AN OPTICAL ARRANGEMENT AND A METHOD OF FORMING THE SAME

Cross-Reference To Related Application

[0001] This application claims the benefit of priority of Singapore patent application No. 201106529-9, filed 12 September 2011, the content of it being hereby incorporated by reference in its entirety for all purposes.

Technical Field

[0002] Various embodiments relate to an optical arrangement and a method of forming the optical arrangement.

Background

[0003] Abbe's classical diffraction limit states that the minimum resolvable distance between two closely spaced objects is at best half the wavelength used for imaging. Hence, assuming 500 nm as the mid-spectrum wavelength for visible light, this limit dictates that an idealized lens-based optical microscope can resolve juxtaposed colour elements down to a pitch of 250 nm. However, colours produced by depositing materials, such as dyes and quantum emitters or by iridescence of periodic structures cannot yet achieve this printing resolution.

[0004] In today's colour printers, colours are rendered by colour dyes that are deposited onto different positions on a substrate (i.e. paper). In such a system, a range of colours is achieved by combining two or more colour dyes in different proportions. Colour printers have mechanical/optical systems that can position dyes accurately to achieve colour pixel sizes as small as several microns.

[0005] However, the need for more than one material to be deposited requires a reservoir of the various colour dyes, e.g. in the form of cartridges. Furthermore, the colours achieved by mixing dyes of fixed light-absorption wavelengths are not as spectrally pure as those achieved by tuning the absorption wavelengths of materials, which could

produce colours more vibrant to the eye. Finally, the resolution of the images produced is limited to the smallest amount of dye that can be deposited onto the substrate, typically microns in size.

[0006] Industrial techniques such as inkjet and laserjet methods print at sub-10,000 d.p.i. resolutions because of their micrometre-sized ink spots. Research-grade methods are capable of dispensing dyes at higher resolution but are serial in nature and, to date, only monochrome images have been demonstrated.

[0007] Plasmon resonances in metal nanostructures have been used to create colours in stained glasses since the 4th century AD. Plasmon resonances in metal films have also been used in macroscopic colour holograms, full colour filters and polarizers. The colour filters in particular exhibit the phenomenon of extraordinary optical transmission (EOT, an effect of Fano resonance) through periodic subwavelength holes in the film. The colours produced are set by the periodicity of the structures, so multiple repeat units are required, resulting in large (micrometre-sized) pixels. In an alternative arrangement, small (tens of nanometres) isolated metal nanoparticles can be used, which scatter colours depending on their shapes and sizes, but do not scatter strongly enough to be viewed plainly in a microscope, especially when deposited in direct contact with a substrate.

[0008] However, only recently have researchers reported several methods to achieve colour micro-images using plasmon resonances, as shown in FIGS. 1A to 1C.

[0009] FIG. 1A shows a scanning electron microscopy (SEM) image 100 and a corresponding darkfield microscopy image 102 (D. Inoue et al., "*Polarization independent visible color filter comprising an aluminum film with surface-plasmon enhanced transmission through a subwavelength array of holes*", Applied Physics Letters 98, 093113, 2011), which is only visible under specific lighting conditions. The pattern and the colours of the NIMS logo of FIG. 1A were obtained via patterning of nanoholes within an aluminium (Al) film (inset SEM image 101), and observed using grazing angle microscopy (darkfield). The colours achieved are blue for the figure portion 104 of the logo and for the text portion of the logo, pink for the letter 'N' 106, orange for the letter 'I' 108, yellow for the letter 'M' 110 and green for the letter 'S' 112. A similar method where an aluminium (Al) film was perforated was used to obtain the Christmas tree darkfield microscopy image 120 of FIG. 1B, with the bulbs of the tree being red 122,

green 124 and blue 126, and the text 'Season's Greetings' 128 being green (http://www.worldrecordacademy.com/technology/smallest_Christmas_card_University_of_Glasgow_set_world_record_102035.html). Both of these methods employed localized surface plasmon resonance of the nanostructures in order to obtain the colours seen.

[0010] FIG. 1C shows a darkfield microscopy micro image 140 of an apple with the illusion of three-dimensions (3D) using surface plasmon resonance, with the apple 142 being red, and the leaf 144 and the stem 146 being green (M. Ozaki et al., "*Surface-Plasmon Holography with White-Light Illumination*", Science Vol. 332, 218-220 (2011)).

[0011] As shown in FIGS. 1A to 1C, the darkfield microscopy images 102, 120, 140 have dark backgrounds.

[0012] These methods (including stained glasses) are based on transmitted light, hence limiting the application to transparent substrates and/or requiring special illumination techniques.

[0013] There is therefore need for further techniques that allow the generation of coloured images by making use of plasmon resonance. There is also need for further techniques that create pixels that support individual colours, that may be miniaturized and juxtaposed at the optical diffraction limit, and also produce vivid colours when observed in a bright-field optical microscope. The present invention meets these needs.

Summary

[0014] In a first aspect of the invention, an optical arrangement is provided. The optical arrangement includes a substrate, and a plurality of spaced apart elongate nanostructures extending from a surface of the substrate, wherein each elongate nanostructure includes a metal layer on the end distal from the surface of the substrate.

[0015] In a second aspect of the invention, a method of forming an optical arrangement is provided. The method includes providing a substrate, forming a plurality of spaced apart elongate nanostructures extending from a surface of the substrate, and forming a metal layer on the end of each elongate nanostructure distal from the surface of the substrate.

Brief Description of the Drawings

[0016] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0017] FIGS. 1A to 1C show colour micro-images of the prior art.

[0018] FIG. 2A shows a schematic block diagram of an optical arrangement, according to various embodiments.

[0019] FIG. 2B shows a flow chart illustrating a method of forming an optical arrangement, according to various embodiments.

[0020] FIG. 3A shows cross-sectional views of a method of forming an optical arrangement, according to various embodiments.

[0021] FIG. 3B shows a perspective view of an optical arrangement that may be obtained from the method illustrated in FIG. 3A, according to various embodiments.

[0022] FIG. 3C shows simulated reflectance spectra of Ag/Au nanodisks hovering above a reflective Si surface in vacuum, according to various embodiments.

[0023] FIG. 4A shows a scanning electron micrography (SEM) image of an optical arrangement, according to various embodiments. The scale bar represents 200 nm.

[0024] FIG. 4B shows a scanning electron micrography (SEM) image of an optical arrangement, according to various embodiments.

[0025] FIGS. 5A and 5B show optical micrographs, according to various embodiments.

[0026] FIG. 5C shows measured and simulated reflectance spectra of metal nanodisks with a spacing, *s*, of 120 nm, according to various embodiments.

[0027] FIG. 5D shows a plot illustrating the correlation of the dips and peaks observed in the reflectance spectra of FIG. 5C, according to various embodiments.

[0028] FIG. 6A shows simulated reflectance spectra of plasmonic nanostructures with a periodicity of 120 nm for different cross sectional dimensions, according to various embodiments.

[0029] FIG. 6B shows plots of electric field enhancement and plots of time-averaged power flow vector for a single repeat structure with a cross sectional dimension of 90 nm at wavelengths of 450 nm, 590 nm and 900 nm corresponding to the simulated reflectance spectra of FIG. 6A.

[0030] FIG. 7 shows simulated reflectance spectra of optical arrangements with and without presence of nanoholes in the backreflector plane, for a periodicity of 120 nm and cross sectional dimensions of 50 nm and 90 nm, according to various embodiments.

[0031] FIGS. 8A to 8C show optical images, according to various embodiments. The respective scale bar represents 25 μm.

[0032] FIG. 9 shows full-colour image printing, according to various embodiments.

[0033] FIG. 10 shows a scanning electron micrography (SEM) image of part of an optical arrangement, according to various embodiments. The scale bar represents 500 nm.

[0034] FIG. 11 shows resolution test patterns, according to various embodiments.

[0035] FIG. 12 shows a photograph of an optical arrangement and a corresponding scanning electron micrography (SEM) image, according to various embodiments.

Detailed Description

[0036] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural and logical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0037] Embodiments described in the context of a device are analogously valid for a method, and vice versa.

[0038] In the context of various embodiments, the phrase "at least substantially" may include "exactly" and a variance of +/- 5% thereof. As an example and not limitations, "A is at least substantially same as B" may encompass embodiments where A is exactly the

same as B, or where A may be within a variance of +/- 5%, for example of a value, of B, or vice versa.

[0039] In the context of various embodiments, the term "about" or "approximately" as applied to a numeric value encompasses the exact value and a variance of +/- 5% of the value.

[0040] As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0041] Various embodiments may provide a process/method to achieve microscopic bright-field colour images using plasmonic resonances in nanostructures, as well as optical arrangements or optical patterns that produce the bright-field colour images.

[0042] Various embodiments may provide a method to create high resolution colour images, micro-images or nanophotographs, based on plasmonic resonances in nanostructures. These colour images or photographs may be employed as security features, for example, on credit cards or currency notes or coins. The use of plasmonic resonances provides the benefit that the plasmonic colours do not degrade over time.

[0043] Various embodiments may provide a method of forming an optical arrangement, for example fabricating metal nanostructure (e.g. a nanostructure having a layer of metal on an end of the nanostructure) patterns on a substrate, that may achieve a range of different colours on a microscopic length scale. In various embodiments, the variation in colours is obtained by tuning the plasmonic resonances of the nanostructures by changing the sizes and/or the shapes of the nanostructures. When the optical arrangement is irradiated with light, these plasmonic resonances determine the colour(s) of light that is absorbed by the nanostructures, thereby allowing a range of different colours to be reflected and hence observable.

[0044] Various embodiments may provide a non-colourant method (e.g. without a dye, pigment, ink or other substances that provide or change the colours of a material) that may achieve bright-field colour prints or images with resolutions up to the optical diffraction limit. Colour information may be encoded in the dimensional parameters and positions of metal nanostructures (e.g. nanostructures having a layer of metal on an end of each nanostructure), so that tuning of the plasmon resonance of the nanostructures may determine the colours of the individual pixels.

[0045] In various embodiments, different cross-sectional sizes and/or cross-sectional shapes of the nanostructures may be obtained by way of a lithography process, e.g. by patterning a resist layer corresponding to the cross-sectional sizes and/or the cross-sectional shapes of the nanostructures required, during the lithography process. Therefore, a range of different colours in colour images produced from the optical arrangement of various embodiments may be determined solely by patterning to form an array of nanostructures, and with a single colour-producing material such as a thin coating of metal (e.g. noble metal) on an end of each nanostructure.

[0046] The approach or colour-mapping technique of the various embodiments may be applied to create a full-colour image or micro-image with high levels of details, with both sharp colour changes and fine tonal variations. Such an image may be employed as a highly secure (e.g. anti-fraud) element on items such as smart cards/credit cards as a result of the high levels of details/resolutions due to the high-level of technology involved in creating the micro-image. In addition, the micro-images produced may be used for steganography, nanoscale optical filters and high-density spectrally encoded optical data storage.

[0047] As the images are of high resolutions, the images cannot be printed with existing colour printers, which have a resolution limit of ~ 10,000 dpi (dots per inch). In contrast, the colour micro-photography technique of various embodiments may produce a pixel density as high as ~ 100,000 dpi, for example where the individual colour elements (or pixels) have a pitch of about 250 nm. Therefore, the technique of various embodiments enable the printing of colour micro-images or micro-photographs having a resolution with more than an order of magnitude higher than state-of-the-art printers.

[0048] While the methods of the prior art and the images produced therefrom are based on transmitted light, various embodiments may provide an optical arrangement that produces a colour image/palette as well as a method that forms the optical arrangement, where the colour image is observable based on the reflection of light from the optical arrangement, in a similar way of viewing a photograph by way of reflection of light from the photograph.

[0049] Various embodiments may seek to address two issues related to prior art. Firstly, there exists an inability in the prior art to fabricate coloured nanoscale photos with

control in two-dimensions on substrates in a single lithographic step. This is compounded by the fact that in most lithographic processes, there is a need for a lift-off step to remove all traces of unpatterned resist from the substrate, thereby encumbering the process. Secondly, most coloured nanophotographs of the prior art, based on nanoplasmonics, require the use of grazing-angle microscopy, which is not the natural way the human eye views objects and images. In this regard, the method of various embodiments of forming an optical arrangement for producing a colour image therefrom is free of a lift-off step. In addition, the optical arrangement of various embodiments produces a colour image or photograph therefrom that is visible in bright-field microscopy, as opposed to grazing-angle microscopy (darkfield).

[0050] Various embodiments may address the above-mentioned issues via a method that patterns an array or plurality of elongate nanostructures or nanoposts (e.g. high aspect ratio nanostructures), compared to continuous filling-in of polygons over large areas as in the prior art. Upon deposition of a thin metal layer on top of each nanopost of the array of nanoposts, thereby forming plasmonic nanoposts, colours or a colour image may be observed as a result of plasmonic resonance of the plasmonic nanoposts (i.e. the array of nanoposts and the layer of metal formed on each nanopost co-operate by way of plasmonic resonance) when light is irradiated or provided to the array of plasmonic nanoposts. The colours are visible in bright-field microscopy. In embodiments where the patterned area is sufficiently large, the colours may be visible to the naked eyes.

[0051] In addition, various embodiments provide a simple fabrication process which pre-empts the need for a lift-off step for the fabrication of optical arrangements for producing colour nanophotographs. This would remove a major step in a large-scale fabrication set-up, thereby reducing the costs and the time needed to fabricate such optical arrangements.

[0052] Various embodiments may generate a colour palette from the optical arrangements of various embodiments, for example using the method of various embodiments. Different colours of the colour palette correspond to plasmonic nanostructures with different cross-sectional dimensions and/or cross-sectional shapes and/or pitches. Therefore, the conditions for producing one or more plasmonic nanostructures corresponding to a particular colour may be derivable based on the colour palette.

[0053] Various embodiments may also provide a computer program or a software code, for creating a template or lay-out for the lithography system (e.g. electron beam lithography) to produce the plurality of elongate nanostructures for the optical arrangements of various embodiments. The computer program or a software code may be, for example, stored in a computer readable storage medium or in a memory, and executable by a processor (e.g. a computer's processor (CPU) or a controller's processor), or a hardware configuration program using programmable hardware elements.

[0054] Various embodiments may also provide a colour image or photograph, the colour image including a substrate, a plurality of spaced apart elongate nanostructures extending from a surface of the substrate, wherein each elongate nanostructure includes a metal layer on the end distal from the surface of the substrate. The plurality of elongate nanostructures and the metal layer formed at the end of each elongate nanostructure co-operate by way of plasmonic resonance to produce the colour image in response to a light irradiated on the plurality of elongate nanostructures and the metal layer. The colour image is observable using a bright-field illumination. In various embodiments, each elongate nanostructure may have an aspect ratio greater than 0.25. In various embodiments, the height of each elongate nanostructure is larger than the thickness of the metal layer.

[0055] FIG. 2A shows a schematic block diagram of an optical arrangement 200, according to various embodiments. The optical arrangement 200 may produce a colour image or photograph therefrom. The optical arrangement 200 includes a substrate 202, and a plurality of spaced apart elongate nanostructures 206 extending from a surface 204 of the substrate 202, wherein each elongate nanostructure 206 includes a metal layer 208 on the end distal from the surface 204 of the substrate 202. The line represented as 210 is illustrated to show the relationship between the substrate 202, the plurality of spaced apart elongate nanostructures 206 and the metal layer 208, which may include optical coupling and/or electrical coupling and/or mechanical coupling.

[0056] In other words, the optical arrangement 200 includes a plurality of spaced apart elongate nanostructures 206 on the substrate 202, which extend away from or above the surface 204 of the substrate 202. Adjacent elongate nanostructures 206 are spaced apart, for example by a spacing or distance or gap, *s*.

[0057] The plurality of elongate nanostructures 206 may be arranged at least substantially vertically or perpendicularly to the surface 204. However, it should be appreciated that any one or more or all of the plurality of spaced apart elongate nanostructures 206 may be arranged slightly angled to the surface 204, for example about 1° to 10° from an axis defined perpendicularly to the surface 204.

[0058] Each elongate nanostructure 206 has an end (i.e. proximal end) formed on the substrate 202, and includes a metal layer 208 on an opposite end (i.e. distal end) away from the surface 204 of the substrate 202. The plurality of spaced apart elongate nanostructures 206 may be formed directly on the surface 204 on the substrate 202.

[0059] In the context of various embodiments, the height of each elongate nanostructure 206 may be larger than the thickness of the metal layer 208 (e.g. the metal layer 208 is thinner than the height of each elongate nanostructure 206). However, it should be appreciated that the height of each elongate nanostructure 206 may be smaller than the thickness of the metal layer 208 (e.g. the metal layer 208 is thicker than the height of each elongate nanostructure 206).

[0060] In the context of various embodiments, the term "nanostructure" may have a size in at least one dimension in the nanometer (nm) range, for example, a range between 1 nm and 500 nm, e.g. a range between 1 nm and 200 nm, a range between 1 nm and 100 nm, a range between 10 nm and 100 nm or a range between 50 nm and 100 nm.

[0061] In the context of various embodiments, the term "elongate" as applied to a nanostructure may mean a nanostructure that extends longitudinally, e.g. extending from a surface of the substrate on which the elongate nanostructures are formed.

[0062] In the context of various embodiments, each elongate nanostructure 206 may have an aspect ratio greater than 0.25 (> 0.25), e.g. between 0.25 and 20, between 0.25 and 10, between 0.25 and 4, between 0.25 and 2, between 1 and 20, between 1 and 4, or between 4 and 10, for example an aspect ratio of 0.25 where the length of the nanostructure is a quarter of the dimension of its width, an aspect ratio of 1, an aspect ratio of 2 where the length of the nanostructure is twice as much compared to its width, an aspect ratio of 5, an aspect ratio of 10, an aspect ratio of 20. It should be appreciated that the each elongate nanostructure 206 may also have any higher aspect ratio more than 20. In the context of various embodiments, the term "aspect ratio" as applied to a nanostructure may mean a

ratio of the length (or height) to the width (or cross sectional dimension) of the nanostructure. The length-to-width aspect ratio of the nanostructure represents the proportional relationship between its length and its width.

[0063] In the context of various embodiments, each elongate nanostructure 206 may have an aspect ratio greater than 1 (> 1), with a length/height that is larger than a width (e.g. a cross sectional dimension) of the nanostructure, i.e. the nanostructure has a dimension in the longitudinal axis of the nanostructure that is larger than a dimension in the transverse axis (perpendicular to the longitudinal axis) of the nanostructure. Therefore, the nanostructure may be very long in length or height while being very short in diameter or width.

[0064] In the context of various embodiments, each elongate nanostructure 206 may be or may include a nanopost. The term "nanopost" may include a reference to a nanocolumn, a nanotube, a nanopillar or the like. Each elongate nanostructure 206 may be a nanostructure with a columniform shape.

[0065] Each elongate nanostructure 206 and its corresponding metal layer 208 may form a plasmonic nanostructure. In the context of various embodiments, the plurality of elongate nanostructures 206 and the layer of metal 208 formed at the end of each elongate nanostructure (i.e. plurality of plasmonic nanostructures) co-operate by way of plasmonic resonance to produce a colour image in response to light (e.g. white light) irradiated on the optical arrangement 200. Therefore, in the context of various embodiments, the optical arrangement 200 may produce a colour image therefrom, which may be observable using a bright-field illumination (e.g. using a bright-field microscope). A variety of colours or shades of colours of the visible or optical spectrum may be produced and observed.

[0066] In the context of various embodiments, the term "plasmonic nanostructure" may mean or include a nanostructure having a metal layer on an end of the nanostructure, where both co-operate by way of plasmonic resonance such that a certain range of wavelengths of light in the visible range may be absorbed by the plasmonic nanostructure, thereby allowing the observation of the colour(s) reflected (i.e. not absorbed by the plasmonic nanostructure) from the plasmonic nanostructure.

[0067] In the context of various embodiments, the term "plasmonic resonance" may mean a behaviour or condition where a particular frequency (or wavelength) range of the incident wave (e.g. light) causes excitation of free electrons in a metal layer, which may cause a drop in the reflectivity of the metal layer as the energy of the incident wave (e.g. light), rather than being reflected by the metal layer and the plasmonic nanostructure, is coupled into plasmon modes. In the context of various embodiments, the plasmon modes may include surface plasmon modes which propagate along the surface of the metal layer or bulk plasmon modes which propagate inside the metal layer.

[0068] In various embodiments, the optical arrangement 200 may include another metal layer on portions of the surface 204 of the substrate 202 without the plurality of elongate nanostructures 206, e.g. in the spacings between adjacent elongate nanostructures 206 and/or at the edges/periphery of the substrate 202. Therefore, there may be nanoholes in this metal layer where the bases of the elongate nanostructures 206 are located. This metal layer may act as a backreflector or retro-reflector to reflect light (e.g. white light) irradiated on the optical arrangement 200 onto the plurality of plasmonic nanostructures to further enhance the colour absorption in the plasmonic nanostructures.

[0069] In the context of various embodiments, the thickness of the metal layer 208 on the end of each elongate nanostructure 206 may be between about 5 nm and about 100 nm, e.g. between about 5 nm and about 50 nm, between about 5 nm and about 20 nm, between about 20 nm and about 100 nm or between about 20 nm and about 50 nm, for example a thickness of about 5nm, about 20 nm, about 50 nm or about 100nm.

[0070] In the context of various embodiments, the thickness of the metal layer on portions of the surface 204 of the substrate 202 without the plurality of elongate nanostructures 206 may be the same as the thickness of the metal layer 208.

[0071] In the context of various embodiments, the height of each elongate nanostructure 206 may be between about 10 nm and about 500 nm, e.g. between about 10 nm and about 300 nm, between about 10 nm and about 100 nm, between about 10 nm and about 50 nm, between about 100 nm and about 500 nm or between about 100 nm and about 200 nm, for example a height of about 10nm, about 50 nm, about 100 nm, about 300 nm or about 500 nm.

[0072] In the context of various embodiments, each elongate nanostructure 206 may have a cross sectional dimension, *d*, of between about 10 nm and about 250 nm., e.g. between about 10 nm and about 200 nm, between about 10 nm and about 100 nm, between about 10 nm and about 50 nm, between about 100 nm and about 250 nm, or between about 50 nm and about 200 nm, for example a cross sectional dimension of about 10 nm, about 50 nm, about 100 nm or about 250 nm. The term "cross sectional dimension" may mean a dimension of a cross section of the elongate nanostructure 206 defined along a transverse axis (perpendicular to the longitudinal axis) of the elongate nanostructure 206.

[0073] In various embodiments, the plurality of elongate nanostructures 206 may have different cross sectional dimensions. In other words, each or some of the elongate nanostructures 206 may have a different cross sectional dimension compared to other elongate nanostructures 206. For example, some elongate nanostructures 206 may have a cross sectional dimension, *d1*, while some other elongate nanostructures 206 may have a different cross sectional dimension, *d2*. Furthermore, a cluster of elongate nanostructures 206 at one area/region of the substrate 202 may have a cross sectional dimension that is different from another cluster of elongate nanostructures 206 at another area/region of the substrate 202. The cross sectional dimensions of the plurality of elongate nanostructures 206 may depend on the colour(s) that is to be produced.

[0074] In the context of various embodiments, each elongate nanostructure 206 may have a cross sectional shape that is a square or a rectangle or a circle or an ellipse or a triangle or a hexagon or an octagon. The term "cross sectional shape" may mean a shape of a cross section of the elongate nanostructure 206 defined along a transverse axis (perpendicular to the longitudinal axis) of the elongate nanostructure 206. However, it should be appreciated that each elongate nanostructure 206 may have other shapes, e.g. any polygonal shape.

[0075] In various embodiments, the plurality of elongate nanostructures 206 may have different cross sectional shapes. In other words, each or some of the elongate nanostructures 206 may have a different cross sectional shape compared to other elongate nanostructures 206. For example, some elongate nanostructures 206 may have a cross sectional shape, e.g. circular, while some other elongate nanostructures 206 may have a different cross sectional shape, e.g. triangular. Furthermore, a cluster of elongate

nanostructures 206 at one area/region of the substrate 202 may have a cross sectional shape that is different from another cluster of elongate nanostructures 206 at another area/region of the substrate 202. The cross sectional shapes of the plurality of elongate nanostructures 206 may depend on the colour(s) that is to be produced.

[0076] In the context of various embodiments, two adjacent (or neighbour) elongate nanostructures 206 of the plurality of elongate nanostructures 206 may be spaced apart by a distance or spacing or gap, *s*, of between about 20 nm and about 300 nm, e.g. between about 20 nm and about 200 nm, between about 20 nm and about 100 nm, between about 20 nm and about 50 nm, between about 50 nm and about 300 nm, or between about 100 nm and about 200 nm, for example a spacing of about 20 nm, about 50 nm, about 100 nm or about 200 nm.

[0077] In various embodiments, adjacent elongate nanostructures 206 may be spaced apart by a distance, *s*, that is at least substantially the same. Accordingly, the pitch, *p*, defined as the distance between the respective centres of adjacent elongate nanostructures 206 may be at least substantially the same. The pitch may be defined as (*d*+*s*), where *d* is the cross sectional dimension of an elongate nanostructure 206, and *s* is the distance or spacing between two adjacent (or neighbour) elongate nanostructures 206.

[0078] In the context of various embodiments, the plurality of elongate nanostructures 206 may have a periodicity (or pitch) of (*d*+*s*) that is at least substantially the same. The periodicity may be between about 30 nm and about 550 nm, e.g. between about 30 nm and about 300 nm, between about 30 nm and about 100 nm, between about 50 nm and about 200 nm, between about 100 nm and about 550 nm, or between about 100 nm and about 200 nm, for example a periodicity of about 30 nm, about 50 nm, about 120 nm, about 200 nm, about 300 nm or about 550 nm.

[0079] In various embodiments, adjacent elongate nanostructures of the plurality of elongate nanostructures 206 may be spaced apart by different distances, *s*, thereby changing the areal densities of the elongate nanostructures 206 on the substrate 202. In other words, some adjacent elongate nanostructures 206 may have a different spacing, *s*, and therefore also the pitch, *p*, compared to other adjacent elongate nanostructures 206. For example, some adjacent elongate nanostructures 206 may have a spacing, *s1*, or pitch, *p1*, while some other adjacent elongate nanostructures 206 may have a different

spacing, *s2*, or pitch, *p2*. Furthermore, a cluster of adjacent elongate nanostructures 206 at one area/region of the substrate 202 may have a spacing or a pitch, and therefore also an areal density of elongate nanostructures 206, that is different from another cluster of adjacent elongate nanostructures 206 at another area/region of the substrate 202. The spacings or pitches of the plurality of elongate nanostructures 206, and therefore also the areal densities of the elongate nanostructures 206 on the substrate 202, may depend on the colour(s) and/or the intensity of the colour(s) that is to be produced.

[0080] In the context of various embodiments, the term "areal density" may refer to the density or population or number of elongate nanostructures 206 at a particular area of the substrate 202.

[0081] In the context of various embodiments, the metal layer 208 and/or the metal layer on portions of the surface 204 of the substrate 202 without the plurality of elongate nanostructures 206, may include a noble metal.

[0082] In the context of various embodiments, the metal layer 208 and/or the metal layer on portions of the surface 204 of the substrate 202 without the plurality of elongate nanostructures 206 may include but not limited to any one of or a combination of gold (Au), silver (Ag), copper (Cu), aluminium (Al), chromium (Cr), ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) or platinum (Pt). It should be appreciated that other metals may be used. In various embodiments, different colours observable from the optical arrangement 200 may depend on the material of the metal layer 208 and/or the material of the metal layer on portions of the surface 204 of the substrate 202 without the plurality of elongate nanostructures 206.

[0083] In the context of various embodiments, the metal layer 208 and the metal layer on portions of the surface 204 of the substrate 202 without the plurality of elongate nanostructures 206 may be of the same or different metals.

[0084] In the context of various embodiments, any one of or each of the metal layer 208 and the metal layer on portions of the surface 204 of the substrate 202 without the plurality of elongate nanostructures 206 may be a single layer of metal (e.g. Au), two layers of different metals arranged one over the other (e.g. a layer of Au and a layer of Ag), three layers of different metals arranged one over the other (e.g. a layer of Cr, a layer of Au and a layer of Ag, a layer of Au sandwiched in between layers of Ag or a

layer of Ag sandwiched in between layers of Au) or any number of layers of different metals.

[0085] In the context of various embodiments, each elongate nanostructure 206 may include but not limited to an epoxy-based polymer (e.g. SU-8 photoresist), hydrogen silsesquioxane (HSQ), poly(methyl methacrylate) (PMMA), polycarbonate, titanium dioxide (TiO_2) or silicon oxide (SiO_x). However, it should be appreciated that each elongate nanostructure 206 may be of any material having a refractive index of between about 1.3 and about 5 for producing colours from the optical arrangement 200, e.g. between about 1.3 and about 3, between about 1.3 and about 2, between about 2 and about 5, or between about 2 and about 3, e.g. a refractive index of about 1.3, about 2, about 3 or about 5. In addition, it should be appreciated that materials having a refractive index of more than 5 may also be used. In various embodiments, the material of each elongate nanostructure 206 may depend on the material of the resist used to form the plurality of elongate nanostructures 206.

[0086] In the context of various embodiments, the substrate 202 may be non-transmissive to light (e.g. optically non-transmissive). In various embodiments, the substrate 202 may be but not limited to a silicon (Si) substrate, a silicon-on-insulator (SOI) substrate or a germanium (Ge) substrate.

[0087] In the context of various embodiments, the substrate 202 may be transmissive to light (e.g. optically transmissive), e.g. including but not limited to quartz or polycarbonate.

[0088] In the context of various embodiments, the cross sectional dimension, and/or the cross sectional shape of an elongate nanostructure 206, and/or the spacing (or pitch) of adjacent elongate nanostructures 206, and/or the material of the metal layer 208 on an end of the elongate nanostructure 206, and therefore also of the plasmonic nanostructures, may be changed depending on the colour(s) to be produced. In other words, the colour(s) that is produced or reflected by a plasmonic nanostructure may correspond to its cross sectional dimension and/or its cross sectional shape and/or its distance from another plasmonic nanostructure and/or the metal layer of the plasmonic nanostructure or a combination of any two, three or all of these features.

[0089] As a non-limiting example, in order to produce the colour blue to be observed, an optical arrangement having a plurality of elongate cylindrical nanostructures having a diameter of about 90 nm, with a spacing of about 100 nm between adjacent cylindrical nanostructures, may be provided. Each elongate cylindrical nanostructure includes a metal layer of 1 nm Cr, 15 nm Ag and 5 nm Au deposited on an end thereof.

[0090] In the context of various embodiments, the cross sectional dimension and/or the cross sectional shape of the metal layer deposited on the end of an elongate nanostructure 206 may correspond to that of the elongate nanostructure 206, and/or the spacing (or pitch) of adjacent metal layers deposited on the ends of adjacent elongate nanostructures 206 may correspond to that of adjacent elongate nanostructure 206.

[0091] FIG. 2B shows a flow chart 240 illustrating a method of forming an optical arrangement, according to various embodiments.

[0092] At 242, a substrate is provided.

[0093] At 244, a plurality of spaced apart elongate nanostructures extending from a surface of the substrate is formed.

[0094] At 246, a metal layer is formed on the end of each elongate nanostructure distal from the surface of the substrate.

[0095] In various embodiments, at 244, the plurality of spaced apart elongate nanostructures may be formed such that each elongate nanostructure 206 may have an aspect ratio greater than 0.25 (> 0.25) or greater than 1(> 1). For example, each elongate nanostructure may have an aspect ratio of between 0.25 and 20, between 0.25 and 10, between 0.25 and 4, between 0.25 and 2, between 1 and 20, between 1 and 4, or between 4 and 10, for example an aspect ratio of 0.25, an aspect ratio of 1, an aspect ratio of 2, an aspect ratio of 5, an aspect ratio of 10, an aspect ratio of 20 or any higher aspect ratio more than 20.

[0096] In various embodiments, at 244, the plurality of spaced apart elongate nanostructures may be formed or fabricated using a patterning process, for example a lithography process. The lithography process may include depositing a resist layer on the surface of the substrate, exposing the resist layer to an energy source to define a pattern corresponding to the plurality of elongate nanostructures, and removing portions of the resist layer to form the plurality of elongate nanostructures.

[0097] In the context of various embodiments, the dosage (exposure dosage) of the energy source may be varied during exposure of the resist layer. Varying the dosage may vary the cross sectional dimension of the elongate nanostructures and/or the pitch between adjacent elongate nanostructures to be formed, so that different colours may be observed from the optical arrangement.

[0098] In the context of various embodiments, the resist layer may be a positive resist where the portion(s) of the positive resist exposed to an energy source is developed and removed, or a negative resist where the portion(s) of the negative resist unexposed to an energy source is developed and removed.

[0099] In the context of various embodiments, the resist layer may be exposed to an energy source including but not limited to ultraviolet (UV) radiation (e.g. photolithography), including extreme ultraviolet lithography (EUV) radiation with wavelengths, for example, shorter than 157 nm, or electron beam (E-beam) radiation (i.e. exposed to a beam of electrons). Any high-resolution photolithography techniques may also be employed.

[0100] In various embodiments, at 244, elongate nanostructures may be formed with different areal densities on the substrate.

[0101] In various embodiments, at 244, elongate nanostructures may be formed with different cross sectional dimensions on the substrate.

[0102] In various embodiments, at 244, elongate nanostructures may be formed with different cross sectional shapes on the substrate.

[0103] In various embodiments, at 244, adjacent elongate nanostructures spaced apart by a distance or spacing that is at least substantially same may be formed on the substrate.

[0104] In various embodiments, at 246, the metal layer may be formed or deposited using electron beam (e-beam) evaporation.

[0105] In various embodiments, the method further includes forming another metal layer on portions of the surface of the substrate without the plurality of elongate nanostructures. This metal layer may be formed at 246 at the same time of forming the metal layer on the end of each elongate nanostructure, e.g. this metal layer on portions of the surface of the substrate without the plurality of elongate nanostructures and the metal

layer on the end of each elongate nanostructure may be formed or deposited in a single step, or in separate steps or processes.

[0106] In various embodiments, each elongate nanostructure may have a cross sectional shape that is a square or a rectangle or a circle or an ellipse or a triangle or a hexagon or an octagon. However, it should be appreciated that each elongate nanostructure 206 may have other shapes, e.g. any polygonal shape.

[0107] In various embodiments, the metal layer on the end of each elongate nanostructure and/or the metal layer on portions of the surface of the substrate without the plurality of elongate nanostructures may include but not limited to any one of or a combination of gold (Au), silver (Ag), copper (Cu), aluminium (Al), chromium (Cr), ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) or platinum (Pt). It should be appreciated that other metals may be used.

[0108] In various embodiments, each elongate nanostructure may include but not limited to an epoxy-based polymer (e.g. SU-8 photoresist), hydrogen silsesquioxane (HSQ), poly(methyl methacrylate) (PMMA), polycarbonate, titanium dioxide (TiO2) or silicon oxide (SiOx). However, it should be appreciated that each elongate nanostructure may be of any material having a refractive index of between about 1.3 and about 5, e.g. between about 1.3 and about 3, between about 1.3 and about 2, between about 2 and about 5, or between about 2 and about 3, e.g. a refractive index of about 1.3, about 2, about 3 or about 5. In addition, it should be appreciated that materials having a refractive index of more than 5 may also be used. In various embodiments, the material of each elongate nanostructure may depend on the material of the resist used to form the plurality of elongate nanostructures.

[0109] In various embodiments, the height of each elongate nanostructure is larger than the thickness of the metal layer formed on the end of each elongate nanostructure (e.g. the metal layer is thinner than the height of each elongate nanostructure). However, it should be appreciated that the height of each elongate nanostructure may be smaller than the thickness of the metal layer (e.g. the metal layer is thicker than the height of each elongate nanostructure).

[0110] In various embodiments, the plurality of elongate nanostructures may have a periodicity (or pitch) of $(d+s)$ that is at least substantially the same. The periodicity may

be between about 30 nm and about 550 nm, e.g. between about 30 nm and about 300 nm, between about 30 nm and about 100 nm, between about 50 nm and about 200 nm, between about 100 nm and about 550 nm, or between about 100 nm and about 200 nm, for example a periodicity of about 30 nm, about 50 nm, about 120 nm, about 200 nm, about 300 nm or about 550 nm.

[0111] In various embodiments, the method may be free of a lift-off process. This may mean that the method may be free of any step(s) of depositing a sacrificial layer and subsequently removing the sacrificial layer.

[0112] The optical arrangements and the fabrication methods of various embodiments, and the associated results will now be described by way of the following non-limiting embodiments and examples.

[0113] For the purpose of numerical simulations of the reflectance spectra, simulations were carried out using a frequency domain solver from the Computer Simulation Technology (CST AG) microwave studio commercial software. Unit-cell boundaries were used in the plane of the metal nanodisks (metal layers on the ends of the elongate nanostructures) and Floquet ports were used for terminating the domain in the direction of incidence. The frequency-domain solver incorporated measured wavelength dispersion of the permittivity of the various materials used in the structure. The material for the elongate nanostructures, e.g. hydrogen silsesquioxane (HSQ), was simulated using a constant refractive index of 1.4.

[0114] For the purpose of optical measurements, the optical properties of the fabricated structures and extinction spectra were measured in reflection mode using a QDI 2010 UV-visible-NIR range microspectrophotometer (CRAIC Technology). Both incident and collected light were at normal incidence to the substrate, with the electric field of the unpolarized light in plane with the substrate surface.

[0115] Optical images or micrographs were acquired using a Nikon MM-40/L3FA (Nikon) set-up with a ×100, 0.9 NA air objective lens as well as with an Olympus MX61 set-up with a ×150, 0.9 NA air objective lens, using a JVC Colour Video Camera TKC14-81EG (JVC Corp) for the former and an SC30 Olympus Digital Camera for the latter.

[0116] FIG. 3A shows cross-sectional views of a method of forming an optical arrangement, according to various embodiments. The method allows bright-field colour images to be produced using plasmonic resonances in the nanostructures of the optical arrangements. The optical arrangement and the resulting colour image are observable using bright-field illumination.

[0117] A substrate (e.g. a silicon (Si) substrate) 300 is first provided. A resist material may then be spin-coated on the substrate 300 to obtain a resist layer of a desired thickness on the substrate 300. FIG. 3A shows a structure or optical arrangement 340 that may be obtained, with a resist layer 342 spin-coated on the substrate 300.

[0118] A plurality or array of elongate nanostructures or high aspect ratio nanostructures (e.g. aspect ratio > 0.25), for example nanoposts, of a sufficient length/height (e.g. about 100 nm) are then lithographically defined on the substrate 300 and subsequently developed. The plurality of elongate nanostructures may be spaced apart. FIG. 3A shows a structure or optical arrangement 310 that may be obtained, where the optical arrangement 310 includes a plurality of spaced apart elongate nanostructures 302 formed on the substrate 300. The plurality of elongate nanostructures 302 extend from a surface 304 of the substrate 300. The plurality of elongate nanostructures 302 may extend at least substantially vertically to the surface 304, i.e. extend perpendicularly to the surface 304.

[0119] A thin layer of metal (e.g. a noble metal, e.g. gold (Au), or a combination of silver (Ag) and gold (Au), Ag/Au), for example having a thickness of about 20 nm, is then deposited at an end of each elongate nanostructure 302 of the array of elongate nanostructures 302, on top of each elongate nanostructure 302.

[0120] At the same time of depositing the thin metal layer on the plurality of elongate nanostructures 302, a layer of the same metal, for example having a thickness of about 20 nm, may also be deposited at portions of the surface 304 of the substrate 300 without the plurality of elongate nanostructures 302, including the spaces in between adjacent elongate nanostructures 302. Therefore, a single step may be performed to deposit a blanket metal layer over the optical arrangement 310, thereby covering the top ends of the plurality of elongate nanostructures 302, and the portions of the surface 304 of the substrate 300 without the plurality of elongate nanostructures 302. Alternatively, a

separate step may be performed to deposit the metal layer at portions of the surface 304 of the substrate 300 without the plurality of elongate nanostructures 302.

[0121] FIG. 3A shows a structure or optical arrangement 330 that may be obtained after the step of thin metal deposition. The optical arrangement 330 includes a plurality of spaced apart elongate nanostructures 302 formed on the substrate 300 and a layer of metal 320 deposited on top of each elongate nanostructure 302 at the end of each elongate nanostructure 302 distal from the substrate 300. Each elongate nanostructure 302 with the layer of metal 320 forms a plasmonic nanostructure 324. The optical arrangement 330 further includes a layer of metal 326 deposited at portions of the surface 304 of the substrate 300 without the plurality of elongate nanostructures 302. The metal layer 326 acts as a backreflector.

[0122] The optical arrangement 330 may then be observed using bright-field illumination to view the colour image that is produced, corresponding to the optical arrangement 330.

[0123] In various embodiments, during the lithography process, elongate nanostructures 302 with the same or different cross sectional dimensions and/or cross sectional shapes, where the cross section is defined as a plane along the line A-A' (i.e. the cross section of each elongate nanostructure 302 as seen in the direction B), may be patterned and formed. In this way, all of the plurality of elongate nanostructures 302 may have the same cross sectional dimensions and/or cross sectional shapes, or some of the plurality of elongate nanostructures 302 may have different cross sectional dimensions and/or cross sectional shapes compared to the others. Therefore, the plurality of elongate nanostructures 302 may have different cross sectional shapes, for example, one or more elongate nanostructures 302 may have a circular cross section, one or more elongate nanostructures 302 may have a rectangular cross section and one or more elongate nanostructures 302 may have a triangular cross section. In addition, the plurality of elongate nanostructures 302 may have different cross sectional dimensions, for example, one or more elongate nanostructures 302 may have a cross sectional dimension *d1*, one or more elongate nanostructures 302 may have a cross sectional dimension *d2* and one or more elongate nanostructures 302 may have a cross sectional dimension *d3*.

[0124] Furthermore, elongate nanostructures 302 with the same or different distances/spacings between adjacent elongate nanostructures 302 (or alternatively the

pitch, defined as the distance between the centre points of adjacent elongate nanostructures 302) may be patterned and formed. In this way, all of the plurality of elongate nanostructures 302 may have the same pitch, or some of the plurality of elongate nanostructures 302 may have the same pitch, but that is different to the pitch of some other elongate nanostructures 302. As a result, elongate nanostructures 302 may be patterned and formed with the same or different areal densities on the substrate 300. For example, some elongate nanostructures 302 at one area of the substrate 300 may have a pitch *p1*, while some elongate nanostructures at another area of the substrate 300 may have a pitch *p2*.

[0125] In various embodiments, any one, two or all of the cross sectional dimension and/or the cross sectional shape and/or the pitch may be varied for the plurality of elongate nanostructures 302.

[0126] Therefore, the plurality of elongate nanostructures 302, and therefore also the plurality of plasmonic nanostructures 324, may be arranged according to the colour image to be produced. For example, the plurality of plasmonic nanostructures 324 may be formed in regions of the substrate 300 where colours are to be observed, where the regions may be of any shapes and/or sizes and/or at different portions of the substrate 300. In addition, the plurality of plasmonic nanostructures 324 may be formed to produce colours in the form of a dot, a line (e.g. a straight line, a wavy line or any types of line) and an area/region.

[0127] In various embodiments, the process(es) for depositing the metal layers 320, 326 may include electron beam evaporation in which an electron beam is directed and focused on a target material to be deposited until the material evaporates and its vapour deposits over the plurality of elongate nanostructures 302 and/or the surface 304 of the substrate 300 to deposit the metal layers 320, 326.

[0128] In various embodiments, the height (length) of the elongate nanostructures (e.g. nanoposts) 302 may be larger than the thickness of the metal layers 320 on the top of the elongate nanostructures 302, such that the metal layers 320 may be considered as isolated plasmonic metal nanodisks displaying plasmonic resonance behavior. Plasmon resonance results in the extinction of a certain range of wavelengths of light in the visible range, for example by being absorbed by the plasmonic nanostructures 324, thereby

allowing the observation of the colours reflected from the plasmonic nanostructures 324. By changing the size or cross sectional dimension of the elongate nanostructures 302, other corresponding wavelengths may be extinguished as a result of a change in the plasmonic resonance, thereby resulting in different colours being reflected and observed. In addition, by changing the areal density of the elongate nanostructures 302 on the substrate 300, the intensity of the colours observed may be changed accordingly. Furthermore, in various embodiments, the metal layer 326 on portions of the surface 304 without an elongate nanostructure 302 (e.g. spaces in between elongate nanostructures 302) act as retro-reflectors that may further enhance the colour absorption in the plasmonic nanostructures 324.

[0129] In various embodiments, the scattering strength of particle resonators may be increased by raising them above a metal backreflector to obtain 250 nm-pitch pixels that reflect individual colours without a dependence on periodicity. FIG. 3B shows a perspective view of an optical arrangement 350 that may be obtained from the method illustrated in FIG. 3A, according to various embodiments, for two such pixels.

[0130] The optical arrangement 350 includes a substrate 300 and a plurality of spaced apart elongate nanostructures (e.g. nanoposts) 302 formed on the substrate 300. Each elongate elongate nanostructure 302 includes a metal layer 320 (e.g. metal nanodisk) deposited on top of each elongate nanostructure 302 at the end of each elongate nanostructure 302 distal from the substrate 300. In a non-limiting example, the metal layer 320 may include a layer of silver (Ag) 351 and a layer of gold (Au) 352. Each elongate nanostructure 302 with the metal layer 320 forms a plasmonic nanostructure 324. The optical arrangement 350 further includes a layer of metal 326, as a backreflector, at portions of the surface of the substrate 300 without the plurality of elongate nanostructures 302. In a non-limiting example, the metal layer 326 may include a layer of silver (Ag) 353 and a layer of gold (Au) 354. In various embodiments, a single metal evaporation step may be performed to deposit the metal layers 320, 326.

[0131] As illustrated in FIG. 3B, elongate nanostructures 302 and therefore also the plasmonic nanostructures 324 may have different cross sectional dimensions or diameters, d, and/or spacing, s, between adjacent nanostructures 302.

[0132] In various embodiments, each pixel 355, 356, may include four plasmonic nanostructures 324 that support particle resonances, although any number of plasmonic nanostructures 324 per pixel may be provided. As shown in FIG. 3B, the metal nanodisks 320 are raised above equally sized nanoholes, where the bases of the elongate nanostructures 302 are located, on the backreflector 326. The backreflector plane 326 functions as a mirror to increase the scattering intensity of the metal nanodisks 320.

[0133] FIG. 3C shows simulated reflectance spectra of Ag/Au nanodisks 320 hovering above a reflective Si surface 304 in vacuum, according to various embodiments. FIG. 3C shows the simulated reflectance spectrum 370 for 140 nm diameter nanodisks and the simulated reflectance spectrum 371 for 50 nm diameter nanodisks, in periodic arrays with gaps or spacings, *s*, of about 30 nm.

[0134] When the nanodisks 320 are placed directly on a reflective surface (h = 0 nm), all visible wavelengths appear to be reflected almost equally, which results in a dull gray colour. Where the nanodisks 320 are allowed to hover above the surface 304 even at a distance, h, of 20 nm, the spectrum shifts drastically and plasmonic scattering is observed for the larger nanodisks of 140 nm, while certain wavelengths are absorbed by the smaller nanodisks of 50 nm. At a distance, h, of 180 nm, more of the low wavelength regions are reflected by the nanodisks 320, resulting in a bluish tinge to the colours observed.

[0135] The behaviour of the nanodisks 320 in the vicinity of a backreflector 326, while not wishing to be bound by any theory, may be explained via the existence of a screening dipole, which is a mirror dipole, and thus has an opposite effect to the original dipole. The original and screening dipoles are thus cancelled out. The cancellation may be most effective when the dipoles are closest to each other. Thus, when the nanodisks 320 rest on the surface 304 of a substrate 300, there is almost full cancellation. As the nanodisks 320 are raised, the cancellation becomes less effective. Therefore, the plurality of elongate nanostructures 302 may play a role in reducing the effects of the screening charges. Therefore, when the nanodisks 320 are separated far enough from the surface 304, the configuration of nanodisks 320 and the reflective surface 304 may produce a superposed response of the individual spectra from the nanodisks 320 and the silicon surface 304.

[0136] In various embodiments, the optical arrangement 350 may include groups of plasmonic nanostructures 324, for example with different diameters, *d*, and/or spacing, *s*,

to reflect different colours sufficiently to be detected in an optical bright-field microscope, regardless of the periodicity (d+s) or pitch, p, of the plasmonic nanostructures 324.

[0137] As a non-limiting example, FIG. 3B illustrates the interaction of white light, e.g. a combination of red wavelength light 360, green wavelength light 362 and blue wavelength light 364, with two closely spaced pixels 355, 366, each including four nanodisks 320 raised above the backreflector 326. As a result of the different diameters, d, and spacings, s, of the nanodisks 320 within each pixel 355, 356, different wavelengths of light may be preferentially reflected back. For example, the pixel 355 may be configured to reflect green wavelength light 362 while the pixel 356 may be configured to reflect red wavelength light 360. Therefore, colour information may be encoded in the diameter, d, of the nanoposts 302 and the spacing, s, between adjacent nanoposts 302.

[0138] It should be appreciated that the optical arrangement 350 may include any number of plasmonic nanostructures 324 or metal nanodisks 320 per pixel and/or any number of pixels.

[0139] As opposed to other methods of generating plasmonic nanostructures that rely on etching and lift-off processes, the approach of various embodiments avoids any of these steps.

[0140] A non-limiting example of a method of forming the optical arrangement of various embodiments, using electron beam (e-beam) lithography to define the initial resist structures, will now be described.

[0141] First, a hydrogen silsesquioxane (HSQ) negative resist layer was prepared on a silicon (Si) substrate by spin-coating a HSQ solution to the desired layer thickness on the Si substrate. The HSQ (from Dow Corning) solution was prepared with 6% concentration in a methyl isobutyl ketone (MIBK) solvent. The HSQ solution was then spin-coated on the Si substrate at approximately 3000 rpm (revolutions per minute), resulting in a HSQ resist layer with a thickness of about 95-100 nm. No baking of the HSQ resist layer was carried out to avoid thermally induced cross-linking of the HSQ molecules or monomers, which may reduce its resolution.

[0142] A computer-generated layout having arrays of disks with a range of diameters, *d*, (e.g. 50–140 nm) and spacings, *s*, (30–120 nm) was designed. Electron-beam (e-beam) lithography was then performed on the HSQ resist layer in an Elionix ELS-900 or Elionix ELS-7000 system, with an acceleration voltage of about 100 kV and a beam current of about 500 pA to define a pattern corresponding to a plurality of nanoposts. The write field was set to 150×150 mm and the exposure step size was about 2.5 nm. The dose used for the nanodisk structures may be about 12 mC cm^{-2}. No proximity-effect correction was performed for the exposure. The HSQ became cross-linked by exposure to the e-beam. A number of patterns were generated, consisting of disks and triangles where the cross sectional dimensions, the pitches and the e-beam exposure doses were varied.

[0143] In order to achieve well-defined nanodisk structures with steep sidewalls, a high-contrast development process was used. The unexposed (not cross-linked) HSQ portions were removed during development in a salty developer solution (1% NaOH, 4% NaCl in deionized (DI) water) at about 24°C for about 1 minute, leaving HSQ nanoposts on the Si substrate. The samples were then rinsed under running DI water for about 2 minutes, and isopropyl alcohol (IPA), and blown-dried under a steady stream of nitrogen (N_2).

[0144] Subsequently, a metal layer structure of about 1 nm of chromium (Cr) as an adhesion layer, about 15 nm of silver (Ag), and about 5 nm of gold (Au) as a capping layer were sequentially deposited using a Denton Explorer E-beam evaporator unit. All metals were deposited at a rate of 1Ås^{-1}. The working pressure during evaporation was approximately 1×10^{-6} torr. The temperature of the sample chamber was maintained at about 20°C during the entire evaporation process, with the sample holder rotating at a rate of about 50 r.p.m. to ensure uniformity of the deposition. The chromium adhesion layer provided scratch resistance in the resulting metal layers and had minimal effect on the optical properties of the structures, while the gold capping layer hindered the sulphidation of silver.

[0145] The resulting optical arrangements including the plasmonic nanostructures were observed using a bright-field microscope as well as an Elionix ESM-9000 scanning electron microscope with an accelerating voltage of about 10 kV and a working distance of about 5 mm.

[0146] FIG. 4A shows a scanning electron micrography (SEM) image 400 of an optical arrangement, according to various embodiments. The optical arrangement 400 includes a plurality of plasmonic nanostructures 402, i.e. a plurality of elongate nanostructures (e.g. nanoposts) having a thin metal layer (e.g. metal nanodisk) deposited on the top end of each elongate nanostructure. The plasmonic nanostructures 402, and therefore the plurality of elongate nanostructures and the metal nanodisks have circular cross sectional shapes. The cross sectional dimension (also diameter in this embodiment), *d*, of each elongate nanostructure, and also each metal nanodisk may be about 90 nm, while the spacing, *s*, between adjacent plasmonic nanostructures 402 may be about 80 nm, and the pitch, *p*, between adjacent plasmonic nanostructures 402 may be about 170 nm. However, it should be appreciated that other cross sectional shapes and/or cross sectional dimensions, *d*, and/or spacings, *s*, and/or pitches, *p*, may be possible.

[0147] While FIG. 4A shows an array of elongate nanostructures having circular cross sectional shapes (e.g. nanodisks), it should be appreciated that linear structures (e.g. nanotriangles or nanosquares) and/or an array of holes, with varying areal densities on a substrate, may also be fabricated, which may also achieve the results as shown in, for example, FIGS. 8A to 8C as described below.

[0148] While the plurality of plasmonic nanostructures 402, and therefore also the plurality of elongate nanostructures (e.g. nanoposts) are arranged in a uniform or regular pattern/configuration (e.g. periodic), as shown in FIG. 4A for example in a grid-like manner, it should be appreciated that the positioning of the plasmonic nanostructures 402 may be in a random manner while maintaining the spacing, *s*, between adjacent plasmonic nanostructures 402 at approximately equal distance.

[0149] FIG. 4B shows a scanning electron micrography (SEM) image 410 of an optical arrangement, according to various embodiments, obtained at a 70° side-angle of a small area of an optical arrangement. The optical arrangement includes a plurality of elongate nanostructures 412, each coated with a nanodisk 414, and with a layer of backreflector 416.

[0150] The elongate nanostructures, before and after metal deposition, thereby forming plasmonic nanostructures, were characterized using a reflection bright-field microscope, a scanning electron microscope (SEM) and a microspectrophotometer.

[0151] In various embodiments, in order to achieve a full palette of colours that span the visible range, the diameters, *d*, of the metal nanodisks and also that of the elongate nanostructures, as well as the interdisk separations or equivalently the spacings, *s*, between adjacent elongate nanostructures, may be varied.

[0152] FIG. 5A shows an optical micrograph 500 of arrays 502 of HSQ elongate nanostructures (or nanoposts), according to various embodiments. Each array 502 is a 12 μm square having a square lattice of nanoposts of periodicity (*d*+*s*). The diameter, *d*, of the nanoposts was varied between 50 nm and 140 nm from the bottom row to the top row of arrays 502, while the spacing, *s*, was varied between 30 nm and 120 nm from the left column to the right column of arrays 502. The arrays 502 of elongate nanostructures display grey-scale variations, without displaying any colour.

[0153] FIG. 5B shows an optical micrograph 500 of arrays 512 of plasmonic nanostructures, after deposition of a metal layer (e.g. 1 nm Cr, 15 nm Ag, 5 nm Au) on top of each HSQ elongate nanostructure, according to various embodiments. The addition of metal layers of a uniform thickness transformed the grey-scale arrays of HSQ nanostructures as observed in FIG. 5A into a brilliant display of colour arrays 512 as in FIG. 5B (viewed using reflection bright-field microscopy).

[0154] For example, in the direction M → M', the colour changed from yellow to green, in the direction N → N', the colour changed from yellow to green to blue, in the direction P → P', the colour changed from dark brown to light brown (i.e. different shades of brown), in the direction Q → Q', the colour changed from yellow to green to blue to brown, in the direction R → R', the colour changed from green to blue to violet to brown, in the direction S → S', the colour changed from yellow to green to blue to brown, and in the direction T → T', the colour changed from green to blue to brown.

[0155] Following deposition of thin metal layers of a uniform thickness, the full palette of colours may be obtained. Nanostructure arrays with substantially similar or moderate change in colours may be observed in the direction T → T', indicating that arrays 512 with similar fill factors, ($d/(d+s)$), may produce arrays 512 of substantially similar colours. Nanostructures with the same periodicity, (*d*+*s*), may display a wide range of colours as may be observed in the direction S → S'.

[0156] From these arrays 512 of colours, three factors attest to the role of plasmon resonances in colour formation: (i) colours were observed only upon the introduction of a metal layer on top of an elongate nanostructure; (ii) equiperiodic regions (constant $d+s$) traversing the arrays 512 diagonally in the direction S → S' did not exhibit the same colour (unlike light diffraction off periodic structures); and (iii) regions of a similar fill factor ($d/(d+s)$) have similar colours (noticeably in the dark band going from the mid-point between T-T' and in the direction of T'), in accordance with the plasmon resonances operating close to the quasi-static limit, where retardation effects may be minimal and resonances are independent of size scaling.

[0157] FIG. 5C shows measured 520 and simulated 522 reflectance spectra of metal nanodisks with a spacing, s, of 120 nm, of the rightmost column (as indicated by the box 514) of arrays 512 in FIG. 5B, according to various embodiments. The measured reflectance spectra 520 exhibit peaks and dips that may be tuned across the visible spectrum by varying d and thus the periodicity ($d+s$). The simulated reflectance spectra 522 demonstrates a qualitative agreement with the corresponding measured reflectance spectra 520, as is further shown in FIG. 5D, where both peaks (triangles) and dips (squares) redshift with increasing diameter, d. The dotted trendlines shown in FIG. 5C approximate the movement of the peaks and dips with varying sizes or dimensions, d, of the plasmonic nanostructures.

[0158] Through simulations (results not shown), a subtle difference may be found in the origin of the spectral dips, observed in the reflectance spectra 520, 522, for $d < 100$ nm when compared with larger nanodisks. The dips for smaller nanodisks may be due to power absorption by the nanodisks and, to a lesser extent, the backreflector. Together, the nanodisk, the elongate nanostructure and the backreflector may effectively act as an antireflection stack at the wavelength corresponding to the dip.

[0159] Conversely, the dips for larger nanodisks may be due to Fano resonances that result from the interference between the broad resonance of the nanoholes on the backreflector where plasmonic nanostructures are formed (i.e. the nanoholes at the base of the plasmonic nanostructures), and the nanodisks with the sharp resonance of the surface modes. Fano resonance is a type of resonant scattering phenomenon that gives rise to an asymmetric line-shape, due to interference between a background and a

resonant scattering process. At this resonance condition, optical power flows around the nanodisks, through the nanoholes, and is absorbed by the backreflector and/or the substrate. The peaks observed in the reflectance spectra 520, 522, correspond to the plasmon resonances of the nanodisks, which intensify for larger nanodisks because of their increased scattering strengths.

[0160] In various embodiments, optical arrangements having plasmonic nanostructures with a constant periodicity ($d+s$) that may produce a range of colours, in contrast to nanoholes in a metal film, whose periodicity determines the optical resonance.

[0161] FIG. 6A shows simulated reflectance spectra of plasmonic nanostructures with a periodicity, ($d+s$), of 120 nm for different cross sectional dimensions, d, according to various embodiments. Plasmonic nanostructures with $d+s$ = 120 nm and with different d exhibit different colours. For example, for d = 50 nm, a light brown colour is observed, for d = 60 nm, a dark brown colour is observed, for d = 70 nm, a black colour is observed, for d = 80 nm, a dark green colour is observed, and for d = 90 nm, a light green colour is observed. These are represented by the respective square boxes corresponding to the respective d values.

[0162] In FIG. 6A, solid lines show the reflectance spectra of an optical arrangement with plasmonic nanostructures and a metal backreflector, dotted lines show the reflectance spectra of an optical arrangement with elongate nanostructures, without metal nanodisks at the end of each elongate nanostructure, and with a metal backreflector, while dashed lines show the reflectance spectra of an optical arrangement with plasmonic nanostructures, and without a metal backreflector.

[0163] The simulated reflectance spectra show that an optical arrangement without the metal nanodisks or without a backreflector plane does not produce the corresponding colours observed as mentioned above. For an optical arrangement without metal nanodisks (i.e. dotted lines), a fairly constant spectrum is obtained across arrays with the same periodicity, with a point of inflexion at about 900 nm indicating a Fano resonance profile, and a dip at about 450 nm that may be attributable to the elongate nanostructures and the metal backreflector effectively acting as an antireflection stack at this wavelength, as described earlier. In addition, the dip at 450 nm is observed to be invariant to a changing periodicity, ($d+s$). In other words, the absorbance at this region of about

450 nm is independent of periodicity. As shown in FIG. 6A, the feature corresponding to the Fano resonance occurs at a constant wavelength of about 900 nm for all values of *d* from 50 nm to 90 nm.

[0164] For an optical arrangement without a metal backreflector (i.e. dashed lines), a single peak is observed corresponding to the nanodisk plasmon resonance that blueshifts and intensifies with increasing *d* within a narrow spectral range between the wavelength, λ, of about 570 nm and about 590 nm.

[0165] As shown in FIG. 6A, colour variation at constant periodicity may be achieved only for the optical arrangement with plasmonic nanostructures and a metal backreflector (i.e. solid lines), where, as the scattering strength of the nanodisks increases, the spectrum peak shifts in favour of the nanodisk resonance and away from the Fano resonance.

[0166] FIG. 6B shows plots of electric field enhancement (top row) and plots of time-averaged power flow vector (or Poynting vector plots) (bottom row) for an optical arrangement with plasmonic nanostructures and a metal backreflector plane, with a cross sectional dimension of 90 nm, at wavelengths of 450 nm, 590 nm and 900 nm corresponding to the simulated reflectance spectra of FIG. 6A. Electric field enhancement may be calculated as electric field (E) divided by the incident field (E_{inc}), and the power flow vectors (S) may be normalized by the incident Poynting vector (S_{inc}). Plane wave illumination is incident from above in the z-direction and polarized along the y-axis.

[0167] The metal nanodisk plays different roles at each of the three wavelengths. At the wavelength of 450 nm, light is absorbed by both the plasmonic nanostructure and the substrate (e.g. silicon), in other words, the nanodisk is absorbing as an effective antireflection stack. At the wavelength of 590 nm, the plasmon resonance of the nanodisk acts as a dipole antenna that re-radiates light back to the observer, in other words, the nanodisk scatters the light. At the wavelength of 900 nm, there is resonance where power flows around the nanodisk, through a nanohole, and is absorbed by the bottom rim of the nanohole array and substrate, in other words, the nanodisk enhances absorption around the associated nanohole. These effects may be observed in FIG. 6B in the channelling of the Poynting vectors into the nanodisk at $\lambda = 450$ nm, the strong fields signifying nanodisk plasmon resonance at $\lambda = 590$ nm, and the directing of power flow around the

nanodisk and into the base of the nanohole at λ = 900 nm. The decreased reflectance at λ = 900 nm for an optical arrangement having plasmonic nanostructures and a metal backreflector compared to an optical arrangement with elongate nanostructures with a metal backreflector, but without metal nanodisks, as shown in FIG. 6A, indicates that the nanodisk acts as an antenna that may enhance the absorption around the nanohole.

[0168] FIG. 7 shows simulated reflectance spectra of optical arrangements with and without presence of nanoholes in the backreflector plane, for a periodicity, $d+s$, of 120 nm and cross sectional dimensions, d, of 50 nm and 90 nm, according to various embodiments. The simulated reflectance spectra show that an optical arrangement with a planar backreflector (i.e. without nanoholes) display substantially similar colours as that of an optical arrangement with a holey backreflector (i.e. with nanoholes), but with no observable Fano resonance (i.e. no inflexion points at 900 nm). In various embodiments, Fano resonance may help to narrow the main spectral peaks, so as to produce purer colours. For a cross sectional dimension, d, of 90 nm, the nanoholes reduce reflectance in the red part of the spectrum and at longer wavelengths, thereby accentuating the blue and green colours.

[0169] FIGS. 8A to 8C show optical images or nanophotographs, according to various embodiments, illustrating the variety of patterns that may be produced as well as the variety of colours that may be produced/observed, based on the optical arrangements and/or methods of various embodiments. The optical images were observed using a bright-field microscope, where the optical images have a light/white background.

[0170] FIG. 8A shows an optical image 800 generated by square arrays 802 of a plurality of plasmonic nanostructures, including a plurality of elongate nanostructures or nanoposts with a metal layer of 1 nm Cr, 15 nm Ag and 5 nm Au deposited on at end of each nanopost, with varying cross sectional dimensions or sizes and varying pitches between adjacent nanoposts to produce a palette of colours. Each array 802 is a 7 μm square. A variety of colours were observed from the optical image 800 using bright-field illumination. For example, in the direction C → C', the colour changed from yellow to green, in the direction D → D', the colour changed from yellow to blue to violet, in the direction E → E', the colour changed from violet to red to pinkish, in the direction F → F', the colour changed from yellow to violet to greyish, in the direction G → G', the

colour changed from green to blue to violet to red to pinkish to greyish, in the direction H → H', the colour changed from yellow to blue to violet to red to pinkish to greyish, and in the direction I → I', the colour changed from green to blue to violet to red to pinkish to grayish.

[0171] Using some of the colours from the palette as illustrated by the optical image 800, differently coloured images may be obtained, as illustrated in FIGS. 8B and 8C. FIG. 8B shows an optical image 820 of a duck whose beak 824, shirt stripes 826, shirt buttons 828 and feet 830 are yellow, while the cap 832 and the shirt 834 are golden. The face 836, the hands 838 and the body 840 of the duck are not coloured (or white), e.g. no plasmonic nanostructures were formed in these portions.

[0172] FIG. 8C shows an optical image 840 where the background 842 as the backdrop for the letter 'a' 844 and the star 850, and the words 'A*STAR' 846 and 'IMRE' 848 are deep blue in colour, while the letter 'a' 844 is white and the star 850 is red in colour.

[0173] As shown in FIGS. 8A to 8C, a plurality of elongate nanostructures (e.g. nanoposts) with varying cross-sectional dimensions and pitches may be fabricated using the approach of various embodiments as illustrated by the schematic diagrams of FIG. 3A, producing colour images with colours ranging from violet to red in the visible spectrum. In addition, it should be appreciated that more or different colours may be achieved by changing the material of the metal layer deposited over the plurality of elongate nanostructures.

[0174] The fabrication of microscopic colour images to demonstrate the creation of arbitrary images with colour and tonal control will now be described by way of the following non-limiting example.

[0175] In order to create a photo-image, colour information from bitmap images was coded pixel by pixel into the position, diameter (*d*) and separation (*s*) of nanoposts formed in a HSQ resist. A code was first written in Matlab to generate pattern layouts for the electron-beam lithography tool based on a bitmap image. The code then extracted the red, green and blue (RGB) values for each pixel and found a closest match to a combination of *d* and *s* from the colour palette using a least-squares error method. Each pixel was defined to occupy an area, which could be set to any value, e.g. 250 nm by 250 nm square.

[0176] In order to fit the metal nanodisks and the plasmonic nanostructures into the pixel array, two approaches were used. In the first approach, the exact d and s obtained from the closest match was used and a 2×2 array of nanodisks were fitted into the square area. The 2×2 array may be fitted inside the square array if the condition $2*(d+s) < 250$ nm was satisfied. However, if a situation arose such that $2*(d+s) > 250$ nm, only a single nanodisk of size d was positioned at the center of the square. However, this approach may lead to inaccuracies in the colour reproduction.

[0177] The second approach was based on the fact that lines of almost equal colour exists on the d versus s plot (e.g. FIG. 5B). The closest match for d and s were first determined, as also employed in the first approach. Subsequently, d and s were scaled to d' and s' along lines of nearly equal colours on the d versus s plot. These lines were approximately defined to be lines of equal slopes such that $(d' - d)/(s' - s) = 1/2$, which satisfies the equation $2*(d' + s') = 250$ nm. The resulting nanodisks may be a periodic array of nanodisks with varying d' and s' values. In cases where a single nanodisk may be sufficient, the code may decide this by comparing the fractional change in d' and s' for both cases to the original d and s and choosing the case with the smaller fractional change. The code may then create an entry in the layout file for the coordinates of these 4 nanodisks (2×2 array) within the pixel area. Further improvements in the code may be obtained by including the ability of colour prediction, interpolation between data points, and by feeding in more data points for a larger range of d and s values.

[0178] The creation of a photo-realistic image was demonstrated in a 50 μm × 50 μm square "Lena" image, as shown in FIG. 9, based on the second approach as mentioned above. The pixel was a 250 nm × 250 nm square (that is, at the theoretical resolution limit of the optical microscope, ×100 objective, numerical aperture (NA) = 0.9, mid-spectrum wavelength of 500 nm). FIG. 9 shows optical micrographs 900 and 902 of the Lena image, respectively before, and after metal deposition to form metal nanodisks on an end of each elongate nanostructure (e.g. nanopost).

[0179] The colour information latent in the grey-scale structures (optical micrograph 900), before deposition of the metal layers as nanodisks, manifested upon deposition of the metal layers (optical micrograph 902). The resulting colour image closely reproduced the details of the original image down to single-pixel elements, as

seen in the appearance of specular reflections in the eyes, as seen in the optical micrograph 904, which is enlarged from the eye region of the optical micrograph 902. FIG. 9 also shows an SEM image 906 corresponding to the dashed box area of the eye of the optical micrograph 904, which had four different colours. While not clearly seen in the SEM image 906, the plasmonic nanostructures have the same centre-to-centre periodicity or pitch, p, of $(d+s)$ of about 125 nm, but different d (e.g. variation of 30 nm) and s to produce different colours. In FIG. 9, for clarity purposes, individual regions of similarly sized nanodisks are separated by the dotted lines in the SEM image 906. Each pixel includes a 2×2 array of nanodisks with a pitch, p, of 250 nm.

[0180] Most pixels included four nanodisks and therefore four plasmonic nanostructures, although single nanodisks were also used, if sufficient, e.g. to achieve the blue/purple colours, as indicated by the dashed ellipse 908 in the optical micrograph 902 of the Lena image.

[0181] FIG. 10 shows a scanning electron micrography (SEM) image 1000 of part of an optical arrangement, according to various embodiments. The SEM image 1000 shows different configurations of 2×2 array of plasmonic nanostructures for the different pixels. The boundaries between different colors observable using bright-field microscopy are shown as dotted lines in the SEM image 1000. The two regions, without plasmonic nanostructures, as represented by the solid line circles indicate bright spots observable in the corresponding colour image, using bright-field microscopy.

[0182] In order to demonstrate the colour pixel resolution at the optical diffraction limit, a set of chequerboard resolution test structures with alternating colours (one colour being darker than the other) was patterned. FIG. 11 shows SEM images 1100, 1102 of a resolution test pattern of four squares 1101, according to various embodiments. Each square 1101 includes 64 square pixels 1103 with a 3×3 array of nanodisks or plasmonic nanostructures 1104, 1106, per pixel 1103. FIG. 11 also shows SEM images 1110, 1112 of a resolution test pattern of four squares 1111, according to various embodiments. Each square 1111 includes 64 square pixels 1113 with a 2×2 array of nanodisks or plasmonic nanostructures 1114, 1116, per pixel 1113. Each square pixel 1103 is about 375 nm in size, while each square pixel 1113 is about 250 nm in size. The centre-to-centre separation or pitch, p, of the nanodisks 1104, 1106, 1114, 1116, is about 125 nm.

[0183] Although the number of nanodisks per pixel is reduced from nine nanodisks 1104, 1106 (SEM image 1102) to four nanodisks 1114, 1116 (SEM image 1112), the colour scheme of each chequerboard test pattern may be preserved.

[0184] The chequerboard patterns are only barely observable, even with a ×150 and 0.9 numerical aperture (NA) objective lens, demonstrating the patterning of colour pixels at the optical diffraction limit. Therefore, the single pixels 1103 of nine nanodisks 1104, 1106, and the single pixels 1113 of four nanodisks 1114, 1116 1116 were able to support individual colours at the optical diffraction limit.

[0185] The method of various embodiments allow the colour information latent in the resist elongate nanostructures to be replicated economically onto multiple substrates using high-throughput methods, for example nanoimprint technology (NIL) once a master mould is fabricated. FIG. 12 shows a photograph 1200 of an optical arrangement and a corresponding scanning electron micrography (SEM) image 1202, according to various embodiments, as obtained using NIL.

[0186] A thermal nanoimprint lithography was used to create a 1 cm × 1 cm area of elongate nanopillars in polycarbonate, to demonstrate the feasibility of scaling-up the throughput of such plasmonic micro-images of various embodiments. The nanoimprint process was performed in an Obducat Sindre 600 thermal nanoimprinting system. A silicon mould (NIL Technology) with a nanohole array (diameter, 100 nm; pitch, 200 nm; depth, 100 nm) occupying an area of 1×1 cm^2 was used as the mould to produce a large-area nanopost array. The substrate for the nanoimprint was a 2×2 cm^2 polycarbonate film with a thickness of about 125 mm. Before the imprinting process, the silicon mould was cleaned and a self-assembled monolayer of 1H,1H,2H,2H-perflourodecyltrichlorosilane (FDTS) anti-stiction coating was functionalized on the surface, so as to facilitate detachment of the mould from the imprinted substrate in the subsequent process. The imprinting process was carried out at about 150°C under a pressure of about 40 bar. This condition was maintained for about 300 seconds, after which the system was cooled to about 30°C before manual detachment of the silicon mould from the imprinted polycarbonate film.

[0187] The nanopillars were subsequently coated with a metal layer using the metal deposition process as described above. The patterned areas (within the dashed box),

having plasmonic nanostructures, had a blue colour, while the unpatterned areas retained the bulk metal layer yellow colour.

[0188] Various embodiments may provide an approach for full-colour printing at the optical diffraction limit by encoding colour information into metal (e.g. silver/gold) nanodisks raised above a holey backreflector, and coated on one end of each of a plurality of elongate nanostructures. The interplay of plasmon and Fano resonances, which may be tuned by varying the cross sectional dimension of the nanodisks (and also the elongate nanostructures) and/or spacing between adjacent nanodisks (and also the elongate nanostructures), may result in colours directly visible under a bright-field optical microscope. These colours may be preserved even when only four nanodisks are present in individual pixels of 250 nm × 250 nm squares, thus enabling colour printing at a resolution of approximately 100,000 d.p.i. This printing resolution approaches the limit of visible-light imaging, where the individual colour pixels may just be barely resolvable using diffraction-limited optics. Applications that may utilise the approach of various embodiments may include but not limited to high-resolution print image production, optical data storage, colour filters in lighting and imaging technologies, and security.

[0189] In various embodiments, nanostructures (e.g. elongate nanostructures, e.g. nanoposts) are used as the basic element to form the optical arrangement, and therefore the colour image, thereby allowing control over the variety of colours that may be observed. Arrays of nanoposts, with a metal layer deposied on top of each nanopost, may absorb one or more wavelengths of light dependening on the cross sectional dimension/size and the cross sectional shape of the nanoposts, as well as the pitch between adjacent nanoposts, as a result of plasmonic resonance. Therefore, an exposure layout of a pattern corresponding to the arrays of nanoposts may be designed in order to produce a significantly miniaturized coloured photo/image of an original image. As a non-limiting example, nanodisks having circular cross section or nanotriangles, with heights/lengths of about 100 nm and cross sectional dimensions of about 10 nm, may be fabricated.

[0190] The colour image of various embodiments may be made up of a plurality of pixels, where each pixel may be defined either by a single structure (e.g. including one or more filters) or a cluster of structures for displaying red, green and blue colours (RGB).

Each structure may be termed as "plixel" (a combination of the words "plasmonic" and "pixel"), and made up of a plurality of plasmonic nanostructures. Each plixel may be structured with a minimum size of approximately 300 nm, thereby allowing a resolution of up to about 10^5 dpi.

[0191] The size of each plixel may be reduced, thereby increasing the resolution. This may be achieved, for example, by decreasing the exposure dosage of the energy source during the lithography process so as to fabricate elongate nanostructures or nanoposts with a smaller cross section dimension/size (e.g. diameter).

[0192] Within each pixel area, the plurality of elongate nanostructures (nanoposts) may be positioned in a regular or uniform arrangement (e.g. as shown in FIG. 4A) or may be positioned randomly but maintaining the spacing, *s*, between adjacent elongate nanostructures at approximately equal distance.

[0193] Using the high-resolution patterning process of various embodiments, nano-images or nano-photographs at very small dimensions may be achieved. In addition, the method of various embodiments does not necessarily include a lift-off process or the use of a sacrificial layer. Due to the elimination of the need to lift-off any unpatterned resist, the fabrication process of various embodiments is greatly simplified. It should be appreciated that the method of various embodiments may allow colour images to be reproduced in mass volume using nanoimprinting technology or lithography.

[0194] Conventionally, the colours produced by nanoplasmonic structures can only be viewed using grazing angle or darkfield microscopy. In contrast, the colours displayed by the optical arrangements and therefore the plasmonic nanostructures of various embodiments, and therefore also the colour images or colour nanophotographs produced therefrom, may be viewed in bright-field, for example using bright-field microscopy without the need for complicated optics set-ups. Where the array of nanostructures produced and the resulting colour image is sufficiently large, e.g. $\geq$ 100 μm × 100 μm, the colours of the colour image may be observed by the human eye.

[0195] In various embodiments, in addition to achieving high resolution, the use of plasmonic resonators or nanostructures may also provide secondary degrees of freedom to colour creation, including polarization dependence. Further improvements in resolution

and colour perception may be achieved by using different geometries and/or smaller numbers of plasmonic nanostructures per pixel area.

[0196] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. An optical arrangement comprising:

a substrate;

a plurality of spaced apart elongate nanostructures extending from a surface of the substrate, wherein each elongate nanostructure comprises a metal layer on the end distal from the surface of the substrate, and wherein each elongate nanostructure and the metal layer form a plasmonic nanostructure; and

another metal layer on portions of the surface of the substrate without the plurality of elongate nanostructures, wherein the other metal layer is configured to reflect light irradiated on the optical arrangement onto the plurality of plasmonic nanostructures.

2. The optical arrangement as claimed in claim 1, wherein the thickness of the metal layer on the end of each elongate nanostructure is between about 5 nm and about 100 nm.

3. The optical arrangement as claimed in claim 1 or 2, wherein the height of each elongate nanostructure is between about 10 nm and about 500 nm.

4. The optical arrangement as claimed in any one of claims 1 to 3, wherein each elongate nanostructure has a cross sectional dimension of between about 10 nm and about 250 nm, the cross sectional dimension being defined along a transverse axis of the elongate nanostructure.

5. The optical arrangement as claimed in any one of claims 1 to 4, wherein each elongate nanostructure has a cross sectional shape selected from the group consisting of a square, a rectangle, a circle, an ellipse, a triangle, a hexagon and an octagon, the cross sectional shape being defined along a transverse axis of the elongate nanostructure.

6. The optical arrangement as claimed in any one of claims 1 to 5, wherein two adjacent elongate nanostructures of the plurality of elongate nanostructures are spaced apart by a distance of between about 20 nm and about 300 nm.

7. The optical arrangement as claimed in any one of claims 1 to 6, wherein adjacent elongate nanostructures of the plurality of elongate nanostructures are spaced apart by a distance that is at least substantially the same.

8. The optical arrangement as claimed in any one of claims 1 to 6, wherein adjacent elongate nanostructures of the plurality of elongate nanostructures are spaced apart by different distances.

9. The optical arrangement as claimed in any one of claims 1 to 8, wherein the plurality of elongate nanostructures have different cross sectional dimensions, the cross sectional dimensions being defined along respective transverse axes of the plurality of elongate nanostructures.

10. The optical arrangement as claimed in any one of claims 1 to 9, wherein the plurality of elongate nanostructures have different cross sectional shapes, the cross sectional shapes being defined along respective transverse axes of the plurality of elongate nanostructures.

11. The optical arrangement as claimed in any one of claims 1 to 10, wherein the metal layer comprises a metal selected from the group consisting of gold, silver, copper, aluminium, chromium, ruthenium, rhodium, palladium, osmium, iridium, platinum and any combination thereof.

12. The optical arrangement as claimed in any one of claims 1 to 11, wherein each elongate nanostructure comprises a material selected from the group consisting of an epoxy-based polymer, hydrogen silsesquioxane, poly(methyl methacrylate), polycarbonate, titanium dioxide and silicon oxide.

13. The optical arrangement as claimed in any one of claims 1 to 12, wherein the substrate is non-transmissive to light.

14. The optical arrangement as claimed in any one of claims 1 to 13 for producing a colour image therefrom, wherein the colour image is observable using a bright-field illumination.

15. The optical arrangement as claimed in claim 14, wherein the plurality of elongate nanostructures and the metal layer on the end of each elongate nanostructure co-operate by way of plasmonic resonance to produce the colour image in response to light irradiated on the optical arrangement.

16. The optical arrangement as claimed in any one of claims 1 to 15, wherein each elongate nanostructure has an aspect ratio greater than 0.25.

17. The optical arrangement as claimed in any one of claims 1 to 16, wherein the height of each elongate nanostructure is larger than the thickness of the metal layer on the end of each elongate nanostructure.

18. The optical arrangement as claimed in any one of claims 1 to 16, wherein the height of each elongate nanostructure is smaller than the thickness of the metal layer on the end of each elongate nanostructure.

19. The optical arrangement as claimed in any one of claims 1 to 18, wherein each elongate nanostructure comprises a material having a refractive index of between about 1.3 and about 5.

20. The optical arrangement as claimed in any one of claims 1 to 19, wherein the plurality of elongate nanostructures have a periodicity that is at least substantially the same.

21. The optical arrangement as claimed in claim 20, wherein the periodicity is between about 30 nm and about 550 nm.

22. A method of forming an optical arrangement, the method comprising:

providing a substrate;

forming a plurality of spaced apart elongate nanostructures extending from a surface of the substrate;

forming a metal layer on the end of each elongate nanostructure distal from the surface of the substrate; and

forming another metal layer on portions of the surface of the substrate without the plurality of elongate nanostructures,

wherein each elongate nanostructure and the metal layer form a plasmonic nanostructure, and

wherein the other metal layer is configured to reflect light irradiated on the optical arrangement onto the plurality of plasmonic nanostructures.

23. The method as claimed in claim 22, wherein forming the plurality of elongate nanostructures comprises:

depositing a resist layer on the surface of the substrate;

exposing the resist layer to an energy source to define a pattern corresponding to the plurality of elongate nanostructures; and

removing portions of the resist layer to form the plurality of elongate nanostructures.

24. The method as claimed in claim 23, wherein exposing the resist layer to an energy source comprises varying a dosage of the energy source.

25. The method as claimed in claim 23 or 24, wherein exposing the resist layer to an energy source comprises exposing the resist layer to a beam of electrons.

26. The method as claimed in any one of claims 22 to 25, wherein forming the plurality of elongate nanostructures comprises forming elongate nanostructures with different areal densities on the substrate.

27. The method as claimed in any one of claims 22 to 26, wherein forming the plurality of elongate nanostructures comprises forming elongate nanostructures with different cross sectional dimensions, the cross sectional dimensions being defined along respective transverse axes of the plurality of elongate nanostructures.

28. The method as claimed in any one of claims 22 to 27, wherein forming the plurality of elongate nanostructures comprises forming elongate nanostructures with different cross sectional shapes, the cross sectional shapes being defined along respective transverse axes of the plurality of elongate nanostructures.

29. The method as claimed in any one of claims 22 to 28, wherein each elongate nanostructure has a cross sectional shape selected from the group consisting of a square, a rectangle, a circle, an ellipse, a triangle, a hexagon and an octagon, the cross sectional shape being defined along a transverse axis of the elongate nanostructure.

30. The method as claimed in any one of claims 22 to 29, wherein the metal layer comprises a metal selected from the group consisting of gold, silver, copper, aluminium, chromium, ruthenium, rhodium, palladium, osmium, iridium, platinum and any combination thereof.

31. The method as claimed in any one of claims 22 to 30, wherein each elongate nanostructure comprises a material selected from the group consisting of an epoxy-based polymer, hydrogen silsesquioxane, poly(methyl methacrylate), polycarbonate, titanium dioxide and silicon oxide.

32. The method as claimed in any one of claims 22 to 31, wherein each elongate nanostructure comprises a material having a refractive index of between about 1.3 and about 5.

33. The method as claimed in any one of claims 22 to 32, wherein each elongate nanostructure has an aspect ratio greater than 0.25.

34. The method as claimed in any one of claims 22 to 33, wherein the height of each elongate nanostructure is larger than the thickness of the metal layer on the end of each elongate nanostructure.

35. The method as claimed in any one of claims 22 to 33, wherein the height of each elongate nanostructure is smaller than the thickness of the metal layer on the end of each elongate nanostructure.

36. The method as claimed in any one of claims 22 to 35, wherein the plurality of elongate nanostructures have a periodicity that is at least substantially the same.

37. The method as claimed in claim 36, wherein the periodicity is between about 30 nm and about 550 nm.

38. The method as claimed in any one of claims 22 to 37, wherein the method is free of a lift-off process.