

NANOANTENNA

Technical field

5 The present invention relates to a nanoantenna, devices including a nanoantenna, a method of producing a nanoantenna and a method of operating a device comprising a nanoantenna. In particular, but not exclusively, it relates to Yagi-Uda type nanoantennas.

10 Background

Nanoscale photon emitters such as quantum dots and organic dye molecules have omnidirectional dipole-like emission characteristics, and nanoantennas are required to direct their emission in a desired in-plane direction to reduce crosstalk with other
15 optical components. Via reciprocity, nanoantennas also provide directive reception from a desired direction. These devices therefore provide the potential for wireless communication at the micro- to nano- scales, enable denser packing of photonic nanodevices, and improve the power efficiency of nanoscale light sources by eliminating power leakage through radiation in undesired directions. The ideal
20 nanoantenna should therefore provide a narrow radiation pattern and exhibit low dissipation losses.

The Yagi-Uda (YU) antenna is an antenna configuration originally designed for radio frequencies. A YU antenna typically comprises resonant elements, specifically, an
25 active feed element and additional passive reflector and director elements to increase the emission directivity. Research efforts have succeeded in miniaturizing the YU antenna to the nanoscale. Experimental demonstrations of YU nanoantennas have used metallic materials, enabling enhanced light-matter interactions mediated by excitation of surface plasmons due to high Purcell factors, albeit at the cost of high
30 optical losses due to absorption in the metal (e.g. Ohmic losses).

YU nanoantennas consisting of high index dielectric elements have been proposed theoretically as an alternative to metallic YU nanoantennas but experimental demonstrations of such dielectric YU antennas have been limited to the microwave
35 regime. While high Purcell factors are also theoretically possible with dielectric

structures, it is challenging to realize this in visible to near infrared wavelengths. Directional emission from non-resonant dielectric leaky-wave nanoantennas based on hafnium dioxide operating in the red to near-infrared range has also been demonstrated. However, due to its non-resonant nature, the device has a large footprint and is difficult to miniaturize to the nanometer scale.

It would therefore be desirable to have a nanoantenna which overcomes these problems.

10 Summary

The present invention addresses the problems described above by providing a “hybrid” nanoantenna which includes a metallic feed element and one or more dielectric director elements. Such nanoantennas provide large resonant enhancements in the electromagnetic near-field while avoiding dissipative Ohmic losses.

According to a first aspect of the invention there is provided an antenna, comprising a metallic nanostructure and a dielectric nanostructure. Each nanostructure is disposed on a planar surface of a substrate. The dielectric nanostructure is spaced apart from the metallic nanostructure and configured to direct electromagnetic radiation emitted or scattered by the metallic nanostructure. Directing electromagnetic radiation emitted or scattered by the metallic nanostructure means that the angular distribution (in three dimensions) of the intensity of the emitted or scattered electromagnetic radiation is modified.

The angular distribution may depend upon other elements of the antenna, such as layers deposited over the metallic and dielectric nanostructures. It may include a “preferred direction” (or maximal-intensity direction), which refers to a direction in which the intensity (power) of the directed radiation is maximal. The preferred direction may be in the plane of the substrate, or even into, or away from, the substrate at some angle to the planar surface. The preferred direction may be orthogonal to the planar surface (e.g. in the case that the antenna is to be used in an element of a display), but may also be not orthogonal to the planar surface.

The metallic nanostructure may comprise first and second metallic nanoparticles arranged along an axis in the plane of the planar surface, with the dielectric nanostructure spaced apart from the axis.

5 The first and second metallic nanoparticles may be configured as a bowtie nanostructure. The term “bowtie” as used herein refers to a structure with at least two elements, e.g. triangular elements, which are arranged with their apexes directed towards one another, optionally with a gap between the apexes.

10 The first and second metallic nanoparticles may be separated by a gap (measured in the plane of the planar surface) in the range 5 nm to 40 nm, or in the range 10 nm to 30 nm, or in the range 15 nm to 25 nm.

15 In some embodiments, the metallic antenna is arranged to be excited by an external electromagnetic radiation source. However, in other embodiments, the antenna may comprise a nanoemitter, such as a quantum dot, for emitting electromagnetic radiation in combination with the metallic nanostructure. The nanoemitter may be located in the gap between the first and second metallic nanoparticles.

20 The metallic nanostructure may be a gold nanostructure.

The distance from the metallic nanostructure to the dielectric nanostructure may be in the range 50 nm to 200 nm, or 70 nm to 110 nm, or 80 nm to 100 nm.

25 The dielectric nanostructure may comprise a plurality of dielectric director elements, typically mutually spaced apart. The elements may be arranged in a straight line (e.g. with respective geometric centres of the elements on a straight line) extending across the planar surface and transverse to the axis of the metallic nanostructure. The term “transverse” refers here to a direction which has a component perpendicular to the axis
30 of the metallic nanostructure, for example, a direction which subtends an angle with respect to the axis in the range 45 to 135 degrees, or 60 to 120 degrees, or 80 to 110 degrees, or 85 to 95 degrees.

35 Each of the dielectric director elements may be elongate. The term “elongate” means that the director elements have a greater extent (e.g. at least twice as great) in one direction than another, transverse direction, where these directions are measured in

the plane of the planar surface. The direction in which each director element has its smallest extent may be oriented along the line.

5 The width of each of the dielectric director elements (i.e. the extent of the director element in the direction in which its extent is smallest), measured in the plane of the planar surface, may be in the range 20 nm to 80 nm, 30 nm to 70 nm, or 40 nm to 60 nm.

10 The length of each of the dielectric director elements (i.e. the extent of the director element in the direction in which its extent is greatest), measured in the plane of the planar surface, may be in the range 100 nm to 300 nm, or in the range 150 nm to 250 nm.

15 The metallic nanostructure may be offset from the line of the dielectric director elements by a distance of less than 300 nm or a distance in the range 5 nm to 300 nm, 10 nm to 200 nm, or 15 nm to 170 nm. Such offsets cause the electromagnetic radiation to be directed or “steered” through different angles with respect to the line of the dielectric director elements, whilst still maintaining a high directivity.

20 The dielectric may be silicon. The substrate may be a quartz substrate.

The antenna may be configured to direct visible or infrared electromagnetic radiation emitted or scattered by the metallic nanostructure.

25 The dielectric nanostructure and the metallic nanostructure may be encapsulated in a solid or liquid medium. The medium may have a refractive index which either exceeds or is less than the refractive index of the substrate. The refractive index of the medium may differ from the refractive index of the substrate by less than 20%, less than 10% or less than 5% of the refractive index of the substrate.

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According to a second aspect of the present invention there is provided a display device comprising an antenna as described above.

35 According to a third aspect of the present invention there is provided a sensor device comprising an antenna as described above. The sensor device further comprises a

sensor element for detecting the intensity of electromagnetic radiation emitted by the antenna in a direction in the plane of the planar surface.

5 The antenna may be exposable to a gaseous or liquid medium. The term exposable means that the medium is able to contact or surround one or more of the elements of the antenna, e.g. the antenna does not have a housing or covering which prevents ingress of a gas or a liquid.

10 The metallic nanostructure may be displaceable relative to the dielectric nanostructure to re-direct the electromagnetic radiation, e.g. to move the preferred direction towards or away from a direction from the antenna towards the sensor element.

15 According to a fourth aspect of the present invention there is provided a device comprising first and second antennas as described above and configured to transmit electromagnetic radiation from the first antenna to the second antenna.

20 According to a fifth aspect of the present invention there is provided a method of operating a device comprising an antenna as described above. The method comprises exciting the metallic nanostructure to emit or scatter electromagnetic radiation therefrom and detecting the intensity of the electromagnetic radiation incident on a surface.

25 Detecting the intensity of the electromagnetic radiation incident on a surface may comprise using a lens to image the electromagnetic radiation from an opposing side of the planar surface relative to a side of the planar surface on which the antenna is disposed.

30 The method may further comprise determining the preferred direction in which the electromagnetic radiation is directed by the dielectric nanostructure.

The method may comprise exposing the antenna to a gas or liquid and detecting a change in the preferred direction.

35 The method may also comprise measuring a difference in intensity of the detected radiation in response to a displacement of the metallic nanostructure relative to the dielectric nanostructure.

Exciting the metallic nanostructure may comprise causing the metallic nanostructure to photoluminesce.

5 According to a sixth aspect of the present invention there is provided a method of producing an antenna comprising a metallic nanostructure and a dielectric nanostructure. Each nanostructure is disposed on a planar surface of a substrate. The dielectric nanostructure is spaced apart from the metallic nanostructure and configured to direct electromagnetic radiation emitted or scattered by the metallic nanostructure
10 along a direction in the plane of the planar surface. This may be referred to as a “preferred direction” (or maximal-intensity direction), which is the direction in which the intensity of radiation emitted by the antenna is maximal).

The method may comprise: providing a dielectric layer on a planar surface of a
15 substrate; partially removing the dielectric layer to leave the dielectric nanostructure on the planar surface; providing the planar surface with a metallic layer; and partially removing the metallic layer to leave the metallic nanostructure on the planar surface. The metallic layer may comprise gold and the dielectric layer may comprise silicon.

20 The shapes of the nanostructures may be defined using electron-beam lithography.

In this document, the term “nanostructure” refers to a structure which, in at least one direction and preferably in two transverse directions, has dimensions measured in nanometres (e.g. less than 1000 nm, or less than 500 nanometres, but greater than
25 one nanometre). In general terms, a “metallic nanostructure” is a nanostructure formed of a material which has a dielectric function which has a negative real part, thereby allowing the nanostructure to support plasmonic modes, i.e. collective oscillations of the electron density of the nanostructure. For example, a “metallic nanostructure” may be an electrically conductive nanostructure substantially entirely formed of a metallic
30 material, such as a material which is substantially entirely composed of metal atoms (e.g. at least 95%, or at least 97%). A metallic nanostructure may also comprise, in some cases, semiconductor material or oxide material with a dielectric function which has a negative real part. A dielectric nanostructure is a nanostructure substantially entirely formed of a dielectric material, e.g. a non-metallic material commonly defined
35 as an electrical insulator (or a semiconductor) which can be polarized by an applied electric field. The dielectric material may be a high refractive index material. The

dielectric material of the dielectric nanostructure is typically a low optical loss material, such that only a small fraction of electromagnetic radiation is absorbed by the dielectric nanostructure, e.g. at optical frequencies (such as those corresponding to visible or infrared light), more than 60%, more than 80% or more than 95% of the intensity of the electromagnetic radiation incident on the nanostructure is transmitted by it.

A dielectric nanostructure may have a refractive index which is greater than the refractive index of a vacuum (or a gas or a liquid or solid medium) which wholly or partially surrounds the dielectric nanostructure, such that the dielectric nanostructure is able to modify the direction of light which enters or exits it from the medium.

Brief description of the drawings

Embodiments of the invention will now be described for the sake of example only, with reference to the following drawings in which:

Figure 1 is a schematic perspective view of a hybrid Yagi-Uda nanoantenna according to an embodiment of the invention;

Figure 2 is a schematic top view of the hybrid Yagi-Uda nanoantenna shown in Figure 1;

Figures 4 to 6 are Scanning Electron Microscope (SEM) images of hybrid Yagi-Uda nanoantennas according to embodiments of the invention;

Figure 7 is a schematic perspective view of the hybrid Yagi-Uda nanoantenna of Figure 1 showing a lens for collecting electromagnetic radiation scattered from or emitted by the nanoantenna;

Figure 8, which is composed of Figure 8(a) and Figure 8(b), are schematic perspective views of a hybrid Yagi-Uda nanoantenna at various stages of its fabrication; and

Figure 9 shows an array of nanoantennas which are embodiments of the invention formed on a common substrate.

Detailed description

Figures 1 and 2 show a hybrid Yagi-Uda nanoantenna 1 comprising a gold bowtie nanoantenna (GBN) feed element 2 and a director array 3, each located on a planar surface 4 of a quartz substrate, and separated from each other by a distance of around

90 nm. Two transverse directions x and y are indicated in the plane of the planar surface, and the direction z is perpendicular to the surface. Angles in the plane x - y are denoted by angle φ , and angles in the plane x - z are denoted by angle θ .

5 The GBN feed element 2 comprises two triangular prism-shaped gold nanoparticles 5, 6, each having an isosceles triangle base of length 60 nm (parallel to the x direction) located on the planar surface 4 and a height of 40 nm, measured from the planar surface 4. The gold nanoparticles 5, 6 are arranged with the respective apexes of the isosceles triangles directed at each other parallel to the y direction, to resemble a
10 bowtie or “hour glass” when viewed from a direction perpendicular to the planar surface 4 and spaced apart from one another in the y direction to provide a gap of 20 nm. Other dimensions for the GBN feed element 2 can also be used depending on how the nanoantenna 1 is to be used.

15 The director array 3 has three elongate director elements 7, 8, 9. The term “elongate” means that the director elements 7, 8, 9 have a greater extent in one direction than another direction. In this embodiment, the director elements are silicon nanorods of varying lengths (of several hundred nanometres) and widths of around 50 nm and heights (above the planar surface 4) of around 130 nm. The centres of the director
20 elements 7, 8, 9 are arranged along a straight line (not indicated in the figure, but parallel to the x direction) with the longest axes of each element oriented substantially perpendicular to the line, such that the director elements are largely aligned with one another, i.e. parallel, within the plane of the planar surface 4. The director elements 7, 8, 9 are spaced apart from one another by gaps of varying lengths as discussed below.

25 By using a metallic bow-tie antenna for the Yagi-Uda feed element 2, both the excitation and radiation efficiency of a nanoscale photon emitter, such as a quantum dot, placed in the gap region can be enhanced. In particular, the GBN feed element 2 is able to provide high Purcell factors for enhancement of the excitation and emission of a
30 nanoscale emitter placed in its gap region.

As gold nanoparticles exhibit photoluminescence (PL) which resembles their scattering spectra, it is possible to take advantage of the PL to characterize the nanoantenna 1 without introducing a nanoemitter into the system.

Specifically, the GBN feed element 2 can be excited using a light source, such as a 488 nm CW laser at 5 mW, polarized in the direction of the bowtie long axis. In the absence of the director array 3, the PL from the GBN feed element 2 has a far-field angular intensity distribution characteristic of a dipole source located at the centre of the gap between the gold nanoparticles 5, 6 and oriented along the long axis of the GBN feed element 2. In particular, the PL far-field angular intensity distribution comprises two lobes corresponding to emission in a forward direction and a backward direction perpendicular to the long axis of the GBN feed element 2. However, the configuration of the director array 3 adjacent to the GBN feed element 2 modifies the angular intensity distribution of the PL to increase the intensity of the PL in the forward direction, i.e. towards the director array 3, and to decrease the intensity of the PL in the backward direction. In other words, the director array 3 directs the PL preferentially in the forward direction.

The nanoantenna 1 sustains forward directivity throughout the PL emission range of the GBN feed element 2, over a broad wavelength range from ~575 nm to 800 nm with very low backscattering. The nanoantenna 1 therefore has potential for broadband operation despite the use of resonant nanostructures.

It is believed that electric dipole modes are excited in the silicon nanorod director elements in response to the emission from the gold feed element. The PL excites electric dipole modes with phase delays in the silicon nanorods, resulting in destructive interference in the far-field for the backward direction and constructive interference in the far-field for the forward direction. The relative phase between the silicon nanorods and the metal bowtie feed can be tuned by varying the nanorod length and its distance from the metal bowtie feed. By proper tuning of the phase relation between the first nanorod and the metal bowtie feed element, emission in the backward direction can be substantially completely eliminated without the need for a reflector element. In particular, as the silicon nanorods have very low Ohmic losses, the electric dipole mode excited in the first silicon nanorod in response to emission from the metallic bowtie feed has almost the same amplitude as the metallic bowtie feed emission, allowing substantially complete cancelation of the backward scattering via phase relation tuning between the feed element 2 and the first silicon nanorod 7 without the need for a reflector. The two additional silicon nanorods 8, 9 serve to further narrow the radiation pattern to increase the directivity of the device.

In contrast to conventional nanoantennas, the nanostructure 1 is able to achieve a high directivity without an additional reflector element located behind the feed element 2 (i.e. on the opposite side of the feed element 2 from the director array 3). This allows the nanoantenna 1 to have a smaller footprint e.g. the nanoantenna 1 has a footprint of just 0.38 λ^2 , operating at a wavelength of around 600 nm.

It is not necessary for the nanoantenna 1 to have 3 director elements 7, 8, 9. It may, for example, have only the director element 7 nearest to the GBN feed element 2, i.e. only a single director element. However, additional dielectric director elements such as the silicon nanorods 8, 9 help narrow the angle of the forward-directed beam.

Figure 2 shows the hybrid Yagi-Uda nanoantenna 1 with the following distances labelled distances measured from centre of the GBN feed element 2 and to the centres of: the closest (first) director element 7 (d_1); the next nearest director element 8 (d_2) and the furthest director element 9 (d_3). The lengths of the respective director elements 7, 8, 9 are labelled as l_1 , l_2 and l_3 .

Table 1 provides a set of distances and lengths which may be used to configure the nanoantenna 1 for an operating wavelength of 600 nm. The distances and lengths were determined using a particle-swarm optimization method implemented in Lumerical Finite-Difference Time-Domain (FDTD) solutions. Column 2 of Table 1 shows the distances and lengths obtained when the effect of the substrate is not included. Although the substrate, in this case quartz, affects the resonances of the director elements, the distances and lengths can be re-optimised to obtain the best forward directivity and these refined parameters are shown in column 3 of Table 1.

	Free space (nm)	On quartz (nm)
d_1	80	90
d_2	120	150
d_3	180	175
l_1	325	220
l_2	290	180
l_3	260	175

Table 1

The maximum directivity of the nanoantenna 1 is calculated by taking the ratio of the maximum value of the normalised far-field radiation pattern, i.e. as:

$$\frac{\text{Max} [p(\theta, \varphi)]}{\left(\int_{\varphi} \int_{\theta} p(\theta, \varphi) d\theta d\varphi \right) / 4\pi}$$

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where $p(\theta, \varphi)$ is the radiated power in the direction (θ, φ) and θ and φ are the elevation and azimuthal angles with respect to the substrate, respectively (as shown in Figure 1). Similarly, forward and backwards directivities are calculated from the value of the normalised far-field radiation pattern in the forward ($\theta = 90^\circ, \varphi = 90^\circ$) and backward ($\theta = 90^\circ, \varphi = 270^\circ$) directions.

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Figures 3 to 6 are SEM images of nanoantenna 1 in which the placement of the GBN feed element 2 is varied, as discussed below. Each image includes a scale bar 10 which has a length corresponding to a distance of 100 nm.

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Figure 7 shows an apparatus for measuring the far-field radiation pattern of nanoantenna 1. The apparatus comprises the nanoantenna 1, the quartz substrate 4 (illustrated as a planar, substantially laminar body) and a high numerical aperture lens 11 positioned under the substrate 4, i.e. on the opposite side of the quartz substrate 4 to the nanoantenna 1. The lens 11 may be, for example, an oil immersion objective lens of 40x magnification with a numerical aperture (NA) of 1.4. The lens collects electromagnetic radiation (e.g. PL) of the nanoantenna 1 which is emitted or scattered downwards through the substrate 4 for imaging on an image forming device such as a charge coupled device (CCD). Such resulting back focal plane images plot the pseudo-momentum space ρ which is related to the elevation angle of emission θ of the GBN by the formula:

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$$\rho = n \sin \theta$$

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where n is the refractive index of the immersion oil (e.g. $n = 1.52$). A linear analyzer in the direction of the bowtie long axis may be placed in the detection path to selectively measure the bright dipolar mode and filter out emission due to plasmon dephasing and electron scattering events. As a further optimisation, the PL signal may also be passed through a bandpass filter, e.g. a 600 ± 20 nm bandpass filter.

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Back-focal plane images of the hybrid YU nanoantenna 1 exhibit suppressed emission into the small p region. In addition, the main emission lobes characteristic of a dipole emitter become clearly asymmetric, indicating that there is increased directionality of the hybrid YU nanoantenna. The main lobe was observed at ($\theta_{\max} = 45.5^\circ$, $\varphi_{\max} = 90^\circ$), with fwhms of $\Delta\theta_{\max} = (4.6 \pm 0.4)^\circ$ and $\Delta\varphi_{\max} = (27.3 \pm 2.1)^\circ$. Some emission in the backward direction was also observed, likely due to losses in the silicon nanorods, resulting in reduced amplitude of the electric dipoles excited in the silicon nanorods and imperfect cancellation of the emission in the backward direction. The front-to-back (F/B) ratio, defined as the ratio between the maximum measured intensities at $\theta = 90^\circ$ and $\theta = 270^\circ$, was found to be 4.3 dB. However, taking into account the collection efficiency of the lens, the maximum directivity is estimated to be 16.8 (12.24 dB), and this value would be up to two times higher if the emission in the top half-plane was neglected.

Advantageously, the nanoantenna 1 can be characterised using the imaging method described above based on the PL of the GBN feed element 2, i.e. it is not required that a nanoemitter is positioned in the gap region of the GBN feed element 2 in order to characterise the nanoantenna 1, e.g. for the purposes of quality control. The fabrication process may also be less complicated because the nanoantenna 1 does not require that a reflector element is included.

In general, the nanoantenna 1 may be fabricated by: (i) providing a dielectric layer on a planar surface of a substrate; (ii) partially removing the dielectric layer to leave the dielectric nanostructure 3 on the planar surface; (iii) providing the planar surface with a metallic layer; and (iv) partially removing the metallic layer to leave the metallic nanostructure 2 on the planar surface. These steps overcome some of the challenges of fabricating a nanoantenna with different materials. Steps (iii) and (iv) may be performed after steps (i) and (ii), but may optionally be performed before them, or even interleaved with them.

Specifically, Figure 8 illustrates a method of producing the nanoantenna 1 on a quartz substrate 4 according to the above method and using a two-step aligned electron beam lithography technique. The method involves the following steps:

a: A 130 nm polycrystalline silicon layer 12 is grown onto a thin quartz substrate via chemical vapor deposition. Gold alignment markers 13 were fabricated on top of the silicon layer 12 via standard electron beam lithography and lift-off process with Poly(methyl methacrylate) (PMMA) as the photoresist.

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b: Next, a 30 nm thick hydrogen silsesquioxane (HSQ) photoresist layer 15 (2% dissolved in methyl isobutyl ketone) is spin-coated on the substrate at 5000 rpm. Following this, an Espacer charge dissipating layer (e.g. 300Z obtained from Showa Denko) is spin-coated on the HSQ layer at 1500 rpm. The silicon nanorod directors are defined using electron-beam lithography. Figure 8(a) shows the structure at this time, with the Espacer layer omitted. The Espacer layer is then removed by rinsing with deionized water, and development of the HSQ layer is performed by immersion in a NaOH/NaCl salty solution (1% /4% in deionized water) for 60 s, followed by immersion in de-ionized water for 60 s. Etching of the polysilicon layer with the HSQ protective mask is done using inductively coupled plasma with Cl_2/HBr flow rates of 18 and 22 sccm, respectively, at a temperature of 6°C and pressure of 10 mTorr. Figure 8(b) shows the structure at this time.

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c: Subsequently, an 80 nm thick PMMA photoresist layer (950K molecular weight, 1.67% in anisole) is spin-coated at 3000 rpm on the sample, and baked on a hot plate at 180°C for 90 s, followed by spin-coating of the Espacer layer at 1500 rpm. The GBN pattern was defined with electron-beam lithography, using the gold markers 13 for alignment with respect to the silicon nanorod directors. The Espacer layer was removed by rinsing with deionized water, and development of the PMMA was carried out with a 1:3 MIBK/IPA solution at a temperature of -15°C for 10 s.

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d: A 40 nm layer of gold 14 is evaporated onto the sample with a 2 nm titanium adhesion layer, and

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e: The final hybrid YU nanoantenna structure 1 is obtained after lift-off of the PMMA layer via immersion N-methylpyrrolidone (NMP) solvent at 70°C.

Figure 9 shows how multiple nanoantennas may be fabricated on a single substrate in parallel. For example, a 30 x 30 array of nanoantennas 1 can be created. The positions of the GBN feed elements 2 with respect to the corresponding dielectric nanostructures 3 differ in the x- and/or y- directions (i.e. directly towards or away from

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the dielectric nanostructure 3 or in a transverse (parallel) direction to the direction towards the dielectric nanostructure 3) in order to produce nanoantennas with different respective properties. For example, an offset step size of 8.3 nm in either direction can be used. The nanoantenna 1 with the best alignment can be identified by scanning electron microscopy (SEM) imaging, which may be helpful in cases where the manufacturing process is only able to position the GBN elements 2 within a certain tolerance.

Returning to Figures 3 to 6, these SEM images show different offsets of the GBN feed element 2 relative to the dielectric nanostructure 3. The quoted offsets are in the x-direction relative to the optimum centre-to-centre position of the GBN with respect to the first silicon nanorod set out in Table 1 (i.e. a distance of 90 nm). In Figure 3, the GBN feed element 2 is displaced away from the dielectric nanostructure 3 by 25 nm, whilst and in Figure 4 the GBN feed element 2 is displaced towards the dielectric nanostructure 3 by 6 nm. In both cases, forward directivity was retained, although the measured F/B ratios decreased to 2.7 and 3.5 dB respectively. The hybrid YU nanoantenna 1 is therefore robust against fabrication imperfections that could result in misalignment in the x-axis.

Figures 5 and 6 show SEM images of nanoantennas in which the GBN feed element 2 has been offset in the y direction by -16 nm (i.e. downwards in the SEM image) and +166 nm respectively (i.e. upwards in the SEM image). In the first case, the forward emission lobe was steered 5° to $\varphi_{\max} = 85^\circ$, whilst in the second case, the maximum of the measured far-field emission pattern is shifted 12° to $\varphi_{\max} = 102^\circ$. These examples show that the nanoantenna 1 is capable of high resolving power. With increasing y-offset, the back cancellation becomes weaker as the coupling between the GBN feed element 2 and the silicon nanorod directors 7, 8, 9 will decrease. Simulations show that for y-offsets greater than 300 nm, the GBN element 2 become completely decoupled from the director elements.

In some conventional devices, phase antenna arrays that are several wavelengths in dimensions are required to produce well-defined beam directivity (beam steering). By contrast, the present antenna may be smaller, e.g. having a length (e.g. in the x-direction) of between 1 and 3 wavelengths, or between 1.5 and 2.5 wavelengths or, in some cases, less than 1 wavelength, i.e. the nanoantenna 1 may be a “sub-wavelength” nanoantenna even at optical wavelengths, such as visible or infrared

wavelengths, such as wavelengths in the range 300 nm to 1000 nm or 400 nm to 800 nm. In some examples, the nanoantenna 1 may span an area of the substrate or “footprint” of less than 1 square wavelengths or less than 0.5 square wavelengths. Such small footprints may be particularly useful in applications requiring dense opto-electronic integration of components.

The Hybrid YU nanoantenna 1 is useful for applications in on-chip wireless communications, quantum computing, display technologies, efficient biological sensors and other devices requiring on chip photonic elements and high-density integration of electronic and photonic elements.

The directionality of the nanoantenna 1 is a sensitive parameter of the phase relation between the GBN feed element 2 and the silicon directors 7, 8, 9. Changes to the refractive index of the medium surrounding the nanoantenna 1 modify these phase relations and thereby affect the directionality of the nanoantenna 1. A sensor device may therefore incorporate a sensing element, such as a photodiode or CCD, for example, for detecting the intensity of the far-field intensity pattern of the radiation from the nanoantenna 1 along one or more directions. For example, the F/B ratio of the nanoantenna emission can be measured by locating a pair of sensor elements in the forward and backward directions, or the apparatus of Figure 7 can be used. Such sensor devices can be used, for example, to measure the refractive index (or changes thereof) of the surrounding medium.

Additionally, the sensor device can be configured to measure small changes in the y-axis alignment between the GBN feed element 2 and the dielectric nanostructure 3 by detecting the changes in the emission pattern from the nanoantenna 1, e.g. the rotation or steering of the main emission lobe, as described above. This can be done by integrating the sensor with a Micro-Electro-Mechanical Systems (MEMS) based substrate or carbon nanotubes with electrical tunability of its electroluminescence position. In the first case, the MEMs system may be operative to, for example, directly rotate the entire structure, or displace the feed element and/or the dielectric nanostructure 3 with respect to one another in the y-direction in order to affect the rotation or steering of the main emission lobe. In the second case, the carbon nanotube has an emission pattern which is centred on a position which can be electrically tuned to vary along in the y-direction with respect to a dielectric nanostructure 3, thereby allowing beam steering through different angles. Such a

device may also be used as a nanoscale “wireless” optical router by aligning the directed radiation from the nanoantenna with one or more receiver elements, such as other nanoantennas 1.

- 5 A display device including an array of nanoantennas 1 in combination with nanoemitters (such as a quantum dots) can also be fabricated. Such a display device provides improved energy efficiency by directing the emission from the nanoemitter towards a viewer of the display device. In some cases, each nanoantenna 1 only contains a single dielectric director element (e.g. a single silicon nanorod) which allows
- 10 most of the emission from the nanoemitter in combination with the metallic nanostructure 2 to be directed towards the viewer, whilst preserving wide angle emission such the display device has a wide viewing angle.

- 15 Whilst the foregoing description has described exemplary embodiments, it will be understood by those skilled in the art that many variations of the embodiment can be made within the scope and spirit of the present invention. For example, it would be possible to provide each of the feed elements 2 of the embodiment described above with a respective photon nanoemitter, such as a quantum dot, for emitting electromagnetic radiation.

CLAIMS:

1. An antenna, comprising:

a metallic nanostructure and a dielectric nanostructure, each nanostructure
5 being disposed on a planar surface of a substrate;

the metallic nanostructure arranged along an axis in the plane of the planar
surface;

the dielectric nanostructure being spaced apart from and in front of the metallic
nanostructure and configured to direct electromagnetic radiation emitted or scattered
10 by the metallic nanostructure;

the dielectric nanostructure comprising a plurality of dielectric director elements
arranged in a straight line extending across the planar surface and transverse to the
axis; and

wherein the antenna is without a reflector behind the metallic nanostructure.

2. An antenna according to claim 1, wherein the metallic nanostructure comprises
first and second metallic nanoparticles arranged along the axis.

3. An antenna according to claim 2, wherein the first and second metallic
20 nanoparticles are configured as a bowtie nanostructure.

4. An antenna according to claim 2 or 3, wherein the first and second metallic
nanoparticles are separated by a gap in the range 5 nm to 40 nm, or in the range 10
nm to 30 nm, or in the range 15 nm to 25 nm.

5. An antenna according to any one of claims 1 to 4, and comprising a
nanoemitter, such as a quantum dot, for emitting electromagnetic radiation in
combination with the metallic nanostructure.

6. An antenna according to claim 5 when dependent on claim 4, wherein the
nanoemitter is located in the gap between the first and second metallic nanoparticles.

7. An antenna according to any one of claims 1 to 6, wherein the metallic
nanostructure is a gold nanostructure.

8. An antenna according to any one of claims 1 to 7, wherein the dielectric director elements narrow along the line and away from the metallic nanostructure.
- 5 9. An antenna according to any one of claims 1 to 8, wherein the distance from the metallic nanostructure to the dielectric nanostructure is in the range 50 nm to 200 nm, or 70 nm to 110 nm, or 80 nm to 100 nm.
- 10 10. An antenna according to any of claims 1 to 9, wherein the width of each of the dielectric director elements, measured in the plane of the planar surface, is in the range 20 nm to 80 nm, 30 nm to 70 nm, or 40 nm to 60 nm.
- 15 11. An antenna according to any one of claims 1 to 10, wherein the length of each of the dielectric director elements, measured in the plane of the planar surface, is in the range 100 nm to 300 nm, or in the range 150 nm to 250 nm.
- 20 12. An antenna according to any one of claims 1 to 11, wherein each of the dielectric director elements is elongate with its smallest axis oriented along the line.
13. An antenna according to any one of claims 1 to 12, wherein the metallic nanostructure is offset from the line of the dielectric director elements by a distance of less than 300 nm or a distance in the range 5 nm to 300 nm, 10 nm to 200 nm, or 15 nm to 170 nm.
- 25 14. An antenna according to any one of claims 1 to 13, wherein the dielectric is silicon.
15. An antenna according to any one of claims 1 to 14, wherein the substrate is a quartz substrate.
- 30 16. An antenna according to any one of claims 1 to 15, configured to direct visible or infrared electromagnetic radiation emitted or scattered by the metallic nanostructure.
- 35 17. An antenna according to any one of claims 1 to 16, wherein the dielectric nanostructure and the metallic nanostructure are encapsulated in a solid or liquid medium.

18. An antenna according to claim 17, wherein the refractive index of the medium differs from the refractive index of the substrate by less than 20%, less than 10% or less than 5% of the refractive index of the substrate.

5 19. A display device comprising the antenna of any one of claims 1 to 18 in combination with a nanoemitter, such as a quantum dot.

10 20. A sensor device comprising the antenna of any one of claims 1 to 18, further comprising a sensor element for detecting the intensity of electromagnetic radiation emitted by the antenna in a direction in the plane of the planar surface.

21. A sensor device according to claim 20, wherein the antenna is exposable to a gaseous or liquid medium.

15 22. A sensor device according to claim 20 or 21, wherein the metallic nanostructure is displaceable relative to the dielectric nanostructure to re-direct the electromagnetic radiation towards or away from a direction from the dielectric nanostructure to the sensor element.

20 23. A device comprising first and second antennas according to any of claims 1 to 18 and configured to transmit electromagnetic radiation from the first antenna to the second antenna.

25 24. A method of operating a device comprising an antenna according to any of claims 1 to 18, the method comprising:

exciting the metallic nanostructure to emit or scatter electromagnetic radiation therefrom; and

detecting the intensity of the electromagnetic radiation incident on a surface.

30 25. A method according to claim 24, wherein detecting the intensity of the electromagnetic radiation incident on a surface comprises using a lens to image the electromagnetic radiation from an opposing side of the planar surface relative to a side of the planar surface on which the antenna is disposed.

26. A method according to claim 24 or 25, and further comprising determining the direction in which the electromagnetic radiation is directed by the dielectric nanostructure.

5 27. A method according to any one of claims 24 to 26 and comprising exposing the antenna to a gas or liquid and detecting a change in the direction.

28. A method according to any one of claims 24 to 27 and comprising measuring a difference in the intensity or angular distribution of the detected radiation in response to
10 a displacement of the metallic nanostructure relative to the dielectric nanostructure.

29. A method according to any one of claims 24 to 28, wherein exciting the metallic nanostructure comprises causing the metallic nanostructure to photoluminesce.

15 30. A method of producing an antenna comprising a metallic nanostructure and a dielectric nanostructure, each nanostructure being disposed on a planar surface of a substrate;

the metallic nanostructure arranged along an axis in the plane of the planar surface;

20 the dielectric nanostructure being spaced apart from and in front of the metallic nanostructure and configured to direct electromagnetic radiation emitted or scattered by the metallic nanostructure;

the dielectric nanostructure comprising a plurality of dielectric director elements arranged in a straight line extending across the planar surface and transverse to the
25 axis; and

wherein the antenna is without a reflector behind the metallic nanostructure.

31. A method according to claim 30, comprising:

providing a dielectric layer on the planar surface of the substrate;

30 partially removing the dielectric layer to leave the dielectric nanostructure on the planar surface;

providing the planar surface with a metallic layer; and

partially removing the metallic layer to leave the metallic nanostructure on the planar surface.

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32. A method according to claim 31, wherein the metallic layer comprises gold and the dielectric layer comprises silicon.

5 33. A method according to any one of claims 30 to 32, wherein the shapes of the nanostructures are defined using electron-beam lithography.

34. A method according to any one of claims 30 to 33 and comprising encapsulating the metallic nanostructure and the dielectric nanostructure in a solid or liquid medium on the planar surface.