(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
26 September 2024 (26.09.2024)

WIPO | PCT

(10) International Publication Number
WO 2024/193992 A1

(51) International Patent Classification:
G02B 1/00 (2006.01) *G02B 5/00* (2006.01)

(21) International Application Number:
PCT/EP2024/055501

(22) International Filing Date:
01 March 2024 (01.03.2024)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
2304177.5 22 March 2023 (22.03.2023) GB

(71) Applicant: **UNIVERSITY OF SOUTHAMPTON** [GB/GB]; University Road, Southampton, Hampshire SO17 1BJ (GB).

(72) Inventors: **SUN, Chuang**; University Road, Southampton, Hampshire SO17 1BJ (GB). **PI, Hailong**; University Road, Southampton, Hampshire SO17 1BJ (GB). **YAN, Jize**; University Road, Southampton, Hampshire SO17 1BJ (GB). **ULBRICHT, Hendrik**; University Road, Southampton, Hampshire SO17 1BJ (GB).

(74) Agent: **HAINES, Miles, John**; Keilitz Haines & Partner Patentanwälte PartGmbB, Nigerstraße 4, 81675 München (DE).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report (Art. 21(3))*
— *in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE*

(54) Title: FIELD SENSOR AND FIELD SENSING METHOD

(57) Abstract: A metalens and its method of manufacture, the metalens being designed and fabricated to transform a laser beam into a pre-defined arbitrary optical field carrying spin angular momentum and/or orbital angular momentum in defined directions, which can be transferred to nanoparticles trapped by levitation in the optical field of the laser beam that has passed through the metalens. The metalens can be incorporated into an optical levitation system in which a nanoparticle can be trapped in the arbitrary optical field. Light intensity scattered from the trapped nanoparticle is then measured and used as a basis for measuring a physical field value.

(e)

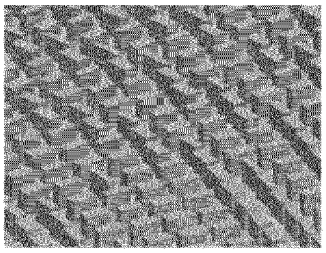

FIG. 5

WO 2024/193992 A1

TITLE OF THE INVENTION

FIELD SENSOR AND FIELD SENSING METHOD

BACKGROUND OF THE INVENTION

The invention relates to a field sensor and field sensing method operating via the principle of optical levitation of nanoparticles, where the field type being sensed includes gravitation field, electric field and magnetic field.

Optical levitation of nanoparticles is a well developed technique based on using force gradients induced by optical fields; this is the so-called optical tweezer approach. It is known that optically levitated nanoparticles in vacuum can provide the basis for ultrasensitive sensors to measure physical parameters such as force, acceleration and torque. For the avoidance of ambiguity of terminology between the field to be measured and the optical field used to trap a nanoparticle, in the following we refer to the field to be measured as a physical field.

Monteiro et al [1] reported high sensitivity force measurements using optically levitated nanoparticles. Reimann, et al [2] demonstrated the stable rotation of an optically levitated nanoparticle of 100 nm diameter at rotation frequencies exceeding 1 GHz. Ahn et al [3] demonstrated an ultrasensitive torque sensor with an optically levitated nanorotor in vacuum. A torque detection sensitivity of (4.2 ± 1.2) × 10^−27 N m Hz^−1/2 was achieved and a rotational speed exceeding 5 GHz for a nanorotor. Rashid et al [4] investigated the dynamics of a levitated nanoparticle in a vacuum and showed that precession motion is a degree of freedom. They estimated that a torque sensitivity of (3.6 ± 1.1) × 10^−31 N m Hz^−1/2 can be achieved at 1 × 10^−7 mbar, which is much higher than the sensitivity 1 × 10^−29 N m Hz^−1/2 obtained using libration motion at 1 × 10^−9 mbar [4]. In addition, it is predicted that the mechanical quality factor (Q factor) of an optically levitated nanoparticle could be as high as 10^12 and a Q factor of 10^10 has been achieved experimentally [section 9 in Ref. 5], which is much higher than the Q factor (~10^6) achieved using microelectromechanical system (MEMS) [6]. The extremely high Q factor and torque detection sensitivity make the precession motion of an optically levitated nanoparticle be suitable for detecting the gravity acceleration with high accuracy.

A drawback of known optical levitation systems is their bulk which makes them unsuitable for many practical applications. In addition, the spin direction of known optical levitation systems can't not be customized which makes the precession motion cannot be well controlled and not suitable for practical gravimeter.

SUMMARY OF THE INVENTION

According to a first aspect of the disclosure there is provided a method of fabricating a metalens for optical levitation of nanoparticles, the method comprising:

providing a substrate to serve as a blank for the metalens; and

nanostructuring a surface of the substrate to form a metasurface that encodes an arbitrary optical field such that, when the metalens is illuminated by a laser beam the arbitrary optical field is formed in a defined region of space, the arbitrary optical field being capable of optically levitating and trapping nanoparticles in a vacuum,

wherein the arbitrary optical field is encoded onto said substrate surface by:

providing the arbitrary target optical field to be encoded onto the substrate surface as expressed in the form:

$$\begin{pmatrix} A_X(x,y)e^{i\phi_X(x,y)} \\ A_Y(x,y)e^{i\phi_Y(x,y)} \end{pmatrix}$$

decomposing the complex amplitudes of the X- and Y-components of the target optical field into left- and right-handed circular polarization bases

$$A_R(x,y)e^{i\phi_R(x,y)}\begin{pmatrix} 1 \\ -i \end{pmatrix} + A_L(x,y)e^{i\phi_L(x,y)}\begin{pmatrix} 1 \\ i \end{pmatrix}$$

so that the target optical field is expressed as the sum of the complex amplitudes of left- and right-handed circularly polarized light; and

reformulating the complex amplitudes of each of the left- and right-handed circularly polarized light as the sum of two phase terms

$$A_R(x,y)e^{i\phi_R(x,y)} = \frac{Max(A_R)}{2}[e^{i\theta_R(x,y)} + e^{i\vartheta_R(x,y)}]$$

$$A_L(x,y)e^{i\phi_L(x,y)} = \frac{Max(A_L)}{2}[e^{i\theta_L(x,y)} + e^{i\vartheta_L(x,y)}]$$

so that the target optical field is expressed by four phase terms θ_R, θ_L, ϑ_R, and ϑ_L,

wherein the metasurface is formed by fabricating a two-dimensional array of nanopillars on the substrate to encode the four phase terms θ_R, θ_L, ϑ_R, and ϑ_L such that an incident laser beam is simultaneously manipulated in local amplitude, phase, and polarization state.

In a first group of embodiments, each element of the two-dimensional array is formed by two pairs of nanopillars, wherein one nanopillar pair encodes the phase terms θ_R and θ_L and the other nanopillar pair encodes the phase terms ϑ_R and ϑ_L. Such embodiments can be realized with the nanopillars having a rectangular cross-section, and the phase terms θ_R and θ_L, being

encoded in one nanopillar pair and the phase terms ϑ_R and ϑ_L being encoded in the other nanopillar pair by varying the nanopillars' width, W_x, length, W_y, and rotational angle, α.

In a second group of embodiments, each element of the two-dimensional array is formed by a single nanopillar, each nanopillar encoding all four of the four phase terms θ_R, θ_L, ϑ_R, and ϑ_L. Such embodiments can be realized with the nanopillars having a cross-shaped cross-section as defined by first and second intersecting bars aligned at a non-zero angle to each other, wherein the phase terms θ_R and θ_L are encoded in the first bar of each nanopillar by varying the first bars' width, W_x^{θ}, length, W_y^{θ}, and rotational angle α^{θ}, and wherein the phase terms ϑ_R and ϑ_L are encoded in the second bar of each nanopillar by varying that second bar's width, W_x^{ϑ}, length, W_y^{ϑ}, and rotational angle α^{ϑ}.

According to a second aspect of the disclosure there is provided a metalens fabricated according to the first aspect.

According to a third aspect of the disclosure there is provided an optical levitation system comprising:

a vacuum chamber;

a source of nanoparticles arranged in the vacuum chamber;

a metalens according to claim 6 configured to transform a laser beam into a pre-defined arbitrary optical field carrying spin angular momentum and/or orbital angular momentum in directions defined by the metalens; and

a laser source arranged to output a laser beam which is directed to pass through the metalens to form the arbitrary optical field in a region of the vacuum chamber, thereby to optically levitate and trap ones of the nanoparticles.

According to a fourth aspect of the disclosure there is provided method of measuring a physical field value with an optical levitation system according to the third aspect, the method comprising the following steps:

obtain a pressure of less than a threshold amount in the vacuum chamber;

directing the laser beam to pass through the metalens;

cause release of nanoparticles from the nanoparticle source;

optically levitating and trapping one or more of the released nanoparticles in the arbitrary optical field;

detecting a light intensity signal scattered from the trapped nanoparticles; and

processing the light intensity signal to obtain a physical field value.

BRIEF DESCRIPTION OF THE DRAWINGS

This invention will now be further described, by way of example only, with reference to the accompanying drawings.

Figures 1(a) and 1(b) are perspective views of an optically levitated gravimeter according to an embodiment of the invention; Figure 1(c) is a side view; and Figure 1(d) is a cross-section along line A-A of (c) showing internal details of the gravimeter.

Figure 2 shows an example optical configuration with external optical components connected to the gravimeter of Figure 1.

Figure 3(a) is a perspective view of an optically levitated gravimeter according to an alternative embodiment based on Laser-Induced Acoustic Desorption (LIAD); and Figure 3(b) is a cross-section showing internal details of the gravimeter.

Figure 4 is a schematic flow diagram illustrating a process for designing a single-layer dielectric metasurface for generating an arbitrary optical field.

Figures 5(a), 5(b) and 5(c) illustrate principles of double phase encoding; Figure 5(d) is a perspective view of a metasurface; and Figure 5(e) is a zoomed-in view of a part of the metasurface of Figure 5(d).

Figures 6(a)-(d) illustrate principles of double phase encoding based on X-shaped nanopillars; Figure 5(e) is a perspective view of a metasurface; and Figure 6(f) is a zoomed-in view of a part of the metasurface of Figure 6(e).

Figure 7(a) is a schematic perspective view showing a metalens with a metasurface providing an arbitrary optical field with a customized axis of spin angular momentum.

Figure 7(b) is a schematic perspective view showing a metalens with a metasurface providing an arbitrary optical field which provides orbital angular momentum.

DETAILED DESCRIPTION

It will be clear to one skilled in the art that many improvements and modifications can be made to the foregoing exemplary embodiment without departing from the scope of the present disclosure. In the following detailed description, we mainly refer to embodiments in which the field being sensed is gravity, i.e. the sensor is a gravimeter, However, as mentioned corresponding embodiments for sensing other field types may be envisaged.

Figures 1(a) and 1(b) are perspective views from below and above respectively of an optically levitated gravimeter according to a first embodiment of the invention based on a dry particle launching method; Figure 1(c) is a side view; and Figure 1(d) is a cross-section along line A-A of Figure 1(c) showing internal details of the gravimeter. The gravimeter is mechanically constructed based on a vacuum chamber formed by the interior space inside a two-part housing 1, 2 comprising an upper part 1 and a lower part 2. (The labels upper and lower are arbitrary and made for ease of reference.) The upper and lower parts 1, 2 of the housing are connected to each other in a vacuum-tight manner by suitable clamping bolts 3 with the mating surfaces between the upper and lower parts 1, 2 of the vacuum chamber housing being provided with a suitable gasket or other sealing joint (not shown). Optical access to the vacuum chamber is provided by an optical fibre feedthrough 4 in the upper vacuum chamber housing part 1. Electrical access to the vacuum chamber is provided by an electrical feedthrough 5 in the lower vacuum chamber housing part 2. A non-evaporative getter (NEG) 6 is provided in the lower vacuum chamber housing part 2 to assist maintenance of the vacuum by removal of residual gas species from the vacuum space. In use, the vacuum pressure is preferably better than 1E-6 mbar, which can be achieved by the NEG 6 which operates as a pump unit once the sensor is sealed. An external vacuum pump (not shown) may also be provided. The optical fibre feedthrough 4 is provided with a suitable collimator lens 7 for coupling into and/or out of an optical fibre (not shown) that may be attached, e.g. by a suitable ferrule, to the optical feedthrough 4. After the collimator lens 7, a continuous-wave, linearly polarized Gaussian laser beam (wavelength $\lambda = 1550nm$) from the fibre laser source 21 is shaped to a collimated beam. A metalens 8 for manipulating the laser beam so that it functions to trap the nanoparticles is supported within the vacuum chamber via suitable holder parts 9, 10 (e.g. plinth 9 and legs 10) attached to an inside surface of the upper vacuum chamber housing part 1. A particle source 14, 15 for the nanoparticles to be optically levitated is arranged within the vacuum chamber mounted on a piezoelectric actuator 11, e.g. made of lead-zirconate-titanate (PZT), which in turn is supported by legs 13 (e.g. 4 of) that are secured by their distal ends to an interior surface of the lower vacuum chamber housing part 2 and whose proximal ends support the piezoelectric actuator 11. A typical particle source will contain of the order of 2000 x 2000 particles, with a single nanoparticle being trapped for any given measurement. The piezoelectric actuator 11 is actuated with a suitable electrical control

signal via an electrical wire connection 12 which is fed from an external controller (not shown) into the vacuum chamber via the electrical feedthrough 5. The particle source 14, 15 comprises an agglomeration of source nanoparticles which are embedded in a polyfluoroethylene (PTFE) coated film 14 that acts as a substrate for holding the source particles prior to their release into the vacuum chamber. Embedding the nanoparticles to be levitated in the film 14 allows the nanoparticles to be directly loaded into the vacuum chamber and then released when needed by ultrasonic vibration of the piezoelectric actuator 11 on which the film 14 is mounted. The film 14 is inexpensive and easily replaceable.

Figure 2 shows an example optical configuration with external optical components connected to the gravimeter of Figure 1 via the optical feedthrough 4. The output of a laser 21 is coupled to an optical fibre 24. The laser light is waveguided through the optical fibre 24 via an optical circulator 23 to another optical fibre 25 connected the optical feedthrough 4, so that the laser light provides an optical tweezer for trapping nanoparticles in the vacuum chamber. Light from the trapped nanoparticles is coupled out of the vacuum chamber via the optical feedthrough 4 and into the optical fibre 24. The coupled-out light is then routed via the optical circulator 23 to another optical fibre 26 and onto a photodetector 22. The photodetector 22 outputs an electrical signal for display and analysis on an oscilloscope 27.

Figure 3(a) is a perspective view of an optically levitated gravimeter according to an alternative embodiment based on the LIAD method; and Figure 3(b) is a cross-section showing internal details of the gravimeter. LIAD is a dry and vacuum compatible method for loading particles into optical traps. In the LIAD method, a pulsed laser beam is focused onto the back side of a substrate upon which particles are distributed. The pulse generates acoustic shock waves through thermo-mechanical stress to locally eject particles from the substrate. The particles are only ejected from the region of the laser focus. LIAD is suitable for launching dielectric particles of size from around 100 nm up to several micrometres at pressures down to 1 mbar. The gravimeter is mechanically constructed based on a vacuum chamber formed by the interior space inside a two-part housing 1, 2 comprising an upper part 1 and a lower part 2. (The labels upper and lower are arbitrary and made for ease of reference.) The upper and lower parts 1, 2 of the housing are connected to each other in a vacuum-tight manner by suitable clamping bolts 3 with the mating surfaces between the upper and lower parts 1, 2 of the vacuum chamber housing being provided with a suitable gasket or other sealing joint (not shown). Optical access to the vacuum chamber is provided by an optical fibre feedthrough 4 in the lower vacuum chamber housing part 2. Electrical access to the vacuum chamber is provided by an electrical feedthrough 5 in the lower vacuum chamber housing part 2. A non-evaporative getter (NEG) 6 is provided in the lower vacuum chamber housing part 2 to assist maintenance of the vacuum by removal of residual gas species from the vacuum space. In use, the vacuum pressure is preferably better than 1E-6 mbar, which can be achieved by the

NEG 6 which operates as a pump unit once the sensor is sealed. An external vacuum pump (not shown) may also be provided. The optical fibre feedthrough 4 is provided with a suitable collimator lens 7 for coupling into and/or out of an optical fibre (not shown) that may be attached, e.g. by a suitable ferrule, to the optical feedthrough 4. A metalens 8 for manipulating the laser beam so that it functions to trap the nanoparticles is supported within the vacuum chamber via suitable holder parts 9, 10 (e.g. plinth 9 and legs 10) attached to an inside surface of the upper vacuum chamber housing part 1. The lower vacuum chamber housing part 2 accommodates the nanoparticle source components. A nanoparticle source chip 16 containing the nanoparticles is mounted on a linear translator 17 which in turn is actuated by a piezoelectric actuator 11 which receives control signals from an external controller (not shown) via an electrical wire connection 12 that passes through the electrical feedthrough 5. A typical particle source will contain of the order of 2000 x 2000 particles, with a single nanoparticle being trapped for any given measurement. The piezoelectric actuator 11 may be made of lead-zirconate-titanate (PZT), for example. A holder or mount 19 in the form of a spigot holds the PZT actuator 11 fixed in relation to the lower vacuum chamber housing part 2. The particle source 16 holds source nanoparticles prior to their release into the vacuum chamber. While the gravimeter of Figure 3 is based on the LIAD method, this is not the standard LIAD method. In a standard LIAD method, to align the laser beam relative to the nanoparticle source, the nanoparticle source chip 16 is mounted in a fixed position within the vacuum and the laser beam is movable by arranging the laser on a translation stage. In the gravimeter of Figure 3 on the other hand the nanoparticle source chip 16 is moved relative to a static laser beam, since the nanoparticle source chip 16 is in direct or indirect contact to the piezoelectric element 11. The piezoelectric actuator 11 and linear translator 17 together form a translation stage that provides for linear motion to allow lateral displacement of the particle source 16 along a motion axis, optionally in two crossed motion axes for xy-motion. The translation stage of piezoelectric actuator 11 acts to change the relative position between the nanoparticle source chip 16 and the focal point of the static pulsed laser beam.

Figure 4 is a schematic flow diagram illustrating a process for designing a single-layer dielectric metasurface for generating an arbitrary optical field. Optical field distribution plays an important role in an optical levitation gravimeter. However, the generation of arbitrary optical field is restricted by the limited manipulation ability of the available devices. Here, we propose a new approach to simultaneously manipulate the local amplitude, phase, and polarization state of an incident laser beam to generate an arbitrary optical field that is capable of forming a nanoparticle trap. The new approach combines the spin multiplexing [7] of a metasurface and double phase holography [8]. Using this novel approach, an arbitrary optical field can be generated on a single-layer dielectric metasurface. As shown in Figure 4, both the complex amplitudes of the X- and Y-components of the target optical field are decomposed into circular polarization bases. As a result, the target optical field can be expressed by summing the

complex amplitudes of the left- and right-handed circularly polarized light (LCP and RCP). Then, the complex amplitudes of the LCP and RCP are reformulated as the sum of two phase terms. Finally, the target optical field is expressed by four phase terms θ_R, θ_L, ϑ_R, and ϑ_L. To encode the four phase terms into a single-layer metasurface, we propose using one of two modulation methods as described below with reference to Figure 5 and Figure 6 respectively. Once the metasurface is designed and fabricated on the substrate, the target optical field can be obtained by illuminating the metasurface with a coherent light beam from a laser.

A field measurement can be performed as follows.

(1) Create a vacuum by turning on the vacuum pump NEG 6 and waiting for the pressure in the chamber to drop to an acceptable value (<1E-6 mbar).

(2) Turn on the fiber laser source 21, photodetector 22, and oscilloscope 27.

(3) Release, levitate and trap a particle in the arbitrary optical field. With the loading method of FIG. 3 (LIAD), a particle is trapped by turning on the pulsed laser and waiting for a particle to be trapped, which can be detected from the signal shown in oscilloscope. With the loading method of FIG. 1, to trap a particle: turn on the controller of the PZT actuator 11 to generate an ultrasonic vibration driver signal and the shockwaves created by the PZT locally eject particles from the film 14 and one will then become trapped, which can be detected from the signal shown in oscilloscope.

(4) Detect a light intensity signal scattered from the trapped nanoparticles. This is done by saving a time trace measured by the oscilloscope 27 (Sampling rate > 10Ms/s, sampling time > 1s).

(5) Determine a physical field value by processing the light intensity signal via frequency analysis according to a physical model specific to the type of field being sensed, e.g. gravity field.

The signal processing to determine the physical field value may proceed as follows in the case of a gravity measurement. The signal detected by oscilloscope is the voltage signal which is linearly dependent on the optical intensity arrived at the photodetector. Based on the voltage signal, the spin and precession speed of the levitated particle can be obtained via frequency spectrum analysis and a calibration conversion algorithm. Then, based on the physical model which describes the quantitative relationship between the spin, precession, and gravity, the gravity value under test is obtained. Specifically, the measured precession frequency scales with the gravity value to be detected.

Figure 5 shows a first example method for fabricating the metalens, in which the nanopillars have a rectangular cross-section (where 'rectangular' is to be understood as including square). The nanopillars are arranged on the metasurface in a two-dimensional array, where each element of the array is formed by two pairs of nanopillars in a 2 x 2 subarray, wherein as illustrated in Figure 5(a) the nanopillar pair formed by the upper left and lower right nanopillars of each subarray encodes the phase terms $\boldsymbol{\theta_R}$ and $\boldsymbol{\theta_L}$ and the nanopillar pair formed by the upper right and lower left nanopillars encodes the phase terms $\boldsymbol{\vartheta_R}$ and $\boldsymbol{\vartheta_L}$. The metalens is based on a single-layer metasurface of a substrate 29 fabricated by grating modulation. Figures 5(a), 5(b) and 5(c) illustrate principles of double phase encoding to form nanopillars 28 on the surface of a suitable substrate 29. The substrate 29 may be made of glass such as silicon dioxide and the nanopillars 28 may be made of silicon. In principle any suitable optically transparent dielectric materials could be used for the substrate and for the nanopillars. Figure 5(d) is a perspective view of a metasurface; and Figure 5(e) is a zoomed-in view of a part of the metasurface of Figure 5(d) showing the arrangement of a group of individual adjacent nanopillars. As shown in Figure 5(a), the target optical field is discretized with a period of 2P, where P is the period of the nanopillars of the metasurface. The optical field located at a position $(\mathrm{x,y})$ is expressed by four phase terms (θ_R, θ_L, ϑ_R, and ϑ_L) and encoded by four nanopillars. The two bars located at up-left and down-right encode the phases θ_R and θ_L, whereas the other two bars encode the phases ϑ_R and ϑ_L. As shown in Figures 5(b) and 5(c), the target two phases are realized by varying each nanopillar's width, W_x (100nm – 650nm), length, W_y (100nm – 650nm), and rotational angle, α (0 – 2π). The nanopillar height *H* and period *P* are respectively fixed at 800nm and 650nm when the operation wavelength is 1550nm. A single layer metasurface can thus be structured to encode any desired arbitrary optical field by forming an array of nanopillars on a substrate surface acting as a lens blank. Suitable materials for the nanopillars include silicon and silica.

The above design of the metasurface allows for a simpler fabrication, since, when all the nanopillars are the same height, the metalens can be fabricated by a single e-beam lithography and etch process. Nevertheless, other embodiments can be realized in which the nanofin height is varied to encode the optical field this would have the drawback of increasing the fabrication complexity compared with encoding the optical field with the orientation angle.

Figure 6 shows a second example method for fabricating the single-layer metasurface, in which the nanopillars have a crossed cross-section, i.e. X-shaped cross-section. The nanopillars are arranged on the metasurface in a two-dimensional array, where each element of the array is formed by a single nanopillar with an X-shaped cross-section that encodes all four phase terms θ_R, θ_L, ϑ_R, and ϑ_L. Figures 6(a)-(d) illustrate principles of double phase encoding based on X-shaped nanopillars; Figure 6(e) is a perspective view of a metasurface; and Figure 6(f) is a zoomed-in view of a part of the metasurface of Figure 6(e). The substrate

29 may be made of glass such as silicon dioxide and the nanopillars 28 may be made of silicon. In principle any suitable optically transparent dielectric materials could be used for the substrate and for the nanopillars. As shown in Figure 6(a), the target optical field is discretized with the same period *P* as that of the nanopillars on the metasurface. Then, we could get the local optical field located at the position (*x,y*), and decompose it into four phase terms (θ_R, θ_L, ϑ_R, ϑ_L). The four phase terms can be classified into two subgroups: θ_R and θ_L; and ϑ_R and ϑ_L. As discussed above and shown in Figure 6(b), the two phases θ_R and θ_L can be simultaneously encoded by varying the fin's width W_x, length W_y , and rotation angle α. Meanwhile, another bar is introduced to the position (*x,y*) for encoding phases ϑ_R and ϑ_L, as shown in Figure 6(c). The two bars encoding the two phase groups can then be physically superposed into a single nanopillar having a cross-shaped (or X-shaped) cross-section as shown in Figure 6(d). An X-shaped nanopillar is thus constructed that simultaneously encodes all four phases. Benefiting from the local interference between the two bars located at the same position, i.e. in the same nanopillar, the target optical field can be directly obtained by illuminating the metasurface. Figure 6(e) is a perspective view of the metasurface and Figure 6(f) a close-up showing individual ones of the X-shaped nanopillars.

Figure 7(a) is a schematic perspective view showing an example metalens with a metasurface providing an arbitrary optical field with a customized axis of spin angular momentum. The spin axis is indicated by the solid arrow. The phenomenon of precession results from the separation between the direction of a spinning axis and the direction of external torque. It is therefore important to manipulate the spin direction of the optical levitated particle in precession-based gravity sensing. However, in conventional optical levitation systems, the direction of the spin angular momentum (SAM) carried by a focused laser beam is always along its optical axis, which results in the spin direction of the levitated nanoparticle also being along the optical axis. This restriction is lifted with the above-described design and fabrication process for the metalens, so the spin axis can be designed to be arbitrary and is no longer fixed to be the same as the optical axis. The three angular components along angles α, β, γ can be independently set when fabricating the metasurface based on requirements including dynamic range and sensitivity. As a result, the spin direction of the levitated particle can be set to lie along any desired axis and is not restricted to being along the optical axis.

Figure 7(b) is a schematic perspective view showing an example metalens with a metasurface providing an arbitrary optical field which provides orbital angular momentum. In this example, the metasurface is designed and fabricated so that the arbitrary optical field is toroidal in shape (i.e. doughnut-shaped). The optical field thus carries orbital angular momentum to induce optically levitated nanoparticles to orbitally rotate around the optical axis (the z-axis). Orbital rotation is another way of generating precession motion.

The above-described metalens design can provide a metalens configured to transform a laser beam into a pre-defined arbitrary optical field carrying spin angular momentum and/or orbital angular momentum in directions defined by the metalens that are capable of efficient transfer of spin angular momentum and/or orbital angular momentum from the laser beam to nanoparticles trapped by levitation in the optical field of the laser beam that has passed through the metalens.

In the above, a way to design and fabricate a metasurface for a metalens has been described to provide an arbitrary optical field, where the term 'arbitrary' refers to the ability to realize any design in a metalens, i.e. the ability to create any pre-defined optical field. We have shown how to construct a specific optical field with a customized spin direction [Figure 7(a)] or orbital angular momentum [Figure 7(b)] for quantitively measuring the relationship between spin, precession, and gravity torque of an optically levitated particle, and thereby realize gravity sensing. An optical field is generated using the metasurface and realizes separation of the particle's spin direction and laser beam's optical axis. The physical field value (e.g. gravity value for a gravimeter embodiment) can then be obtained via the spin direction and optical axis, and the spin and precession speed measured in the experiment.

In summary, the invention relates to a field sensor and field sensing method operating via the principle of optical levitation of nanoparticles, where the field type being sensed includes gravitation field, electric field and magnetic field. The metasurface-based optical levitation sensor as described above is suitable for sensing external forces, torques, and acceleration. Gravity sensing is a specific application of interest. The difference between sensing gravity and other field types is the physical model that is needed to process the measured signals.

REFERENCE NUMERALS

1	vacuum chamber housing, upper part
2	vacuum chamber housing, lower part
3	vacuum chamber clamping bolts
4	optical fibre feedthroughs in upper/lower vacuum chamber housing parts
5	electrical feedthrough
6	non-evaporative getter (NEG)
7	collimator lens for optical fibre coupling
8	metalens
9/10	metalens holder parts
11	piezoelectric actuator
12	electrical wire connection to piezoelectric actuator
13	legs, 4 of
14	PTFE-coated film acting as a substrate for source particles
15	source nanoparticles arranged on PTFE-coated film 14
16	nanoparticle source chip
17	linear translator
19	holder/mount for piezoelectric actuator 18
21	laser
22	photodetector
23	optical circulator
24-26	optical fibres
27	oscilloscope
28	nanopillar
29	substrate for the nanopillars
30	rectangular cross-section nanopillar, arranged in groups of 4
31	cross-shaped cross-section nanopillar
32	first bar of cross-shaped nanopillar, encoding phase terms θ_R and θ_L
33	second bar of cross-shaped nanopillar, encoding phase terms ϑ_R and ϑ_L

REFERENCES

[1] Monteiro, Fernando, et al. "Force and acceleration sensing with optically levitated nanogram masses at microkelvin temperatures." Physical Review A 101.5 (2020): 053835. https://doi.org/10.1103/PhysRevA.101.053835

[2] René Reimann, et al. " GHz Rotation of an Optically Trapped Nanoparticle in Vacuum." Physical review letters 121 (2018): 033602. https://doi.org/10.1103/PhysRevLett.121.033602

[3] Ahn, Jonghoon, et al. "Ultrasensitive torque detection with an optically levitated nanorotor." Nature nanotechnology 15.2 (2020): 89-93. https://doi.org/10.1038/s41565-019-0605-9

[4] Muddassar Rashid, Marko Toros, Ashley Setter, and Hendrik Ulbricht. "Precession Motion in Levitated Optomechanics." Physical review letters 121 (2018): 253601. https://doi.org/10.1103/PhysRevLett.121.253601

[5] James Millen, Tania S Monteiro, Robert Pettit, and A Nick Vamivakas. " Optomechanics with levitated particles." Reports on Progress in Physics 83 (2020): 026401. 10.1088/1361-6633/ab6100

[6] Mohammad H. Asadian, Sina Askari, and Andrei M. Shkel. " An Ultrahigh Vacuum Packaging Process Demonstrating Over 2 Million Q-Factor in MEMS Vibratory Gyroscopes." IEEE Sensors Letters 1(6) (2017): 6500104. 10.1109/LSENS.2017.2762287

[7] Khorasaninejad, et al. "Multispectral chiral imaging with a metalens." Nano letters 16.7 (2016): 4595-4600. https://doi.org/10.1021/acs.nanolett.6b01897

[8] Victor Arrizón and David Sánchez-de-la-Llave." Double-phase holograms implemented with phase-only spatial light modulators: performance evaluation and improvement." Applied optics 41.17 (2002): 3436-3447.https://doi.org/10.1364/AO.41.003436

CLAIMS

1. A method of fabricating a metalens for optical levitation of nanoparticles, the method comprising:

providing a substrate to serve as a blank for the metalens; and

nanostructuring a surface of the substrate to form a metasurface that encodes an arbitrary optical field such that, when the metalens is illuminated by a laser beam the arbitrary optical field is formed in a defined region of space, the arbitrary optical field being capable of optically levitating and trapping nanoparticles in a vacuum,

wherein the arbitrary optical field is encoded onto said substrate surface by:

providing the arbitrary target optical field to be encoded onto the substrate surface as expressed in the form:

$$\begin{pmatrix} A_X(x,y)e^{i\phi_X(x,y)} \\ A_Y(x,y)e^{i\phi_Y(x,y)} \end{pmatrix}$$

decomposing the complex amplitudes of the X- and Y-components of the target optical field into left- and right-handed circular polarization bases

$$A_R(x,y)e^{i\phi_R(x,y)}\begin{pmatrix} 1 \\ -i \end{pmatrix} + A_L(x,y)e^{i\phi_L(x,y)}\begin{pmatrix} 1 \\ i \end{pmatrix}$$

so that the target optical field is expressed as the sum of the complex amplitudes of left- and right-handed circularly polarized light; and

reformulating the complex amplitudes of each of the left- and right-handed circularly polarized light as the sum of two phase terms

$$A_R(x,y)e^{i\phi_R(x,y)} = \frac{Max(A_R)}{2}[e^{i\theta_R(x,y)} + e^{i\vartheta_R(x,y)}]$$

$$A_L(x,y)e^{i\phi_L(x,y)} = \frac{Max(A_L)}{2}[e^{i\theta_L(x,y)} + e^{i\vartheta_L(x,y)}]$$

so that the target optical field is expressed by four phase terms θ_R, θ_L, ϑ_R, and ϑ_L,

wherein the metasurface is formed by fabricating a two-dimensional array of nanopillars on the substrate to encode the four phase terms θ_R, θ_L, ϑ_R, and ϑ_L such that an incident laser beam is simultaneously manipulated in local amplitude, phase, and polarization state.

2. The method of claim 1, wherein each element of the two-dimensional array is formed by two pairs of nanopillars, wherein one nanopillar pair encodes the phase terms $\boldsymbol{\theta_R}$ and $\boldsymbol{\theta_L}$ and the other nanopillar pair encodes the phase terms $\boldsymbol{\vartheta_R}$ and $\boldsymbol{\vartheta_L}$.

3. The method of claim 2, wherein the nanopillars have a rectangular cross-section, and wherein the four phase terms θ_R, θ_L, ϑ_R, and ϑ_L are encoded in each individual nanopillar by varying the nanopillars' width, W_x, length, W_y, and rotational angle, α.

4. The method of claim 1, wherein each element of the two-dimensional array is formed by a single nanopillar, each nanopillar encoding all four of the four phase terms θ_R, θ_L, ϑ_R, and ϑ_L.

5. The method of claim 4, wherein the nanopillars have a cross-shaped cross-section as defined by first and second intersecting bars aligned at a non-zero angle to each other,

wherein the phase terms θ_R and θ_L are encoded in the first bar of each nanopillar by varying the first bars' width, W_x^{θ}, length, W_y^{θ}, and rotational angle α^{θ}, and

wherein the phase terms ϑ_R and ϑ_L are encoded in the second bar of each nanopillar by varying that second bar's width, W_x^{ϑ}, length, W_y^{ϑ}, and rotational angle α^{ϑ}.

6. A metalens fabricated according to the method of any one of claims 1 to 5.

7. An optical levitation system comprising:

a vacuum chamber;

a source of nanoparticles arranged in the vacuum chamber;

a metalens according to claim 6 configured to transform a laser beam into a pre-defined arbitrary optical field carrying spin angular momentum and/or orbital angular momentum in directions defined by the metalens; and

a laser source arranged to output a laser beam which is directed to pass through the metalens to form the arbitrary optical field in a region of the vacuum chamber, thereby to optically levitate and trap ones of the nanoparticles.

8. A method of measuring a physical field value with an optical levitation system according to claim 7, the method comprising the following steps:

obtain a pressure of less than a threshold amount in the vacuum chamber;

directing the laser beam to pass through the metalens;

cause release of nanoparticles from the nanoparticle source;

optically levitating and trapping one or more of the released nanoparticles in the arbitrary optical field;

detecting a light intensity signal scattered from the trapped nanoparticles; and

processing the light intensity signal to obtain a physical field value.

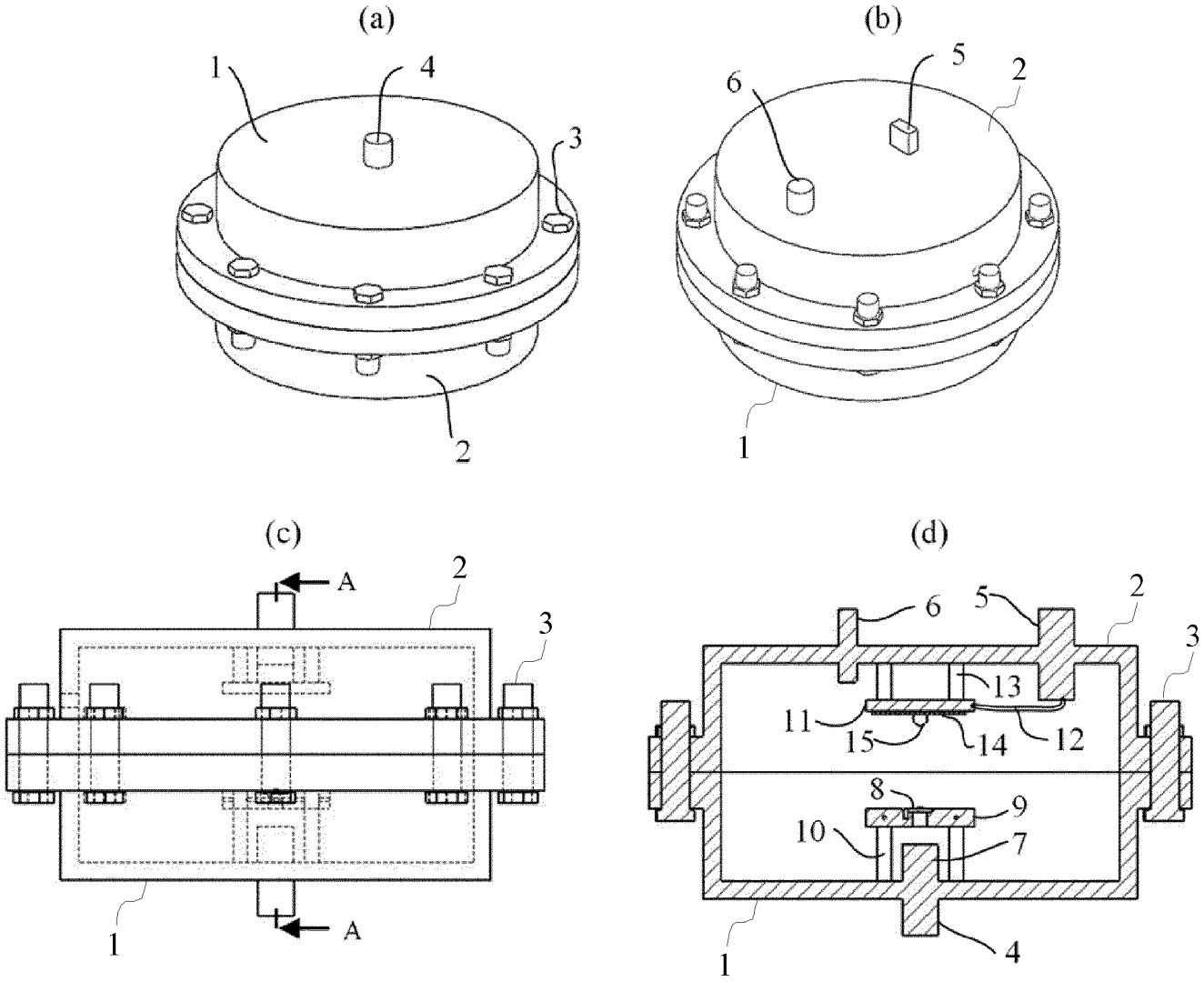

FIG. 1

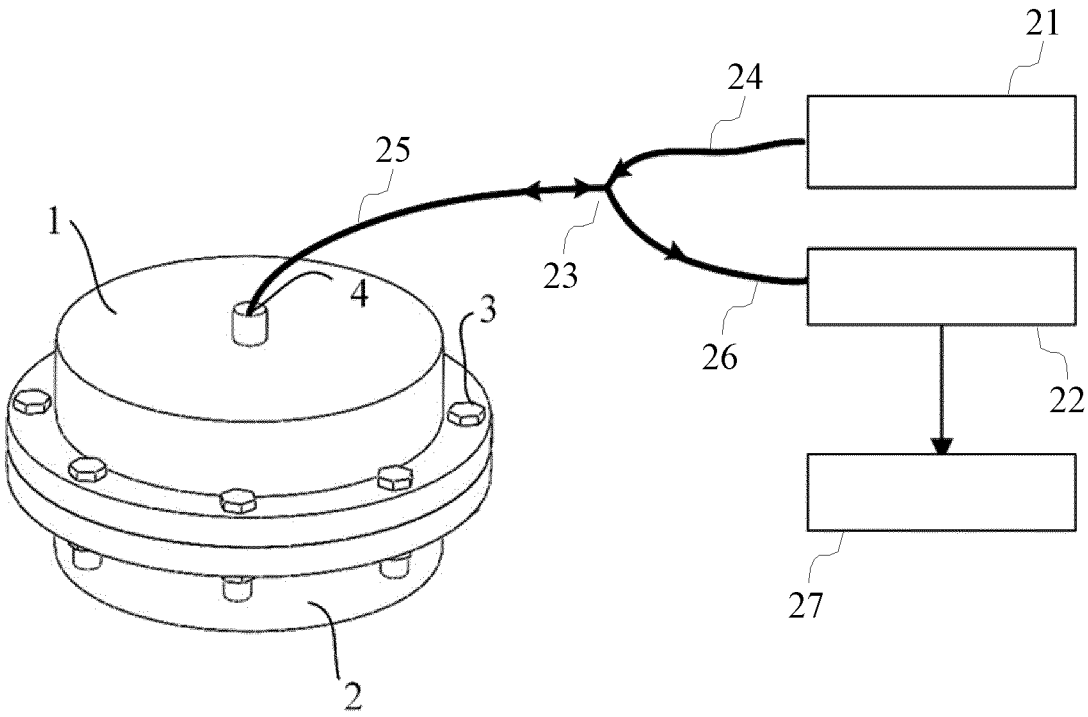

FIG. 2

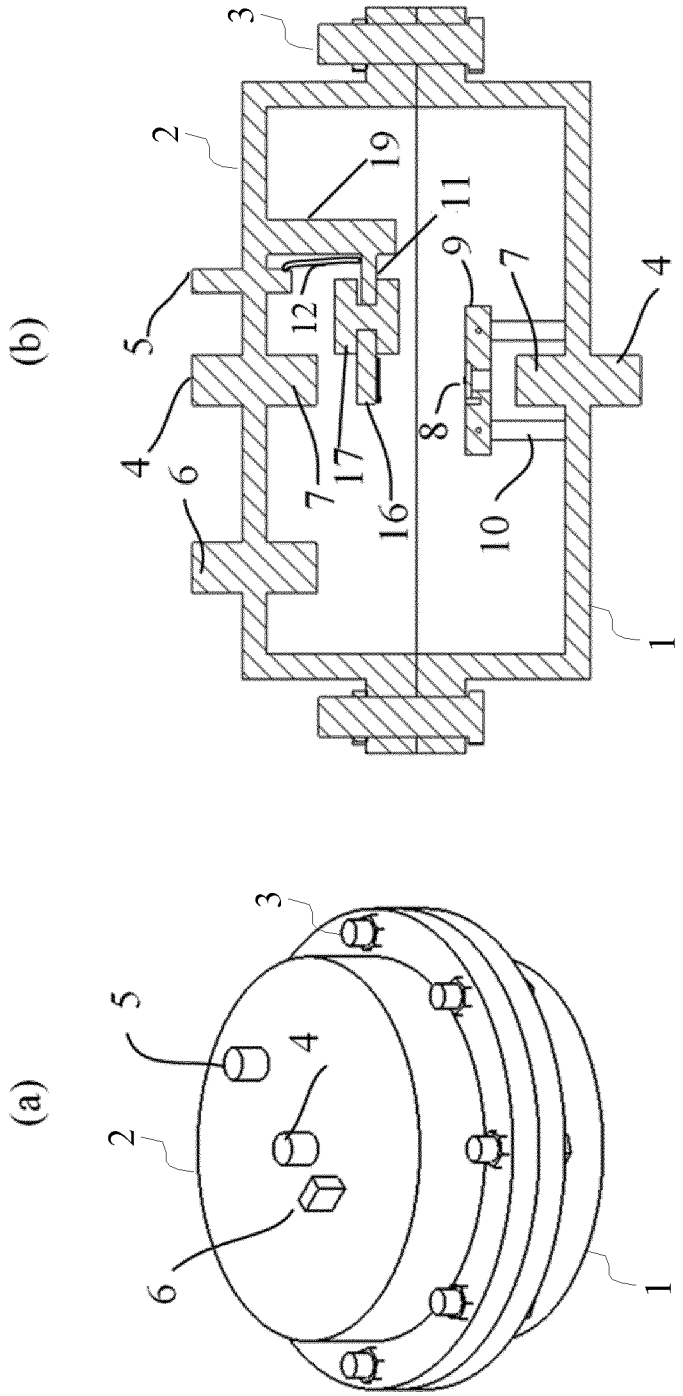

FIG. 3

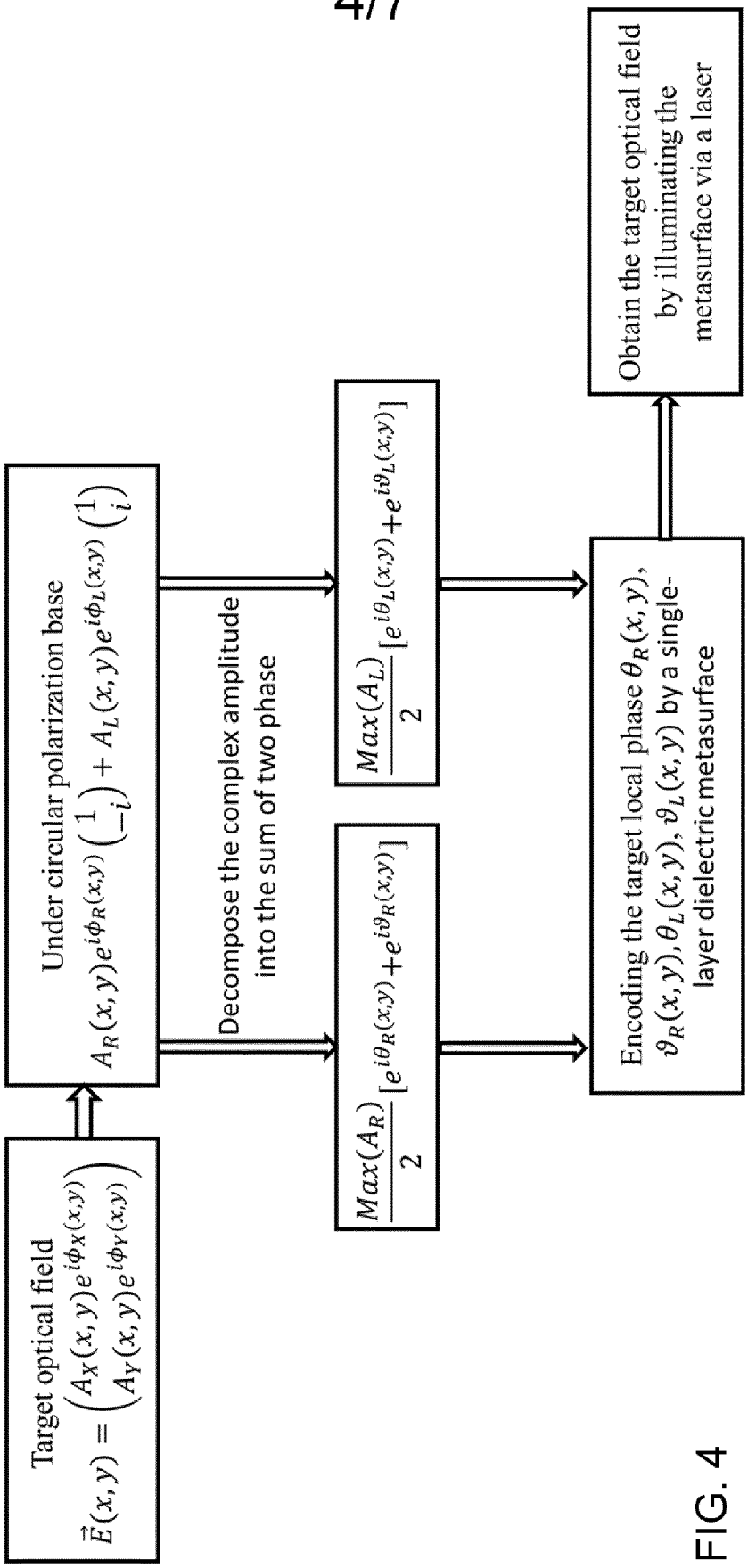
Target optical field
$\vec{E}(x,y) = \begin{pmatrix} A_X(x,y)e^{i\phi_X(x,y)} \\ A_Y(x,y)e^{i\phi_Y(x,y)} \end{pmatrix}$
Under circular polarization base
$A_R(x,y)e^{i\phi_R(x,y)}\begin{pmatrix}1\\-i\end{pmatrix} + A_L(x,y)e^{i\phi_L(x,y)}\begin{pmatrix}1\\i\end{pmatrix}$
Decompose the complex amplitude into the sum of two phase
$\frac{Max(A_R)}{2}[e^{i\theta_R(x,y)}+e^{i\vartheta_R(x,y)}]$
$\frac{Max(A_L)}{2}[e^{i\theta_L(x,y)}+e^{i\vartheta_L(x,y)}]$
Encoding the target local phase $\theta_R(x,y)$, $\vartheta_R(x,y), \theta_L(x,y), \vartheta_L(x,y)$ by a single-layer dielectric metasurface
Obtain the target optical field by illuminating the metasurface via a laser

FIG. 4

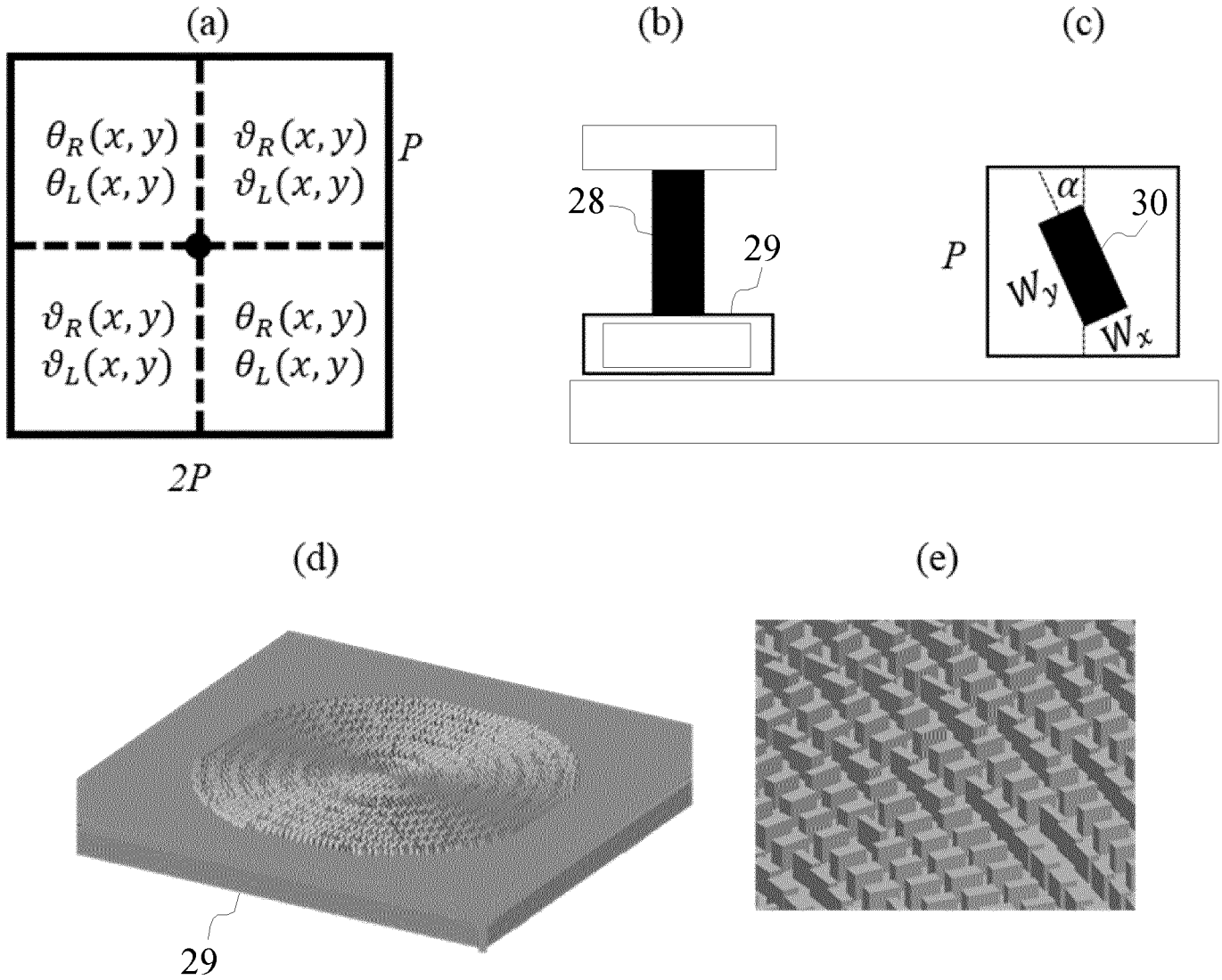
(a)
(b)
(c)
$\theta_R(x,y)$
$\vartheta_L(x,y)$
$\vartheta_R(x,y)$
$\vartheta_L(x,y)$
$\vartheta_R(x,y)$
$\vartheta_L(x,y)$
$\theta_R(x,y)$
$\theta_L(x,y)$
P
2P
28
29
α
30
P
W_y
W_x
(d)
(e)
29

FIG. 5

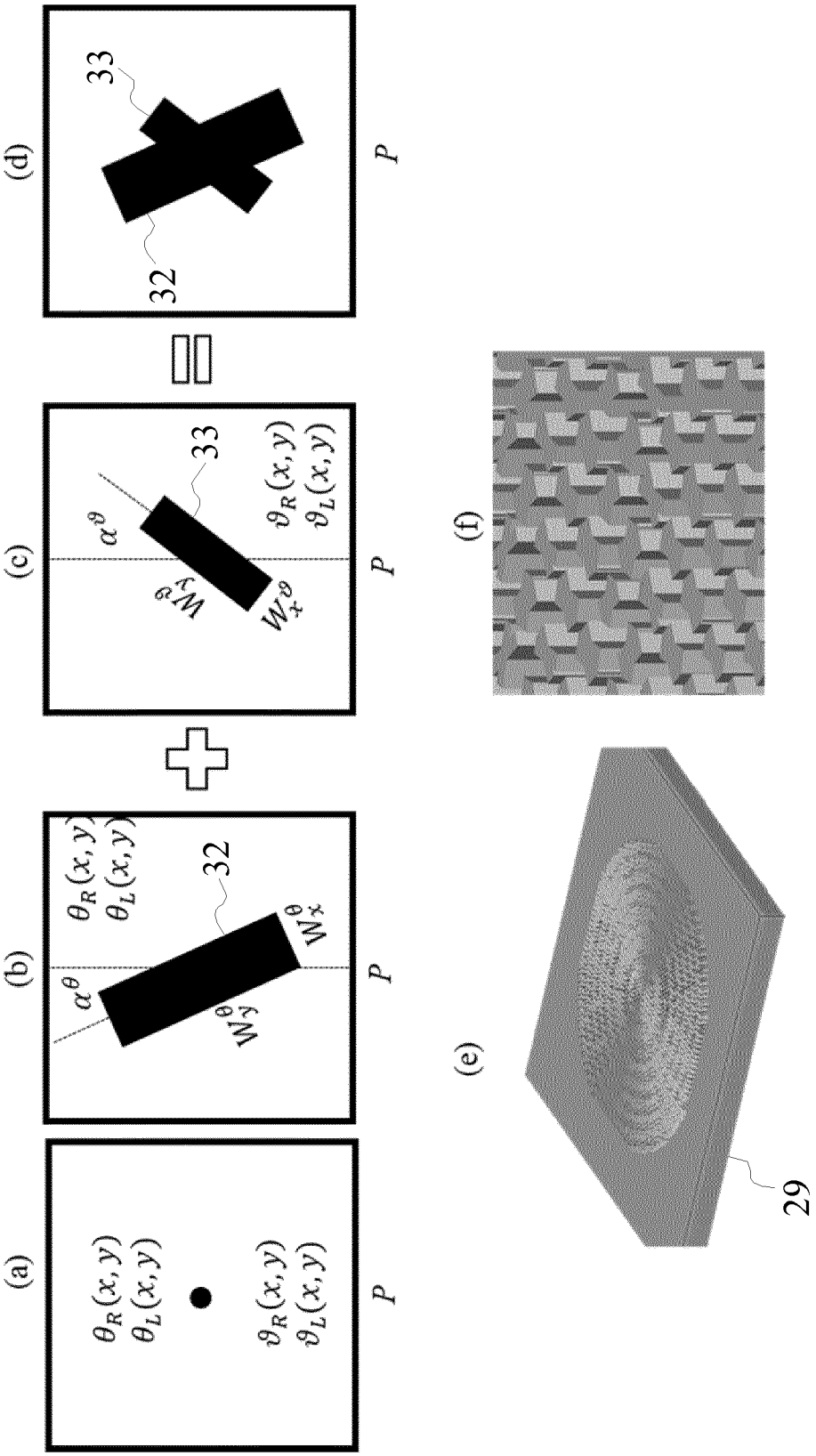
(a)
$\theta_R(x,y)$
$\theta_L(x,y)$
$\vartheta_R(x,y)$
$\vartheta_L(x,y)$
P
(b)
$\theta_R(x,y)$
$\theta_L(x,y)$
32
α^θ
W_y^θ
W_x^θ
P
(c)
33
α^ϑ
W_y^ϑ
W_x^ϑ
$\vartheta_R(x,y)$
$\vartheta_L(x,y)$
P
(d)
33
32
P
(e)
29
(f)

FIG. 6

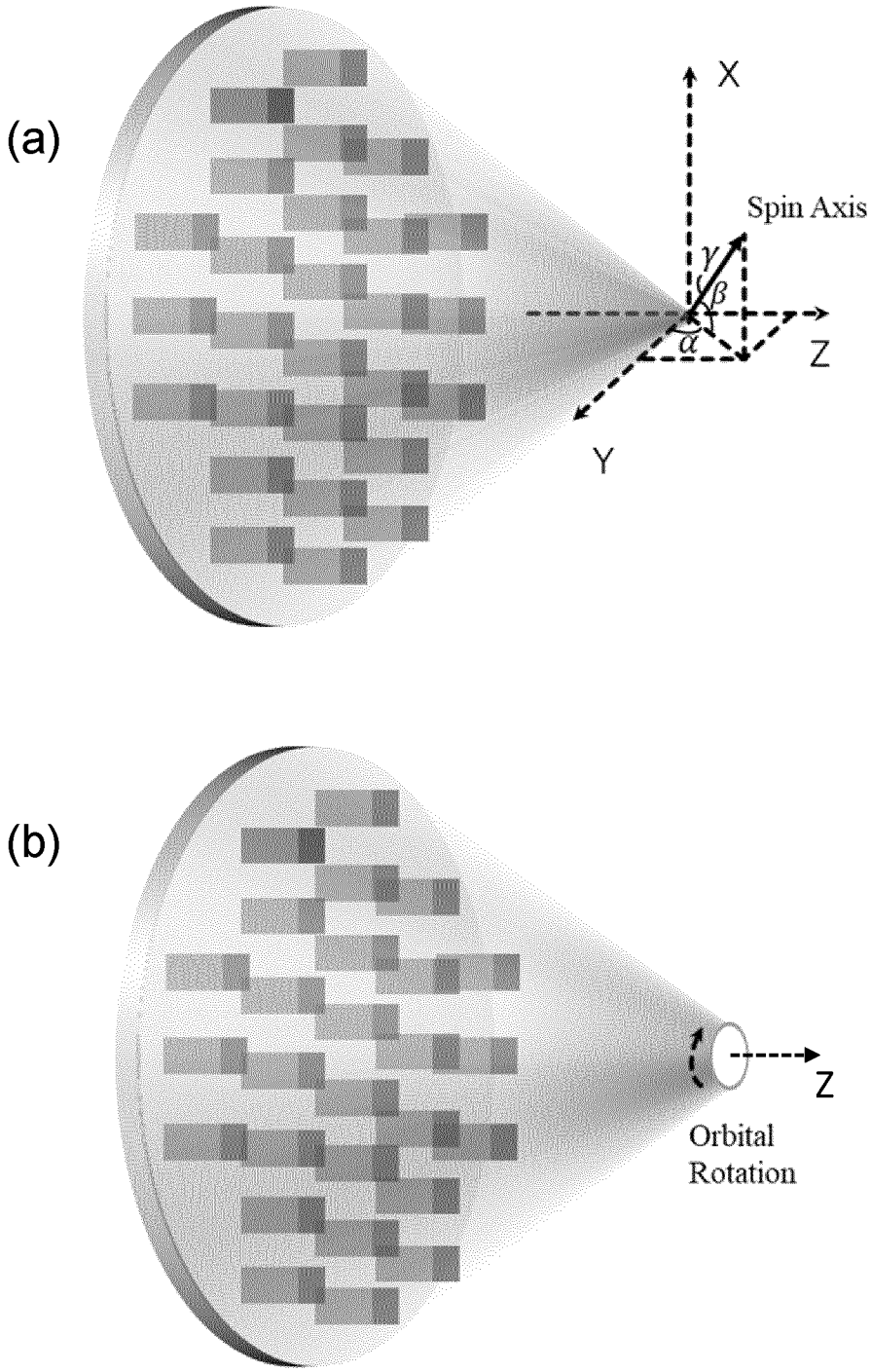

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/055501

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B1/00 G02B5/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SUNAE SO: "Revisiting the Design Strategies for Metasurfaces: Fundamental Physics, Optimization, and Beyond", ADVANCED MATERIALS, vol. 35, no. 43, 25 September 2022 (2022-09-25), XP093161000, DE ISSN: 0935-9648, DOI: 10.1002/adma.202206399 Retrieved from the Internet: URL:https://onlinelibrary.wiley.com/doi/pdf/10.1002/adma.202206399> figure 6a ----- -/--	6

[x] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 May 2024	21/05/2024

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

2

Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GUN-YEAL LEE ET AL: "Complete amplitude and phase control of light using broadband holographic metasurface", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 29 June 2017 (2017-06-29), XP081588335, DOI: 10.1039/C7NR07154J	6
A	figures 1,2	1-5
A	HU TIE ET AL: "Design of scalable metalens array for optical addressing", FRONTIERS OF OPTOELECTRONICS, HIGHER EDUCATION PRESS, HEIDELBERG, vol. 15, no. 1, 4 August 2022 (2022-08-04) , XP037926932, ISSN: 2095-2759, DOI: 10.1007/S12200-022-00035-2 [retrieved on 2022-08-04] equation 5; figure 2	1-8
A	ARRIZON V ET AL: "Double-phase holograms implemented with phase-only spatial light modulators: performance evaluation and improvement", APPLIED OPTICS, OPTICAL SOCIETY OF AMERICA, WASHINGTON, DC, US, vol. 41, no. 17, 10 June 2002 (2002-06-10) , pages 3436-3447, XP007902490, ISSN: 0003-6935, DOI: 10.1364/AO.41.003436 cited in the application figure 7	1-8
X	SHI YUZHI ET AL: "Optical manipulation with metamaterial structures", APPLIED PHYSICS REVIEWS, AMERICAN INSTITUTE OF PHYSICS, 2 HUNTINGTON QUADRANGLE, MELVILLE, NY 11747, vol. 9, no. 3, 17 August 2022 (2022-08-17) , XP012267665, DOI: 10.1063/5.0091280 [retrieved on 2022-08-17] Section IV A Shaping amplitude and phase; figure 5	6,7

-/--

2

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	KUNHONG SHEN: "On-chip optical levitation with a metalens in vacuum", OPTICA, vol. 8, no. 11, 21 October 2021 (2021-10-21), page 1359, XP093160372, US ISSN: 2334-2536, DOI: 10.1364/OPTICA.438410 Retrieved from the Internet: URL:https://opg.optica.org/viewmedia.cfm?URI=optica-8-11-1359> Section 3.2.5; figure 6a	6-8