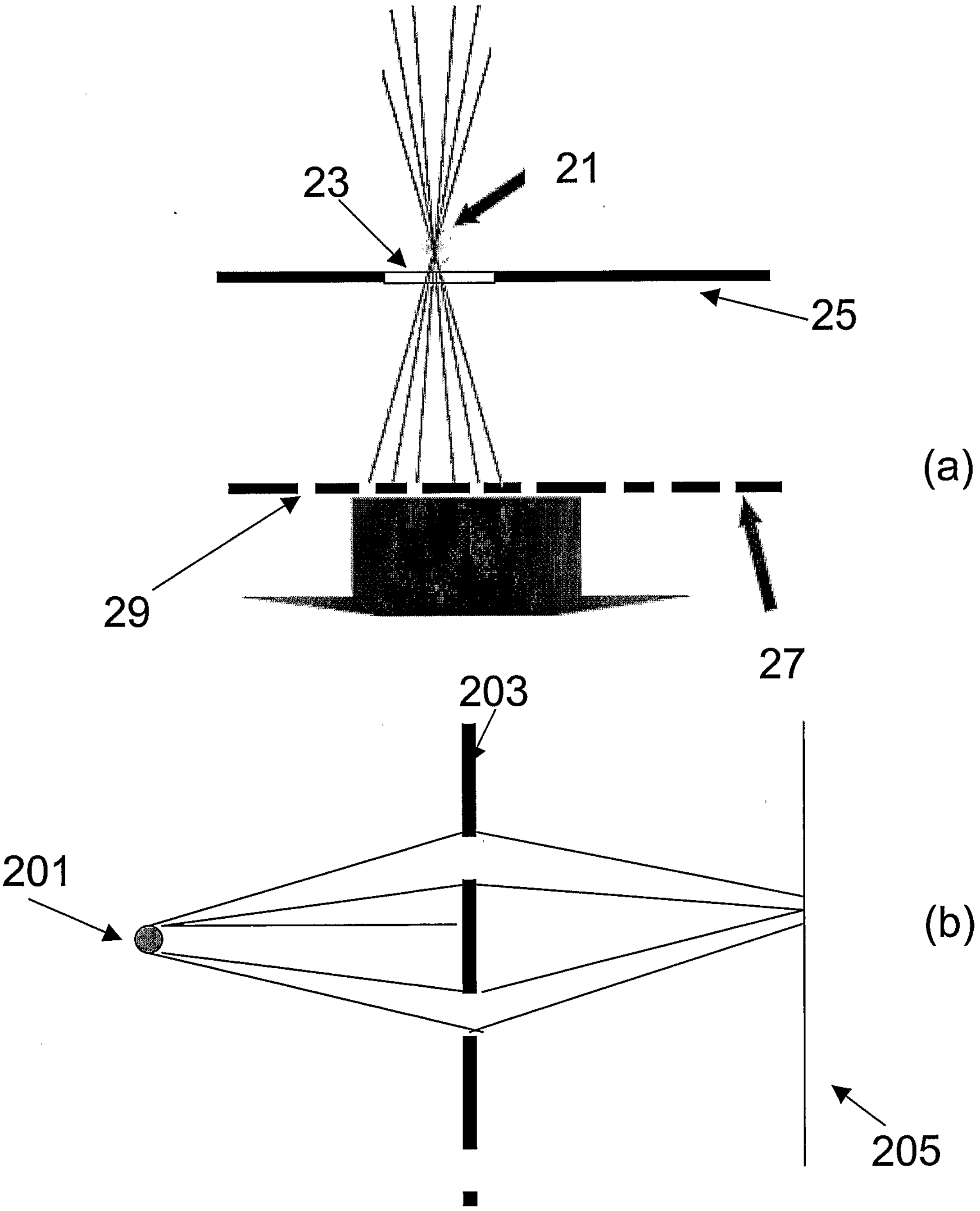

Figure 4

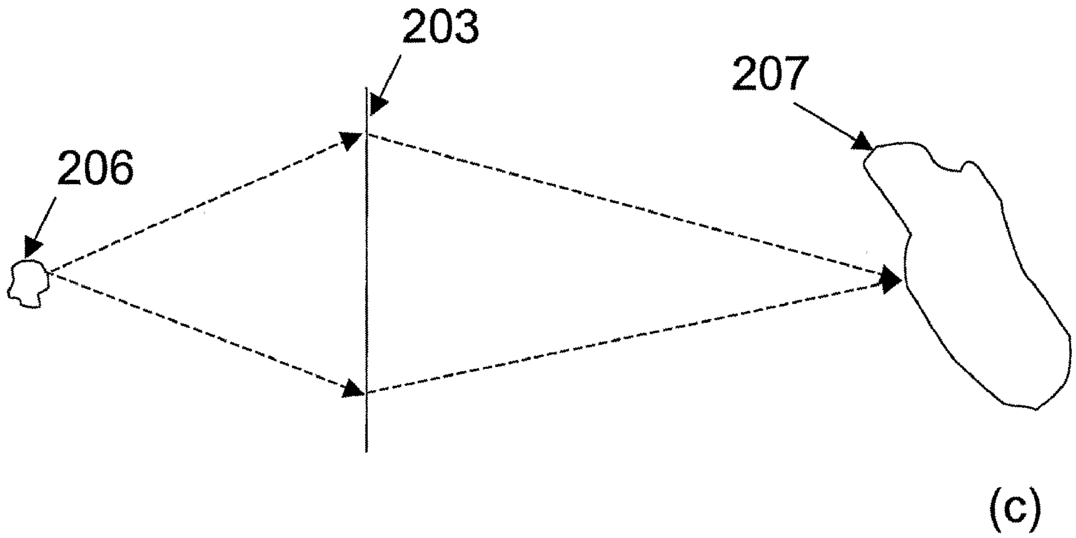

Figure 4

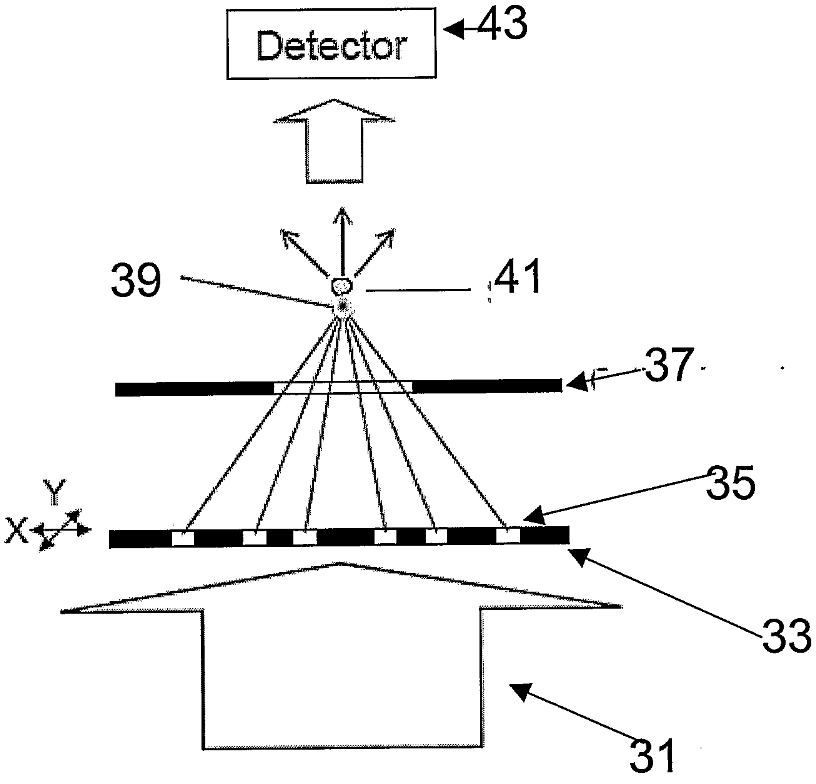

Figure 5a

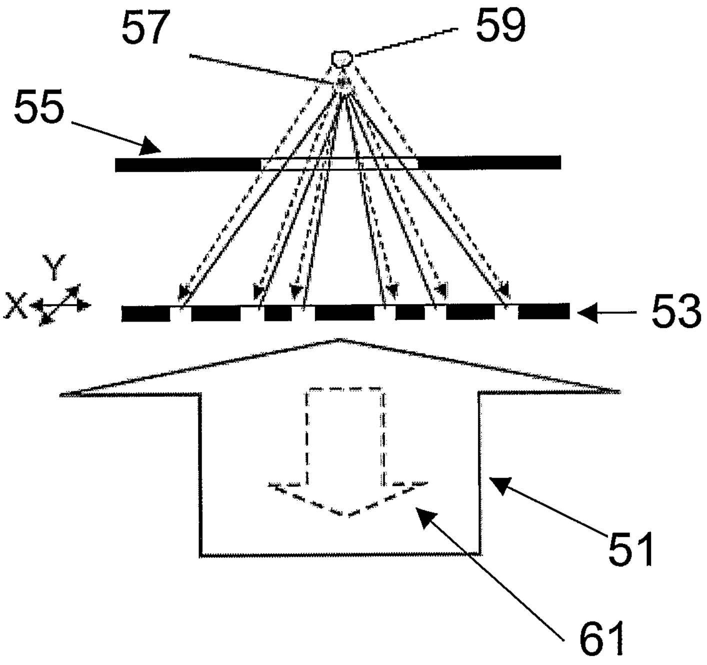

Figure 5b

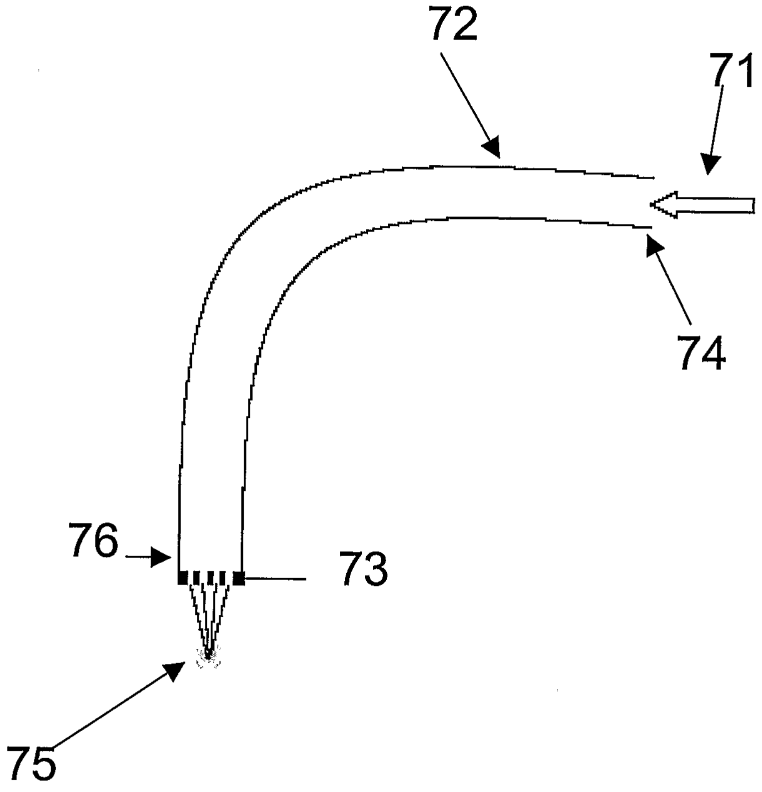

Figure 6

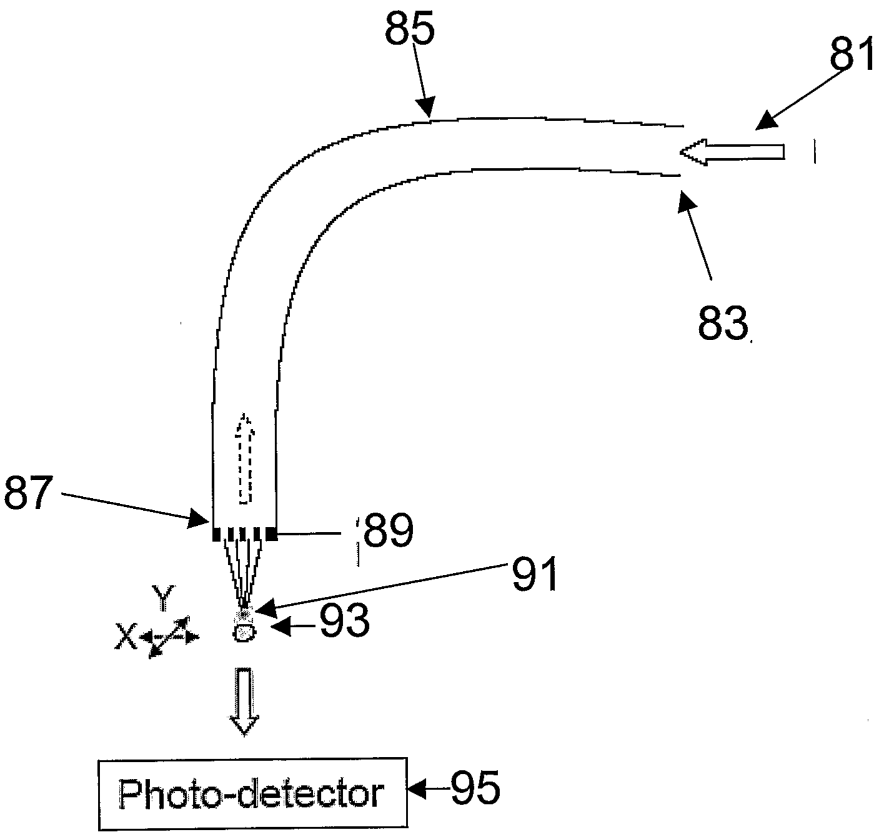

Figure 7

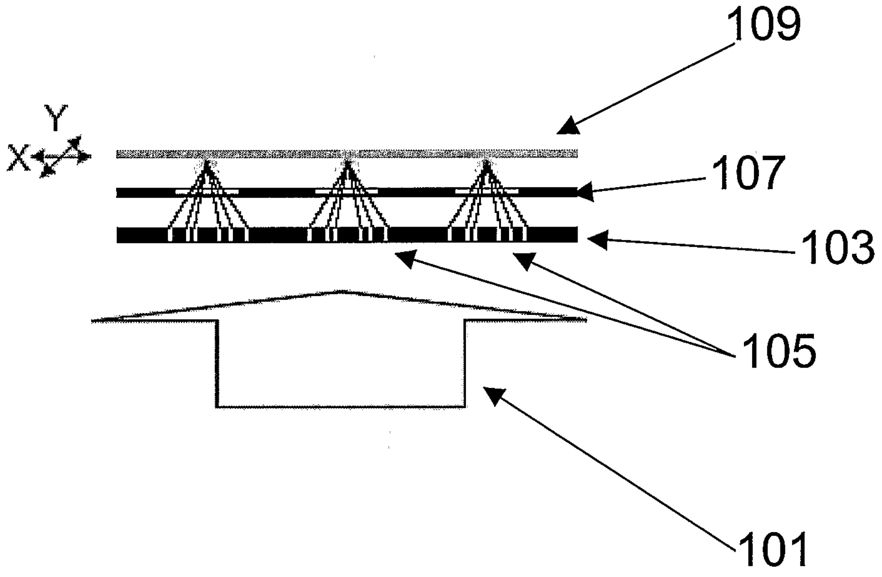

Figure 8

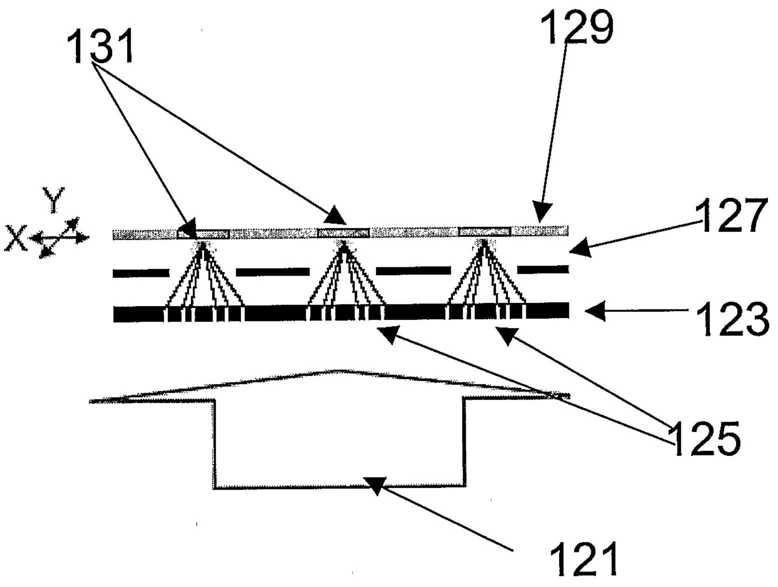

Figure 9

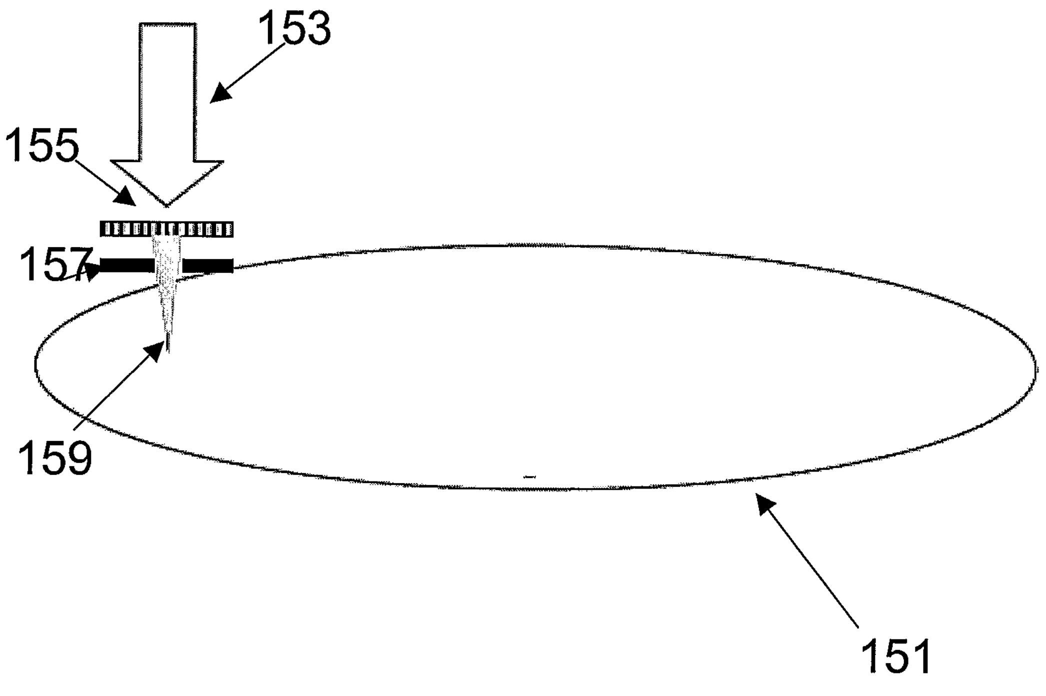

Figure 10

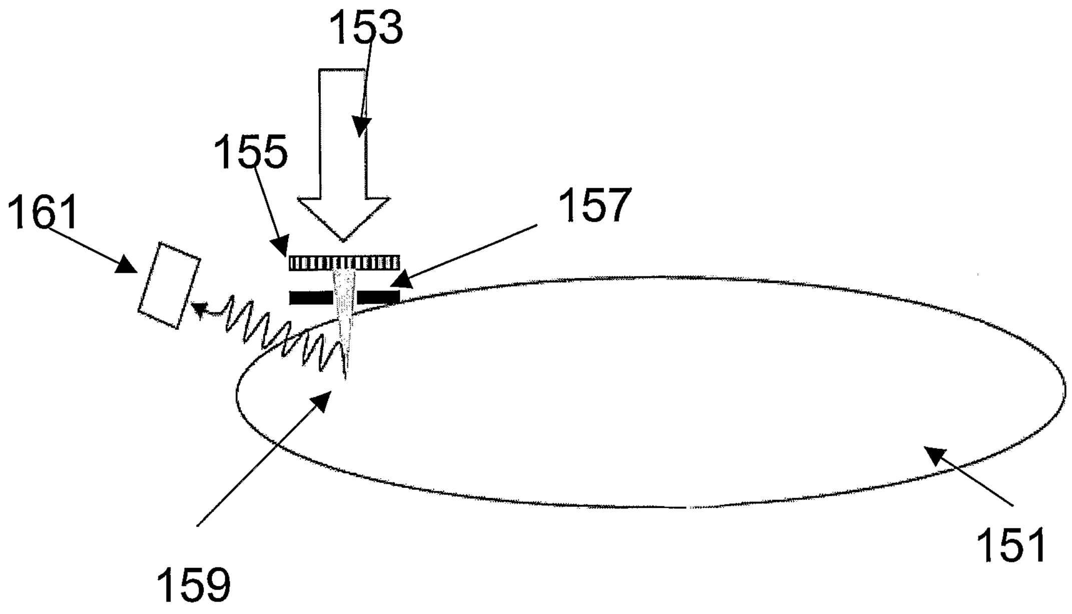

Figure 11

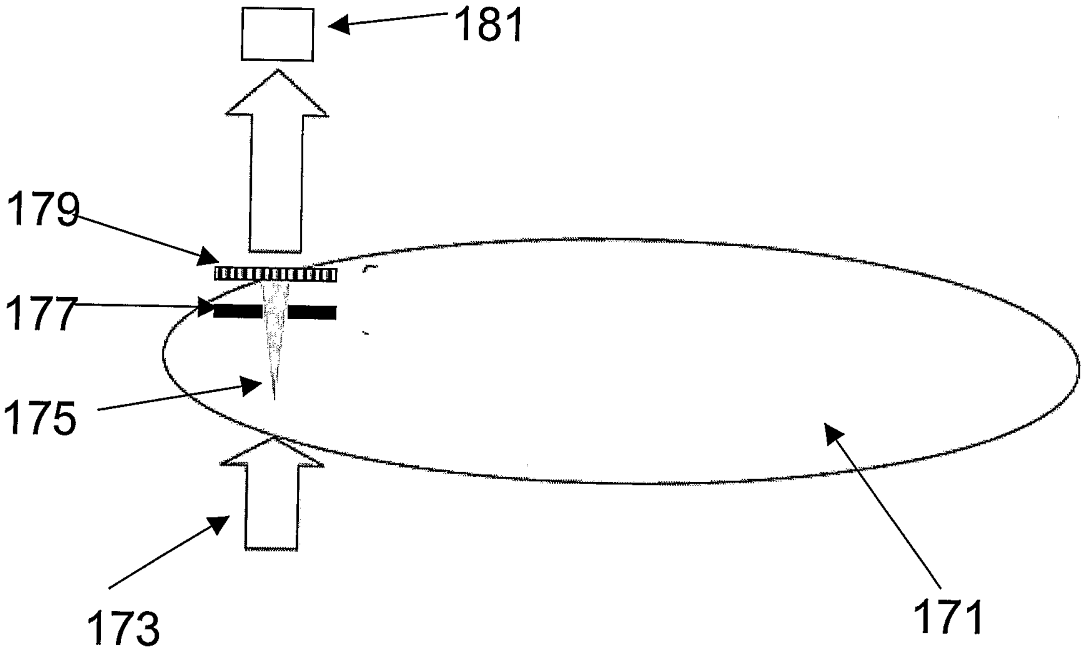

Figure 12

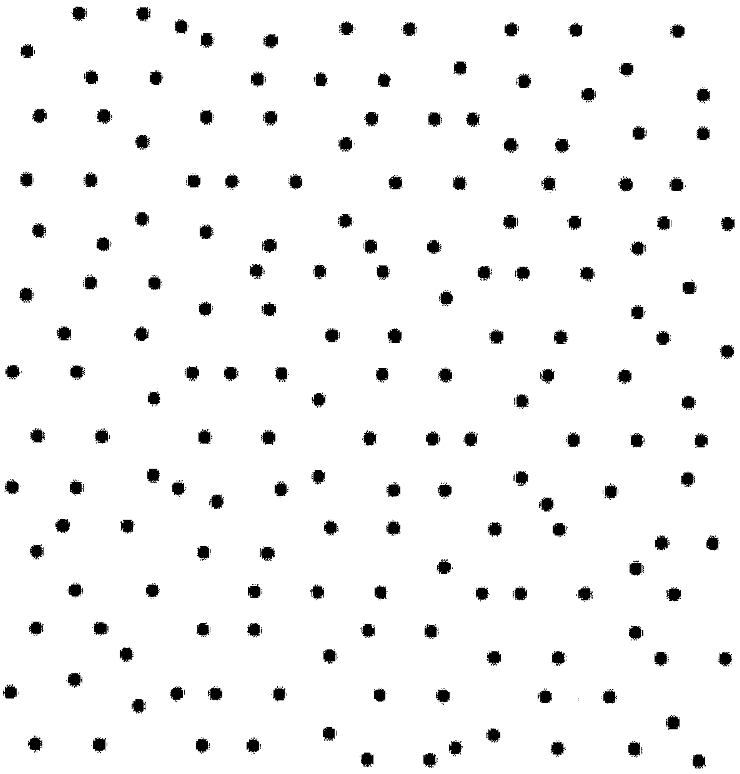

Figure 13

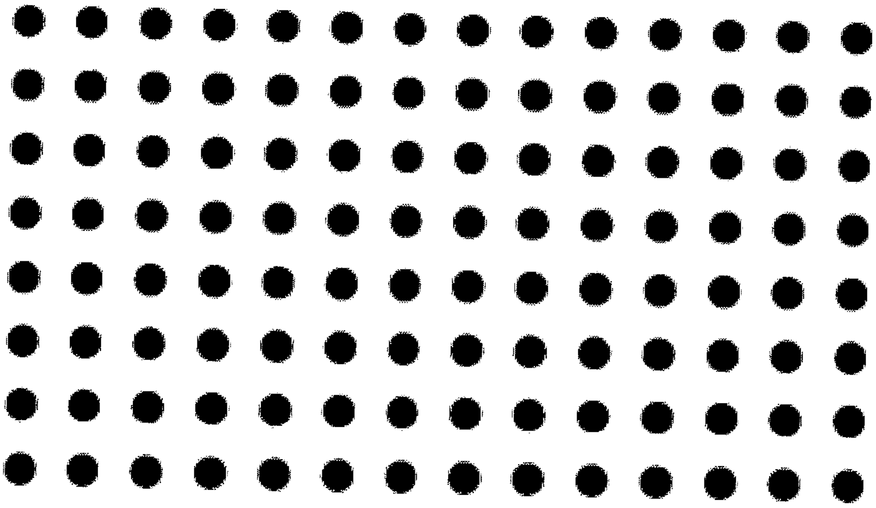

Figure 14

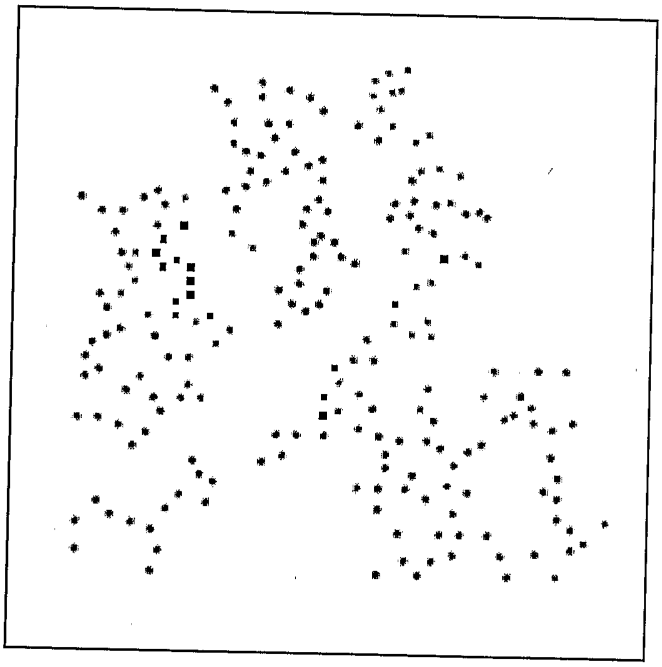

Figure 15

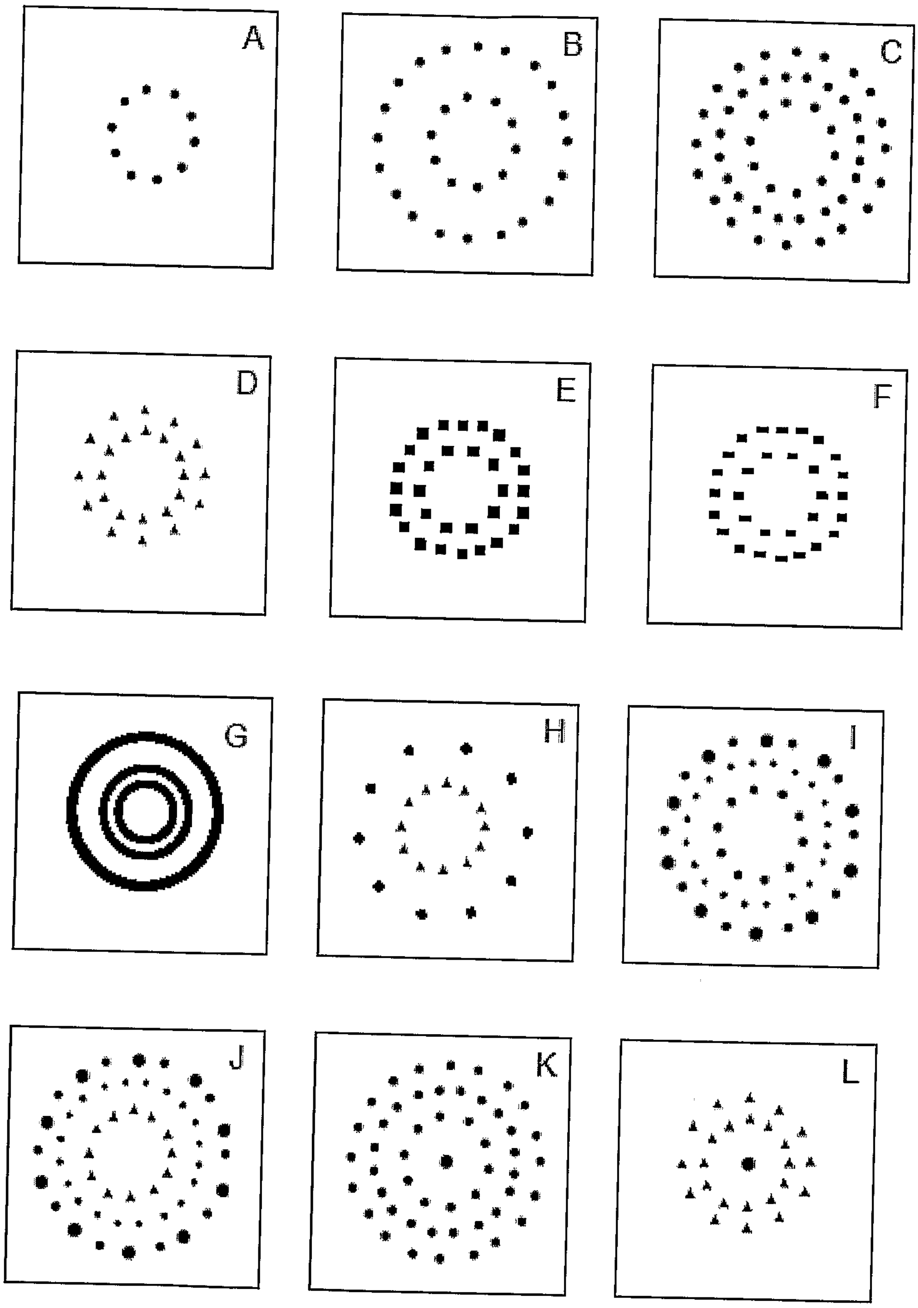

Figure 16

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2007/002715

A. CLASSIFICATION OF SUBJECT MATTER
INV. G11B7/135 G02B27/58

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)
G11B G02B B23K

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, INSPEC, 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	BERRY M V ET AL: "Evolution of quantum superoscillations and optical superresolution without evanescent waves" JOURNAL OF PHYSICS A. MATHEMATICAL AND GENERAL, INSTITUTE OF PHYSICS PUBLISHING, BRISTOL, GB, vol. 39, no. 22, 2 June 2006 (2006-06-02), pages 6965-6977, XP020099548 ISSN: 0305-4470 cited in the application abstract page 6974 - page 6977 figures 8,9 ----- -/--	1-17,19

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

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search
18 October 2007

Date of mailing of the international search report
30/10/2007

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
Moroz, Alexander

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	W. D. MONTGOMERY: "Self-imaging objects of infinite aperture" J. OPT. SOC. AM., vol. 57, no. 6, 1967, pages 772-778, XP007903234 the whole document	1-17,19
X	US 5 973 316 A (EBBESEN THOMAS W [US] ET AL) 26 October 1999 (1999-10-26) the whole document	1-17,19
X	US 2003/039196 A1 (NAKAMURA MIZUKI [JP] ET AL) 27 February 2003 (2003-02-27) abstract paragraphs [0046] - [0054] figures 3-5	1-17,19
A	EP 1 382 941 A (MITUTOYO CORP [JP]) 21 January 2004 (2004-01-21) the whole document	1-19
X	DE 199 62 126 A1 (KOENIG WILHELM [DE]) 28 June 2001 (2001-06-28) abstract figure 1	18
P,X	CN 1 822 150 A (SHANGHAI INST OPTICS & FINE ME [CN]) 23 August 2006 (2006-08-23) the whole document	1-19

INTERNATIONAL SEARCH REPORT

International application No.
PCT/GB2007/002715

Box II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☒ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-17,19

   An optical system and method for sub-wavelength energy concentration

   ---

2. claim: 18

   A laser machining tool

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2007/002715

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
US 5973316	A	26-10-1999	JP	3008931	B2	14-02-2000
			JP	11072607	A	16-03-1999
			US	6052238	A	18-04-2000
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EP 1382941	A	21-01-2004	CN	1495501	A	12-05-2004
			JP	2004053605	A	19-02-2004
			US	2004011948	A1	22-01-2004
DE 19962126	A1	28-06-2001	NONE			
CN 1822150	A	23-08-2006	NONE			