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- (54) **Title:** ROOM TEMPERATURE EXCITON-POLARITON SAGNAC INTERFEROMETER, AND RELATED METHODS

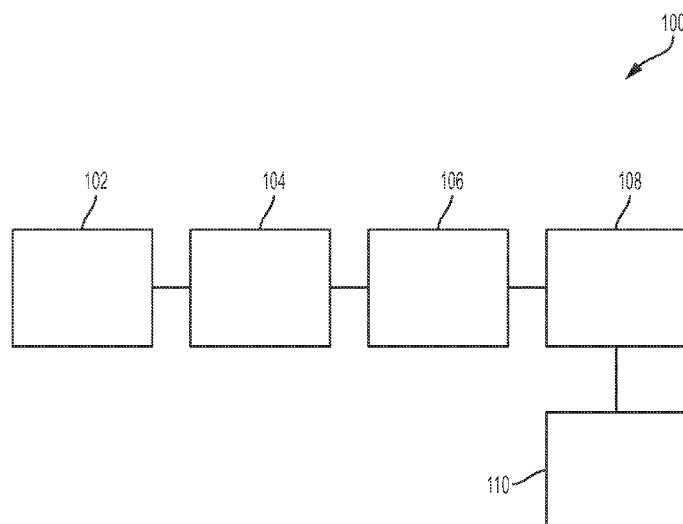


FIG. 1

(57) **Abstract:** According to some embodiments of the invention, a room temperature exciton-polariton Sagnac interferometer includes a light source, an orbital angular momentum superposition state of light component configured to receive light from said light source and output an orbital angular momentum superposition state of light, and a microcavity configured to support an exciton-polariton Bose-Einstein condensate (BEC). The orbital angular momentum superposition state of light is transmitted through the microcavity to induce a vortex superposition state in the exciton-polariton BEC. The room temperature exciton-polariton Sagnac interferometer also includes a photodetector configured to detect light emitted from the microcavity, and a processor configured to determine a Sagnac phase based on the detected light.

ROOM TEMPERATURE EXCITON-POLARITON SAGNAC INTERFEROMETER, AND RELATED METHODS

[0001] This application claims priority to U.S. Provisional Application No. 62/014,394 filed June 19, 2014, the entire content of which is hereby incorporated by reference.

BACKGROUND

1. Technical Field

[0002] Embodiments of this invention generally relate to Sagnac interferometers, and more particularly to a room temperature exciton-polariton Sagnac interferometer, and related methods.

2. Discussion of Related Art

[0003] Sagnac interferometers are widely known and are used for measuring angular velocity. In practice, the first interferometry experiment aimed at observing the correlation of angular velocity and phase-shift was performed by the French scientist, Georges Sagnac, in 1913. Typically, Sagnac interferometers are either optical or atomic. Optical interferometers depend, to some extent, on the wavelength of the optical beam used, and thus are limited in sensitivity. Moreover, optical Sagnac interferometers depend on the area of the configuration – meaning that the sensitivity to rotation is proportional to the area circumscribed by the counter-rotating optical beams. Consequently, manufacturing an optical Sagnac interferometer in a compact form can come at the cost of a decrease in measurement sensitivity. However, one advantage of optical interferometers is that they operate at room temperature. Furthermore, such optical interferometers are relatively inexpensive.

[0004] Ultra cold atomic gases offer highly attractive physical systems for realizing quantum metrological devices, such as gyroscopes, which employ the Sagnac effect. Atomic systems offer exquisite control that originates from quantum optics, such as vortex creation in a Bose-Einstein condensate (BEC) matter wave, and are highly coherent, meaning the interference visibility can be used for interferometry. The rotational measurement sensitivity

of atomic matter wave interferometers per unit area typically exceeds that of optical ones by the ratio $mc^2 / \hbar\omega \sim 10^{10}$. Unfortunately, achieving Bose-Einstein condensation in atomic gases is very difficult and can typically only occur at nanokelvin temperatures. This typically renders atomic interferometers impractical and extremely expensive.

SUMMARY

[0005] According to some embodiments of the invention, a room temperature exciton-polariton Sagnac interferometer includes a light source, an orbital angular momentum superposition state of light component configured to receive light from said light source and output an orbital angular momentum superposition state of light, and a microcavity configured to support an exciton-polariton Bose-Einstein condensate (BEC). The orbital angular momentum superposition state of light is transmitted through the microcavity to induce a vortex superposition state in the exciton-polariton BEC. The room temperature exciton-polariton Sagnac interferometer also includes a photodetector configured to detect light emitted from the microcavity, and a processor configured to determine a Sagnac phase based on the detected light. The exciton-polariton BEC can be formed in a potential permitting infinite effective mass polaritons.

[0006] According to some embodiments of the invention, a method for performing Sagnac interferometry using a room temperature exciton-polariton BEC includes creating an orbital angular momentum superposition state of light, inducing a vortex superposition state in the room temperature exciton-polariton BEC using the orbital angular momentum superposition state of light, detecting light emitted from the exciton-polariton BEC, and determining a Sagnac phase based on the detected light.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Further objectives and advantages will become apparent from a consideration of the description, drawings, and examples.

[0008] Figure 1 is a schematic illustration of a room temperature exciton-polariton Sagnac interferometer according to some embodiments of the invention;

[0009] Figure 2 illustrates the method by which an orbital angular momentum (OAM) state of light can be generated according to some embodiments of the invention;

[0010] Figure 3 shows a Mach-Zehnder interferometer according to some embodiments of the invention;

[0011] Figure 4 is a schematic illustration of microcavity polaritons;

[0012] Figure 5 illustrates an OAM superposition state of light being pumped into a distributed Bragg reflector (DBR) microcavity;

[0013] Figure 6 is a schematic diagram of a room temperature exciton-polariton Sagnac interferometer according to some embodiments of the invention;

[0014] Figure 7 is a schematic diagram of a room-temperature Sagnac interferometer including a STIRAP implementation similar to that used for ultracold atoms;

[0015] Figure 8A shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a flat potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 0$;

[0016] Figure 8B shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a flat potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 0.25$;

[0017] Figure 8C shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a flat potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 0.5$;

[0018] Figure 8D shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a flat potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 0.75$;

[0019] Figure 8E shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a flat potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 1.0$;

[0020] Figure 9A shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a disordered potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 0$;

[0021] Figure 9B shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a disordered potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 0.25$;

[0022] Figure 9C shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a disordered potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 0.5$;

[0023] Figure 9D shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a disordered potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 0.75$;

[0024] Figure 9E shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a disordered potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 1.0$;

[0025] Figure 10A shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a Kagome lattice

potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 0$;

[0026] Figure 10B shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a Kagome lattice potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 0.25$;

[0027] Figure 10C shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a Kagome lattice potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 0.5$;

[0028] Figure 10D shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a Kagome lattice potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 0.75$;

[0029] Figure 10E shows a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a Kagome lattice potential, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at $t = 1.0$; and

[0030] Figure 11 shows how an interference pattern having light regions and dark regions rotates in time, and can be used to determine a Sagnac phase.

DETAILED DESCRIPTION

[0031] Some embodiments of the current invention are discussed in detail below. In describing embodiments, specific terminology is employed for the sake of clarity. However, the invention is not intended to be limited to the specific terminology so selected. A person skilled in the relevant art will recognize that other equivalent components can be employed and other methods developed without departing from the broad concepts of the current invention.

All references cited anywhere in this specification, including the Background and Detailed Description sections, are incorporated by reference as if each had been individually incorporated.

[0032] Some embodiments of the current invention are directed to a system which uses a coherent state of light to create a vortex superposition state in an exciton-polariton Bose-Einstein condensate (BEC) at room temperature. Light emitted by the exciton-polariton BEC can be detected and rotation of the system can be determined from the detected light. Some embodiments of the current invention are directed to a method for performing Sagnac interferometry using a room-temperature exciton-polariton BEC. The method can also be used for any type of metrology related to or based on the determination of a Sagnac phase.

[0033] Figure 1 is a schematic illustration of a room temperature exciton-polariton Sagnac interferometer 100 according to some embodiments of the invention. The room temperature exciton-polariton Sagnac interferometer 100 includes a light source 102, an orbital angular momentum superposition state of light component 104 configured to receive light from the light source 102 and output an orbital angular momentum superposition state of light, and a microcavity 106 configured to support an exciton-polariton BEC. The orbital angular momentum superposition state of light is transmitted through the microcavity 106 to induce a vortex superposition state in the exciton-polariton BEC. The room temperature exciton-polariton Sagnac interferometer 100 also includes a detector 108 configured to detect light emitted from the microcavity 106, and a processor 110 configured to determine a Sagnac phase based on the detected light. The exciton-polariton BEC can be formed in a potential permitting infinite effective mass polaritons.

[0034] According to some embodiments of the invention, the orbital angular momentum superposition state of light component 104 includes a spiral phase plate for generating a Laguerre-Gaussian (LG) laser mode from the light from the laser source. According to some embodiments of the invention, the orbital angular momentum superposition state of light component 104 further includes a Mach-Zehnder interferometer with a Dove prism for generating an orbital angular momentum superposition state from the LG laser mode. Alternatively, according to some embodiments of the invention, the orbital angular momentum superposition state of light 104 includes a cylindrical lens mode converter, a computer generated hologram, or any other device for generating an orbital angular momentum

superposition state of light for inducing a vortex superposition state in an exciton-polariton BEC.

[0035] A method for performing Sagnac interferometry using a room temperature exciton-polariton BEC according to some embodiments of the invention includes creating an orbital angular momentum superposition state of light, and inducing a vortex superposition state in the exciton-polariton BEC using the orbital angular momentum superposition state of light. The method further includes detecting light emitted from the exciton-polariton BEC, and determining a Sagnac phase based on the detected light.

[0036] According to some embodiments of the invention, room temperature indicates any temperatures between about 1 K and about 380 K. According to some embodiments of the invention, room temperature includes temperatures between about 273 K and about 310 K. According to some embodiments of the invention, room temperature includes temperatures between about 293 K and about 299 K.

[0037] Further concepts of the invention are described below with reference to particular examples. The general concepts of the current invention are not limited to the particular examples. Further, concepts from each example are not limited to that example, but may be combined with other embodiments of the system described herein.

[0038] EXAMPLES

[0039] Bose-Einstein condensation (BEC) was first achieved in dilute atomic gases in 1995 [1], which inspired a massive worldwide research effort into investigating its properties. Today, atomic BECs have potential for uses in a variety of fields, such as quantum simulation [2], quantum information [3], and quantum metrology [4]. Following this research effort, it has become apparent in recent years that a BEC of quasi-particles called polaritons can also be made [5]. Polariton BECs are formed in semiconductor microcavities [6], or planar dielectric Fabry-Pérot optical cavities [7], for example, and can be described as half-matter, half-light excitations that are reliably created using laser injection methods [8]. The terms “polaritons” and “exciton-polaritons” are used interchangeably herein.

[0040] Embodiments utilize laser injection methods to generate counter-rotating polariton BEC vortex superpositions using OAM states of light, although metastable condensation can be used to target higher angular momentum states using ring geometries. An alternative method of forming OAM superposition states in polariton BECs is via metastable condensation [36]. For example, a vortex superposition state can be induced in a periodic lattice via metastable condensation, wherein particular momentum modes are reinforced by using pumping profiles with target periodicity. This is another method for inducing vortex superpositions in a polariton BEC, and any other method for inducing a vortex superposition state in a polariton BEC can be used as well.

[0041] The interference pattern of the vortex superposition states can then be used to determine the Sagnac phase, for purposes of quantum metrology, etc. Polariton BECs (e.g., superfluids) can be achieved over a much larger range of temperatures, including much higher temperatures than typical BECs, for example, from about 1 nK to about 380 K, which is advantageous when considering construction of the Sagnac interferometer being developed. Superfluidity is the resistanceless flow of a fluid, and is fundamental to describing many fascinating physical effects. Such effects include the superfluid fountain [9], and the ability of a superfluid to creep up and defy gravity up and outside of containers. Other effects include the superfluid's ability to resist rotation while inside a rotating container. While many substances have been observed to undergo superfluidity (e.g., Helium-4, atomic BECs), typically these substances need to be cooled to temperatures near absolute zero (i.e., zero Kelvin).

[0042] Superconductivity can be regarded as a charged superfluid, where the bosonic particles (or Cooper pairs in this case) are charged [10]. For superconductors, the highest critical temperature attained has been 138K [11]. On the other hand, polaritons maintain the capability of attaining even higher critical temperatures, due to their exceedingly light effective mass (i.e., $\sim 10^{-5} m_e$ electron masses). Consequently, this opens the doorway for new quantum technologies based on room-temperature superfluidity [12], including a polariton Sagnac interferometer [13].

[0043] The benefits of embodiments of the present invention are not limited to quantum metrology applications, since it has been demonstrated that these OAM superposition states can also serve as a quantum memory for OAM photonic qubits [14]. It is well known that an efficient method for transferring the OAM of light to an atomic BEC can involve a process

known as Stimulated Raman Adiabatic Passage (STIRAP) [15]. Moreover, it has recently been demonstrated that solitary waves (i.e., solitons) can be produced in BEC matter waves [16]. During this process, the OAM is transferred to a BEC matter wave in a system of coherent quantum states [17]. For example, OAM photonic qubits could be used to construct a “quantum computer.”

[0044] In order to overcome some of the challenges associated with optical and atomic interferometers, embodiments employ exciton-polaritons, which can form a BEC at room temperature. This provides us a configuration for achieving a matter wave gyroscope (Sagnac interferometer) at temperatures, sensitivities, stabilities, and affordability that have not yet been realized. Moreover, the exciton-polariton BECs can be formed in semiconductor microcavities [6], or planar dielectric Fabry-Perot optical cavities [7], for example, which enables the construction of a Sagnac interferometer of minimal area and maximal sensitivity.

[0045] The components of the room temperature exciton-polariton Sagnac interferometer and methods of performing Sagnac interferometry according to some embodiments of the invention are now described in more detail. According to some embodiments of the invention, an orbital angular momentum (OAM) superposition state of light is used to induce a vortex superposition state in an exciton-polariton BEC. However, the concepts of the invention are not limited to this state of light, or this method of generating vortex superposition states in exciton-polaritons BECs. For example, it has been shown that a high-resolution spatial light modulator can be used to phase-shape a pump laser into a desired intensity pattern on a polariton condensate [59]. Other means of obtaining a coherent state of light are also possible.

[0046] Figure 2 illustrates a method by which an orbital angular momentum (OAM) state of light is generated according to some embodiments of the invention. The lowest order transverse electromagnetic (TEM) mode 200, or Gaussian laser beam, is crossed through a spiral phase plate (SPP) 202 to generate a pure Laguerre-Gaussian (LG) laser mode 204, $|l\rangle$. Other methods can be used to create the LG laser mode 204, for example, methods utilizing cylindrical lens mode converters and computer generated holograms, and any other device that can create a LG laser mode. Figure 2 shows a system in which the number of nonaxial radial nodes $p=0$. However, this value is purely exemplary, and p is not limited to this value.

[0047] Laser light with a Laguerre-Gaussian (LG) amplitude distribution has a well-defined orbital angular momentum (OAM), quantized as an integer value of $l\hbar$. According to some embodiments of the invention, in order to generate an OAM superposition state, pure LG mode states of light can be passed through a Mach-Zehnder optical interferometer which includes a Dove prism to change the handedness of the beam. Figure 3 shows a Mach-Zehnder interferometer 300 according to some embodiments of the invention. The input LG laser mode $|l\rangle$ is incident upon an input beam splitter 302. The input beam splitter 302 is $|R^2|/|T^2|$, where R and iT are the reflection and transmission amplitudes, respectively. The portion of the beam reflected by the first beam splitter 302 reflects off of a first mirror 304 and travels through a phase shifter $e^{i\phi}$ 306 to a second beam splitter 308. The portion of the beam transmitted by the first beam splitter 302 passes through a Dove prism 310 is reflected off a third mirror 312. The Dove prism 310 changes the handedness of the LG mode from $|l\rangle$ to $|-l\rangle$. By setting $\phi = \pi$ and discarding the output at the port 314, the OAM superposition state $T|l\rangle + R|-l\rangle$ is obtained at the output port 316. According to some embodiments, the second beam splitter is 50:50, and the mirrors 304 and 312 are effectively purely reflective. The Mach-Zehnder interferometer 300 shown in Figure 3 is merely one configuration of an interferometer, and other configurations may also be used to create an OAM superposition state of light. For example, the components may be rearranged, and additional or different components, for example, additional mirrors and beam splitters, may be added. Further, other methods may be used to create a coherent state of light. A variant of the vortex-antivortex superposition state is to use counter-propagating currents in ring geometries, where the polariton condensate is placed in a narrow potential, for example.

[0048] Upon exiting the interferometer, the pure LG mode will have been converted to an OAM superposition state of light. This superposition state of optical orbital angular momentum of light will then be transferred to a BEC of exciton-polaritons inside a distributed Bragg reflector (DBR) microcavity or any other configuration permitting a polariton BEC. Reference [7] describes the creation of a non-equilibrium BEC of exciton-polaritons in a microcavity at room temperature. The microcavity provides an environment for Bose-Einstein condensation of exciton-polaritons to occur. Figure 4 is a schematic illustration of microcavity polaritons. Strong interactions between confined photons and quantum-well excitons lead to quasiparticles known as microcavity polaritons, made of fermionic particles such as electrons 400 and holes 402, and photons 404.

[0049] According to some embodiments of the invention, the DBR microcavity comprises a spin-cast polymer, methyl-substituted ladder-type poly(para-phenylene) (MeLPPP). Figure 5 illustrates an OAM superposition state of light 500 being pumped into the DBR microcavity 502. The DBR microcavity 502 comprises a layer of fused silica 504, followed by alternating layers of tantalum pentoxide (Ta_2O_5) 506 and silicon dioxide (SiO_2) 508. The DBR microcavity 502 further comprises a layer of MeLPPP 510 in the central anti-node of the optical field. The MeLPPP layer 510 can have a lattice permitting infinite effective mass polaritons or a trapping potential to contain the polariton BEC, although this is not required. A room-temperature exciton-polariton BEC can be formed in the lattice. The exciton-polariton BEC can be excited through the substrate by discrete or continuous pulses of the OAM superposition state of light 500, and luminescence 512 can be collected from the top of the DBR microcavity 502. The luminescence 512 will include the interference pattern of the counter-rotating vortex superposition states which can then be used to determine the Sagnac phase of the laboratory frame of reference. A laser can be used to pump the DBR microcavity to provide the hot polaritons for condensation.

[0050] Figure 6 is a schematic diagram of the room temperature exciton-polariton Sagnac interferometer according to some embodiments of the invention. A light source 600 such as a laser diode is used to generate a Gaussian beam profile (i.e., TEM_{00}). This light is passed through a spiral phase plate (SPP) 602, generating an orbital angular momentum (OAM) state of light. Once the OAM state of light has travelled through the Mach-Zehnder interferometer 604 with a Dove prism 606, an OAM superposition state of light is made. An absorber 608 can absorb the light that is not directed to the distributed Bragg reflector (DBR) microcavity 610. The remaining light, which is an OAM superposition state of light, can be used to generate an interference pattern in a polariton BEC matter wave within the DBR microcavity 610. A laser 612 can be used to pump the DBR microcavity to provide the hot polaritons for condensation, or to engineer the condensate (e.g., rotate the condensate or slow it down). For example, a $\lambda=755$ nm Ti:Sapphire laser may be used to pump the DBR microcavity. Other lasers or light sources having different wavelengths may also be used. The interference pattern can be imaged by a detector 614, and can then be used by a processor to determine the Sagnac phase, or rotational rate of the polariton BEC, effectively making it a quantum inertial sensor. Many different type of detectors may be used to image the interference pattern, and examples include an Si CCD, a 0.55-m monochromator with a nitrogen-cooled CCD, and a streak camera, though the detector 614 is not limited to these examples.

[0051] Figure 7 is a schematic diagram of a Sagnac interferometer including a STIRAP implementation, similar to that used for ultracold atoms. An OAM superposition state 700 is transferred to an exciton-polariton BEC in a MeLPPP layer 702 of a DBR microcavity 704. The light 706 exiting the DBR microcavity 704 is detected, and a Sagnac phase can be determined from the interference pattern of the detected light 706. A laser can be used to pump the DBR microcavity to provide the hot polaritons for condensation.

[0052] The OAM superposition in the BEC amounts to counter-rotating matter-wave currents causing the density profile of the BEC to become an interference pattern. An alternative method of forming the superposition states is via metastable condensation [36]. The phase accumulated over a given time duration can be calculated using the prescription of the optical Sagnac effect, except now the area of the interferometer is one the order of the size of the condensate, and the Sagnac phase is independent of the area of the BEC and the mass of the particles involved. The Sagnac phase can be detected from the density profile of the BEC, which is detected by a photodetector that collects the light exiting the distributed Bragg reflector configuration, or any other configuration permitting an exciton-polariton BEC. This enables a matter wave Sagnac interferometer at room temperature with minimal area requirements, and in some cases, no area requirements. Following the rotation of an imaginary line drawn in the dark region of the interference pattern in the density profile allows determination of the angular velocity of the laboratory frame of reference. Moreover, by taking one half the curl of the angular velocity, ground velocity measurements can be obtained for purposes of seismology. This permits a seismometer operational at quantum sensitivities.

[0053] For an optical Sagnac interferometer, the phase in one loop is $\phi = \frac{8\pi A_{\text{loop}} \Omega}{\lambda c}$ where the λ is the wavelength of the light, Ω is the angular (rotational) velocity, c is the speed of light, and A_{loop} is the area of the Mach-Zender interferometer. In contrast, the polariton gyroscope indeed does not depend on the mass and is simply $\phi(t) = 2 l \Omega t$, where l is the angular momentum number. This is because the phase around a vortex is fixed no matter what path one takes around the vortex core. There is no mass dependence, because this is topologically fixed. This is also why there is no area dependence to this formula. This is actually no different from the atomic BEC case, because a vortex exists in either case, and mass does not enter, although polariton BECs are achievable at room temperatures, and allow for a compact device design.

[0054] Assuming that the interferometer rotates about a z-axis, the Sagnac phase accumulated is given by

$$\phi_{\Omega}(t) = 2l\Omega t, \quad (1)$$

where l is a positive integer representing the winding number, Ω is the angular velocity of the interferometer, and the accumulated phase occurs in time t . Since the angular velocity $\vec{\Omega}$ is proportional to the ground velocity $\vec{v}$,

$$\vec{\Omega} = \frac{1}{2} \nabla \times \vec{v}, \quad (2)$$

the seismometer can detect the ground velocity from the Sagnac phase according to

$$\phi_{\Omega}(t) = 2lt \left(\frac{1}{2} \nabla \times \vec{v} \right). \quad (3)$$

The determination of the Sagnac phase and the calculation of the ground velocity can be performed by a processor in communication with the detector that detects light emitted from the DBR microcavity. The processor can be configured to determine the Sagnac phase and the ground velocity based on the light detected by the detector.

[0055] According to some embodiments of the invention, the room-temperature exciton-polariton interferometer includes multiple DBR microcavities and photodetectors. For example, an interferometer with three DBR microcavities oriented orthogonally to one another can be used to detect rotational and linear motion in three dimensions. Each DBR microcavity can be used to detect motion along a principle axis. A processor can be in communication with three detectors detecting the interference pattern of light exiting the three DBR microcavities. The processor can use the information from the three detectors to provide rotational and/or ground velocity information in three dimensions. Accordingly, the system can function as a gyrometer, a gravity wave detector, and many other types of detectors, or as an alternative to global positioning systems.

[0056] The preparation and detection of the vortex superposition state in the polariton-exciton BEC according to some embodiments of the invention are now described in more detail. -According to some embodiments of the invention, OAM superposition states of light can be generated by passing a TEM₀₀ beam mode through a spiral phase plate (SPP), followed by a Mach-Zehnder interferometer with a Dove prism. The SPP converts the TEM₀₀ beam

mode to a Laguerre-Gaussian (i.e., $LG_{p,l}$) beam mode of quantized OAM with quantum numbers p and l , and the Dove prism changes the winding of the quantized OAM from $\ell\hbar$ to $-\ell\hbar$. OAM beams have a phase structure that is characterized by the quantized OAM carried by each photon in the beam, $\ell\hbar$.

[0057] The sign of the OAM governs the rotation, and an OAM state with angular momentum $l\hbar$ will have $|l|$ azimuthal phase jumps along a cross section of the beam path. Moreover, the beam structure is time-dependent, meaning that it rotates along the beam axis in a clockwise or counterclockwise direction during propagation, depending on the sign of l . Circularly polarized beams maintain angular momentum, or spin [18], similar to the linear and angular momentum of electromagnetic waves [19]. Along the direction of propagation, light beams with helical wavefronts (e.g., $LG_{p,l}$) have integer quantized OAM [20], which are routinely made via spiral phase plates [21], cylindrical lens mode converters [22], and computer generated holograms [23].

[0058] It has been demonstrated that $LG_{p,l}$ beams are solutions of the paraxial wave equation in cylindrical coordinates [24]. Following this reasoning, the scalar Helmholtz's equation in the paraxial wave approximation is

$$\nabla_t^2 u(\mathbf{r}, z) = -2ik\partial_z u(\mathbf{r}, z), \quad (4)$$

where $k = n\omega / c$ is the wave number, n is the index of refraction of the medium, ω is the angular frequency, and c is the speed of light. It should be pointed out that $\nabla_t^2 = \frac{1}{r^2} \frac{\partial^2}{\partial \phi^2} + \frac{1}{r} \frac{\partial}{\partial r} r \left(\frac{\partial}{\partial r} \right)$, and $LG_{p,l}$ beam modes form a complete orthonormal basis set of solutions for paraxial light beams commonly found in lasers. These modes can be expressed as [20]

$$u_{lp}^{LG}(r, \phi, z) = \sqrt{\frac{2p!}{\pi w^2(z)(|l| + p)!}} \left[\frac{\sqrt{2}r}{w(z)} \right]^{|l|} \exp \left[\frac{-r^2}{w^2(z)} \right] L_p^{|l|} \left(\frac{2r^2}{w^2(z)} \right) \cdot \exp \left[-i \left(\frac{kr^2}{2R(z)} + l\phi - \varphi(z) \right) \right], \quad (5)$$

where the radius of the beam squared is $w^2(z) = 2(z^2 + b^2)/kb$, the radius of curvature is $R(z) = (z^2 + b^2)/z$, the Gouy phase $\varphi(z) = (2p + |l| + 1) \tan^{-1}(z/b)$, b is the Rayleigh range, k is the wave number, and $L_p^{|l|}(r)$ describe the Laguerre polynomials,

$$L_p^{[l]}(r) = \sum_{m=0}^p (-1)^m \frac{(l+p)!}{(p-m)! (|l|+m)! m!} r^m. \quad (6)$$

In Eqs. (5) and (6), p is the number of nonaxial radial nodes, and the index l is known as the winding number. The winding number describes the helical structure of the wavefront and the number of times the phase jumps occur around the beam path in the azimuthal direction. When $l = p = 0$, the $LG_{p,l}$ beam is identical to the fundamental Gaussian beam, or TEM_{00} .

[0059] Utilizing the operator algebra of quantum mechanics, the higher order modes can be calculated using the operator algebra formalism [25]. Analogous to the two-dimensional quantum harmonic oscillator [26, 27], at $z = 0$,

$$\hat{A}_x(0) = \frac{1}{\sqrt{2bk}} (kr \cos(\phi) + b \cos(\phi) \partial_r - br \sin(\phi) \partial_\phi), \quad (7)$$

and

$$\hat{A}_y(0) = \frac{1}{\sqrt{2bk}} (kr \sin(\phi) + b \sin(\phi) \partial_r + br \cos(\phi) \partial_\phi). \quad (8)$$

These operators can be evolved in the z -direction by a propagator $\hat{U}(z)$ for $\partial_\phi \partial_r = \partial_r \partial_\phi$ like

$$\begin{aligned} \hat{U}(z) &= \exp \left[-\frac{i}{2k} \widehat{P^2} z \right] \\ &= \exp \left[-\frac{i}{2k} (\partial_r^2 + r^2 \partial_\phi^2) z \right]. \end{aligned} \quad (9)$$

Next, Eqs. (7) and (8) can be rewritten as

$$\hat{A}_x(z) = \hat{U}(z) \hat{A}_x(0) \hat{U}^\dagger(z), \quad (10)$$

$$\hat{A}_y(z) = \hat{U}(z) \hat{A}_y(0) \hat{U}^\dagger(z), \quad (11)$$

where

$$\begin{aligned} \hat{A}_\pm(z) &= \frac{1}{\sqrt{2}} [\hat{A}_x(z) \mp i \hat{A}_y(z)] \\ &= \frac{1}{2\sqrt{bk}} [kre^{\pm i\phi} + (be^{\pm i\phi} + 2ze^{\pm i\phi})(\partial_r + r\partial_\phi)]. \end{aligned} \quad (12)$$

The operators in Eq. (12) obey the commutation rules

$$[\hat{A}_+(z), \hat{A}_+^\dagger(z)] = 1, [\hat{A}_+(z), \hat{A}_-^\dagger(z)] = 0. \quad (13)$$

Higher-order LG_{*p,l*} beam modes can be obtained from operating on the TEM₀₀ like [26]

$$u_{l,p}^{\text{LG}}(z) = \sqrt{\frac{1}{m!n!}} [\hat{A}_+^\dagger(z)]^n [\hat{A}_-^\dagger(z)]^m \text{TEM}_{00}(z), \quad (14)$$

where $m = (l + p)/2$ and $n = (l - p)/2$. The OAM states $u_{l,p}^{\text{LG}}(z)$ and $u_{-l,p}^{\text{LG}}(z)$ differ only in the direction of the phase winding, that is, clockwise or counterclockwise, respectively. For purposes of demonstration, $p=0$ in the present calculations, but other values of p can also be used.

[0060] Polariton interferometry based on vortex superposition states may require a particular kind of superposition of counter-rotating angular momentum states. The bosonic annihilation operator for the mode that occupies Eq. (14) is denoted as $a_{l,p}$. Then the superposition state is $\alpha a_{l,p} + \beta a_{-l,p}$, where $|\alpha|^2 + |\beta|^2 = 1$. This is because the OAM superposition state of light has two counter-rotating components which will induce an interference pattern in the polariton BEC. Once the characteristic interference of the OAM superposition (e.g., consisting of $2l$ lobes) has been transferred to the polariton BEC, the Sagnac phase can be determined from the angular velocity of the BEC cloud. An ordinary vortex state can be obtained by setting either α or $\beta = 0$.

[0061] Many lasers (i.e., optical resonators) emit light beams which approximate a Gaussian profile, or in other words, a solution to Eq. (4). Following this idea, the TEM₀₀ fundamental transverse mode of the optical resonator can be channeled through a SPP, for example, to generate OAM states of light as seen in Eq. (14). This is illustrated in Figure 2. Although OAM states can also be made with holographs, etc., SPPs offer a simple and convenient way to obtain a pure OAM state $u_{l,p}^{\text{LG}}(z)$ with arbitrary integer l . Moreover, once the pure state $u_{l,p}^{\text{LG}}(z)$ has been obtained, an OAM superposition state can be generated. This can be accomplished using a Mach-Zehnder type of configuration as seen in Figure 3, where the Dove prism is used to transform the $u_{l,p}^{\text{LG}}(z)$ state into a $u_{-l,p}^{\text{LG}}(z)$ state to obtain $(a_{l,p} + a_{-l,p})/\sqrt{2}$ at the real output of the Mach-Zehnder interferometer. If desired, one may choose the first beam splitter as an $\alpha : \beta$ beam splitter, and the second one as a 50 : 50 beam splitter to

obtain an arbitrary superposition of the type $\alpha a_{l,p} + \beta a_{-l,p}$. The second beam splitter is not limited to a 50 : 50 beam splitter, and beam splitters with other transmission-to-reflection ratios may be employed, for example, from about 80:20 to about 20:80. As seen in Figure 6, according to some embodiments of the invention, the two inputs of the first beam splitter are prepared in a coherent state in the LG mode $a_{l,p}$ and the vacuum state, respectively. Hence,

$$a_{\text{IN}} = a_{l,p}. \quad (15)$$

Assuming that the first beam splitter being used is a symmetric 50:50 beam splitter, the OAM state of light has transformed like

$$a_{\text{IN}} = a_{l,p} \mapsto \frac{1}{\sqrt{2}} (b_{l,p} + c_{l,p}), \quad (16)$$

where $b_{l,p}$, $c_{l,p}$ denotes the LG modes in the two arms of the interferometer. The phase shift in the upper arm of the Mach-Zehnder interferometer will cause the coherent amplitude to be replaced by $a_{l,p} \mapsto e^{i\phi} a_{l,p}$, and the Dove prism in the lower arm of the Mach-Zehnder interferometer will cause the coherent amplitude to be replaced by $b_{+l,p} \mapsto b_{-l,p}$. Hence, the OAM state of light seen in Eq. (16) becomes

$$\frac{1}{\sqrt{2}} (b_{l,p} + c_{l,p}) \mapsto \frac{1}{\sqrt{2}} (e^{i\phi} b_{l,p} + c_{-l,p}). \quad (17)$$

[0062] Finally, neglecting the imaginary output of the interferometer, the second beam splitter reverses the transformation and produces the OAM superposition state of light, written as

$$a_{\text{OUT}} = \frac{1}{\sqrt{2}} (a_{+l,p} + e^{i\phi} a_{-l,p}). \quad (18)$$

The superposition of $a_{l,p}$ and $a_{-l,p}$ states in Eq. 18 can be detected using many different techniques, which typically include imaging the interference pattern of the light beams which constitute the superposition state. In particular, once a polariton BEC is induced, an imaging device such as a charge-coupled device (CCD), a complementary metal-oxide-semiconductor (CMOS), and standard near and far-field methods may be used to analyze the coherent condensate state in the polariton microcavity, where the polariton BEC is achieved in a lattice

permitting infinite effective mass polaritons, or any other configuration permitting vortex superposition states of a polariton BEC.

[0063] The laser injection methods of the previous section can be used to resonantly excite the polariton BEC. The phase of the light is directly imprinted on the polariton BEC system, hence the injected polaritons simply follow the same phase relation as the injected light. In this configuration, there is no difference between the interference patterns of the OAM superposition state in light and the vortex superposition state in the polariton BEC, as the polaritons inherit their vortex nature from the light. However, once the initial coherent excitation is induced, the OAM superposition is turned off, and the microcavity system is excited by conventional polariton pumping. This can be performed by an off-resonant pumping where the excitons have a much higher energy than the polaritons, or by pumping at high in-plane momenta (see Fig. 1b in Ref. [60]). Either method creates a large population of uncondensed polaritons from which the polariton BEC is replenished. It is important to note that apart from the initial seed polariton BEC which is induced coherently, the remaining population thereafter is not pumped with the OAM superposition state. Hence, in the second phase in which the conventional polariton BEC pumping is used, any OAM superposition state is a genuine steady state of the polariton BEC, and possesses its own dynamics.

[0064] While vortices and vortex-antivortex pairs have been shown theoretically and experimentally to be stable configurations of polariton BECs [61], [62], whether or not a superposition is a stable configuration is a non-trivial problem. Such vortex-antivortex superpositions have a more complex phase relation than standard vortex configurations, and have the possibility to spontaneously separate spatially, or relax to a zero momentum state. To investigate this, the vortex-antivortex superposition is described herein in a variety of different circumstances to evaluate its stability. Polariton BECs are a non-equilibrium phenomenon achievable at room temperatures via semiconductors [28], or planar dielectric Fabry-Pérot microcavity configurations [7], among others. The spatiotemporal evolution of the non-equilibrium exciton-polariton system can be described by the open-dissipative Gross-Pitaevskii equation (dGPE), expressed as [10]

$$i\frac{\partial\psi(\mathbf{x},t)}{\partial t} = \left[-\frac{\hbar}{2m}\nabla^2 + V_{\text{ext}}(\mathbf{x}) + g|\psi(\mathbf{x},t)|^2 + \frac{i}{2}(P(\mathbf{x}) - \gamma - \eta|\psi(\mathbf{x},t)|^2) \right] \psi(\mathbf{x},t), \quad (19)$$

where $\psi(\mathbf{x}, t)$ is a complex valued condensate order parameter, g is the polariton-polariton interaction constant, m is the polariton mass, V_{ext} is a spatially dependent potential energy, $P(\mathbf{x})$ is the pumping rate, γ is the polariton loss rate, and η is the gain saturation [29, 30].

[0065] The stability of the vortex-antivortex superposition in a variety of different potential landscapes is now described. The Generalized Finite-Difference Time-Domain (G-FDTD) scheme is explicit and permits an accurate solution with simple computation for solving Eq. (19) in multiple dimensions. To this end, the function $\psi(\mathbf{x}, t)$ is first split into real and imaginary components resulting in two coupled equations. The real and imaginary components are then approximated using higher-order Taylor series expansions in time, where the derivatives in time are then substituted into the derivatives in space via the coupled equations. Finally, the derivatives in space are approximated using higher-order finite difference methods. The G-FDTD has been successfully applied for solving both linear and nonlinear Schrödinger equations.

[0066] To better understand how a vortex state, or vortex-antivortex superposition behaves in a basic way, it is instructive to examine the non-equilibrium states as seen in Eqs. (18) and (19) in the absence of a potential energy (i.e., $V_{ext}=0$). Non-equilibrium BEC is particularly important to investigate in this context owing to the question of stability. The quantum interference must exhibit coherence for it to be used for interferometry.

[0067] Figures 8A-8E show a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a flat potential landscape, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at (A) $t = 0$, (B) $t = 0.25$, (C) $t = 0.5$, (D) $t = 0.75$, and (E) $t = 1.0$. It can be seen from Figures 8A-8E and 9A-9E that in the absence of a confining potential, the vortex superposition state of the non-equilibrium BEC is stable and coherent. This vortex superposition state can be generated in a distributed Bragg reflector, as shown in Figure 6, though other configuration for creating the BEC state are also possible.

[0068] Figures 8A-8E also illustrate the phase of the two-dimensional vortex superposition non-equilibrium condensation a flat potential. The phase ranges from $-\pi$ to π . It can be seen that the vortex superposition state tends to become trapped around $t=1$, indicating a steady-state non-equilibrium BEC. As the vortex superposition state consists of lobes, the Sagnac phase can be determined from the rotation of the lobes about an axis of rotation.

[0069] Figures 9A-9E show a real space (upper plot) and phase (lower plot) simulation of a non-equilibrium Bose-Einstein condensate vortex superposition state in a disordered potential landscape, where the G-FDTD scheme was employed with $P(r)=P_0 e^{-\left(\frac{r}{r_0}\right)^2}$, where $P_0 = 2$, $r_0=5.35$, $g = \gamma = \eta = 1$ at (A) $t = 0$, (B) $t = 0.25$, (C) $t = 0.5$, (D) $t = 0.75$, and (E) $t = 1.0$. Upon examination of Figures 9A-9E, it can be seen that in the presence of a disordered potential, the vortex superposition state is coherent and stable. From the phase plots in Figures 9A-9E, it can be seen that the vortex superposition state tends to become trapped around $t=1$, indicating a steady-state non-equilibrium BEC.

[0070] A vortex-antivortex superposition in a two-dimensional (2D) periodic potential, for example, a Kagome lattice, is now described. A 2D Kagome lattice, or a basketweave lattice [31], consists of interlaced triangles and exhibits a higher degree of frustration when compared with other 2D lattices (e.g., square and triangular lattices) [32]. In the tight-binding limit with only nearest-neighbor tunneling, a 2D Kagome lattice geometry possesses a completely flat band. In such a flat band, the polariton condensate order parameters become tightly localized at the potential dips [33]. The curvature of the band gives the effective mass, and for infinite mass there is zero curvature (i.e., $E = \hbar^2 k^2 / 2m$).

[0071] Large effective masses can be advantageous in terms of Sagnac interferometry, as they can increase the measurement sensitivities. In practice it can be difficult to achieve a perfectly flat band, because the next-nearest neighbor tunneling on the Kagome lattice would have to be zero. For realistic implementation, the tunneling would be present to some degree. However, it is possible to achieve heavy particles (effectively) while still having the room temperature condensation. Further, it has recently been demonstrated that it is possible to achieve infinite effective mass polaritons in a micropillar microcavity [58]. Several schemes have been proposed to create flat bands in the 2D Kagome lattice, utilizing metallo-photonic waveguides [34], photonic crystal structures [35], or depositing a thin metal film [36, 37, 38, 39].

[0072] The energy band structure and wavefunctions of states in a Kagome lattice can be calculated using a plane wave expansion of the potential. A Kagome lattice potential V_{ext} can be described as

$$V_{ext} = V_0 \left| f_1(\mathbf{x}) e^{ik_0 \mathbf{b}_1 \cdot \mathbf{x}} + e^{ik_0 \mathbf{b}_2 \cdot \mathbf{x}} + e^{ik_0 \mathbf{b}_3 \cdot \mathbf{x}} \right|^2, \quad (20)$$

where $f_1(\mathbf{x}) = e^{ik_0 p x / (1+4p/3)} \cos(k_0 p x / (1+4p/3))$, $\mathbf{b}_1 = (1/(1+4p/3), 0)$, $\mathbf{b}_2 = (-1/(2+8p/3), -\sqrt{3}/2)$, $\mathbf{b}_3 = (-1/(2+8p/3), \sqrt{3}/2)$, $V_0 > 0$ is the lattice intensity, k_0 is a scalar quantity proportional to the lattice constant, and $p \rightarrow 3/2$ [40, 41]. The above potential is implemented in the open-dissipative Gross-Pitaevskii Eq. (19), and evolved forward in time starting from a resonantly induced vortex-antivortex superposition state.

[0073] Discussed now are the numerical results for the time evolution of the polariton BEC in a Kagome lattice potential. Following Eqs. (19) and (20), the non-equilibrium exciton-polariton BEC are explained via solutions to the dGPE using the G-FDTD scheme for the 2D dGPE [42]. Taking $\mathbf{x} = (x, y)$, for densities near equilibrium

$$|\psi(x, y, t)|^2 = \frac{P(x, y) - \gamma}{\eta}, \quad (21)$$

the imaginary terms on the right hand side of Eq. (19) vanish and a zeroth order estimate can be obtained for solutions which are the same as those for the standard GPE [43]. Starting from this approximation, the numerics should converge towards the true solution for the dGPE, which will in general be different from the standard GPE result. It is assumed that the wavefunction in the z-direction has an insignificant effect on the vortex dynamics in the x-y plane.

[0074] A vortex superposition state in a Kagome lattice potential is now examined. The initial condition is chosen as

$$\frac{P(x, y) - \gamma}{\sqrt{2}\eta} (u_{l=1, p=0}^{\text{LG}}(x, y) + u_{l=-1, p=0}^{\text{LG}}(x, y)). \quad (22)$$

Figures 10A-10E illustrate the condensate density $|\psi(x, y, t)|^2$ of the two-dimensional vortex superposition at various times. Figures 10A-10E also illustrate the phase $a \tan 2[\psi(x, y, t)]$ of the two-dimensional vortex superposition non-equilibrium condensate in a Kagome lattice potential at various times.

[0075] Figures 10A-10E show that in the presence of a Kagome lattice, the vortex superposition state is coherent and stable. From the phase plots in Figures 10A-10E, it can be seen that the vortex superposition state tends to become trapped around $t=1$, indicating a steady-

state non-equilibrium BEC. In the presence of a Kagome lattice, it is probable that the polariton effective mass $m_{\text{eff}} \rightarrow \infty$. As the vortex superposition state consists of lobes, the Sagnac phase can be determined from the rotation of the lobes about an axis of rotation.

[0076] When optical Mach-Zehnder interferometers [44] occupy a large area A_{MZI} , they are typically capable of achieving an excellent rotational measurement sensitivity [45, 46]. Atomic matter wave interferometers can typically only achieve small loop areas and only short-time rotational sensitivities [47, 48]. However, atomic matter wave interferometers have the advantage that their de Broglie wavelength is much shorter than the wavelengths of their optical counterparts. This makes the rotational measurement sensitivity of atom-beam interferometers per unit area exceed that of optical ones by the ratio $mc^2 / \hbar\omega \sim 10^{10}$.

[0077] Typically polariton masses are extremely light, i.e., $m_{\text{eff}} \sim 10^{-4} m_e$, where m_e is the bare electron mass. This almost entirely negates the advantage of polaritons to $c^2 m_{\text{eff}} / \hbar\omega \sim 1$, which is the same level as light. This is not surprising as polaritons themselves are part-matter, part-light quasiparticles, and hence much of their characteristics are inherited from light. In terms of sensitivity, polaritons would appear to be ill-suited for such gyroscopic applications. However, it is now demonstrated herein that this argument in fact does not apply to vortex-antivortex superposition state polariton interferometers.

[0078] Typically, in an optical interferometer scheme, light of wavelength λ propagates in a closed loop. For each completed propagation in the closed loop configuration, the Sagnac phase is usually given by

$$\phi_{\Omega} = \frac{8\pi A_{\text{loop}} \Omega}{\lambda c}, \quad (23)$$

where the λ is the wavelength of the light, Ω is the angular (rotational) velocity, c is the speed of light, and A_{loop} is the area of the Mach-Zehnder interferometer. In contrast, in a BEC the phase around a vortex is fixed purely by the topological winding number. Thus independent of the path, a phase of $2\pi l$ is picked up around a vortex. For a fixed l , the path can in principle enclose an arbitrary area and yet will not pick up any additional phase. It is also independent of the de Broglie wavelength λ for the same reasons. Therefore, for a vortex-antivortex superposition, the Sagnac phase is independent of the area of the BEC and the mass of the

particles involved. As the Sagnac phase directly originates from the interference of two counter-rotating angular momentum, it follows that the Sagnac phase can then be written as

$$\phi_{\Omega}(t) = 2l\Omega t, \quad (24)$$

and can be determined from the Ω of the vortex superposition state in a polariton BEC.

[0079] There is another important difference between the vortex and optical Sagnac interferometers, which is that (23) is dependent on time while (24) is not. This means that as the system rotates, the optical Sagnac interferometer produces a shift in the fringes only when there is a rotation Ω , while the vortex Sagnac interferometer detects the total phase of the rotation. In a vortex Sagnac interferometer the fringes retain the original direction as the experimental apparatus rotates. The system is a quantum mechanical “gyroscope” in this sense. Therefore the longer one waits between comparisons of the interference fringes, the larger the angle difference, and therefore the sensitivity. This means that it is possible, in principle, to arbitrarily improve the sensitivities by increasing the time between measurements. This is in contrast to the optical Sagnac interferometer, where the sensitivity can be arbitrarily improved by increasing the loop area.

[0080] In general, higher sensitivities are achieved by the use of high momentum states due to their short wavelength allowing for high resolutions. A variant of the vortex-antivortex superposition state is to use ring geometries where the polariton condensate is placed in a circular narrow channel potential. In a BEC, high angular momentum states are energetically disfavored, and typically multi-quantized vortices break up into many $l = \pm 1$ vortices [42]. This can be understood to result from the high momentum states that are near the vortex core which have a rapid phase variation. By eliminating the vortex core with the use of a ring potential, high angular momentum states become more stable, which is beneficial from a sensitivity point of view.

[0081] It is now demonstrated that one can regain the area and wavelength dependence of Eq. (23) in a BEC to further improve the sensitivity. For the ring geometry considered above, the area and wavelength dependence is reinstated, as shown below. For the BEC case the Sagnac phase for polaritons can be written [51]

$$\phi_{\Omega}(t) = N(t) \frac{4mA_{\text{loop}}}{\hbar} \Omega. \quad (25)$$

where $N(t)$ is the number of times an atom revolves around the loop in a time t . In a ring geometry of radius r , the counter-propagating momenta $\pm k_0$ is

$$N(t) = \frac{\hbar k_0}{2\pi r m}. \quad (26)$$

This therefore gives

$$\phi_0(t) = 2k_0 r \Omega t. \quad (27)$$

[0082] Each polariton in the BEC cloud has the same magnitude of the angular momentum, which contributes to the signal to noise ratio as will be discussed below. The relation now has a boost in the sensitivity with the radius of the ring, which arises from the fact that the velocity of a wave with momentum k_0 has a value $v = \hbar k_0 / m$. This is in contrast to a vortex which decays with radius $v = \hbar l / mr$. The effect of a shorter de Broglie wavelength for atomic BEC is implicit in (27), as for heavy particles, the typical wavenumber $k_0 = 2\pi/\lambda$ is much higher, which also results in enhanced sensitivities. In this sense, the use of periodic potentials as discussed in the previous section can aid the sensitivity, as this produces effectively larger effective masses, and hence larger typical k_0 .

[0083] In order to be compatible with on-chip technology, in many cases a compact design is more practical (e.g., for use in mobile phones). Furthermore, the operation at room temperature gives the polaritons promise as a more practical alternative to matter wave gyroscopes that can be realized in a compact device. Other advantages that polaritons possess is that they are effectively static in space, so no separate interference is required to perform the gyroscopic measurement. Unlike that of the optical interferometer, the area of the polariton interferometer is given by the area of the polariton BEC cloud, which is on the order of several μm^2 . By implementing a polariton BEC of vortex superpositions, the need for large loop areas can be bypassed, as the area of the polariton BEC (i.e., A_{BEC}), will act as the loop area. Moreover, the short-time rotational sensitivity problem can be overcome as vortex superposition states in BECs are stable and will not decay [49]. Additionally, different materials which change the phase velocity of light have no effect on the Sagnac phase shift [50].

[0084] As a gyroscope requires angular velocity information from three real spatial dimensions, inertial sensing applications may require the use of three polariton interferometers working in tandem, one along each real spatial dimension (i.e., x , y , and z). It should again be pointed out here that A_{BEC} is typically on the order of μm^2 , whereas the area of a typical atom beam interferometer is on the order of several m^2 [52].

[0085] As aforementioned, it is possible to generate an arbitrary two-component vortex superposition state in a polariton using OAM superposition states of light, or metastable condensation, for example. The Sagnac phase can then be written as in (24), and can be determined from the Ω of the vortex superposition state in a polariton BEC. The phase structures of OAM superposition states in light and vortex superpositions in polariton BECs are identical. However, by using vortex superposition states of polariton BECs rather than just the OAM superposition states of light alone, the effective de Broglie wavelength can be tuned [53], and a more efficient room-temperature Sagnac phase measurement can be obtained [8]. Condensation of polaritons in flat bands have been observed [63], which by definition are in the ideal case localized and have an infinite mass [8]. In practice, deviations from the nearest neighbor hopping in models such as the Kagome lattice will give rise to a curvature of the flat band, but such bands typically still have a relatively heavy mass.

[0086] The Kagome lattice is not the only potential that allows for the flat bands in which polaritons have an infinite effective mass. For example, a honeycomb or similar lattice potential may be incorporated to obtain the effective mass that approaches infinity. It has recently been shown that on a honeycomb lattice for polaritons made of hundreds of coupled micropillars etched in a planar semiconductor microcavity, there exists a nondispersive band in which polaritons have an infinite effective mass.

[0087] When the laboratory frame rotates in time, the two counter-rotating matter waves pick up different phases, and the transverse density profile at $z = 0$ is given as $(1 + \cos[2l(\phi + \Omega t)]) |\psi(x, t)|^2$, or for the case of a ring geometry, $(1 + \cos[2k_0 r(\phi + \Omega t)]) |\psi(x, t)|^2$, signifying a rotation of the interference pattern by an angle $\phi_{\Omega}(t)/(2|l|)$ as the Sagnac phase accumulates over time. Following the rotation of an imaginary line drawn in the dark region of the interference pattern, one may determine the angular velocity Ω from the density profile of the polariton BEC. Figure 11 shows an example of an interference pattern having light regions and dark regions. As the laboratory frame rotates

in time, the interference pattern also rotates, as depicted by the arrow in Figure 11. The angle of rotation can be measured and used to determine the Sagnac phase, or any other quantity related to the Sagnac phase. Although $l=3$ in Figure 11, l and p can take any integer value.

[0088] Determining the Sagnac phase using the polariton Sagnac interferometer disclosed herein will depend on the vortex charge ℓ of the polariton BEC superposition state. Owing to the fact that spiral phase plates (SPPs) generally work well for low integer values of l , embodiments disclosed herein have set $l = 1$. However, in principle, l can take on any integer value, although $l = 1$ generally permits a more stable vortex superposition.

[0089] Embodiments of the polariton Sagnac interferometer are based on imaging the standing wave of the polariton BEC, which is comparably much smaller than the area occupied by comparable optical technologies (e.g., ring-laser gyroscopes). Light carrying OAM allows coherent vortices in polariton BECs to be generated, and once a vortex superposition is created, the condensate density will show an interference pattern determined by the phase difference between the amplitudes and charges of the two vortex components. This allows the polariton BEC to be used for the measurement of changes in the Sagnac phase caused by the rotation of the laboratory frame of reference (i.e., the interferometer itself).

[0090] It has been demonstrated that vortex-antivortex superpositions in atomic BECs can be achieved experimentally [55], although OAM superpositions [56] of the non-equilibrium polariton systems have not been found in literature. However, OAM vortex states of polariton condensation have recently been seen experimentally [57, 59], and a flatband in a Kagome lattice has been achieved for polaritons [58]. For typical matter wave interferometer schemes, it is not unusual for the apparatus setup to be overly complex, owing to the number of mirrors and beam splitters required. In order to overcome this obstacle, embodiments use polariton BEC superposition states as the Sagnac interferometer. By exposing DBR microcavities to optical beam pulses, the OAM can be transferred from the light field to the matter wave, inducing an OAM state of polariton condensation. The measurement precision of the interferometer will depend on how well the angular velocity is measured, which is accomplished by imaging the phase contrast of the polariton BEC cloud densities. According to some embodiments of the invention, a charge-coupled device (CCD) or another similar technology can be used at the output location of the device, as shown in Figure 6.

[0091] For an optical Sagnac interferometer, the phase in one loop is $\phi = \frac{8\pi A_{\text{loop}} \Omega}{\lambda c}$ where the λ is the wavelength of the light, Ω is the angular (rotational) velocity, c is the speed of light, and A_{loop} is the area of the Mach-Zender interferometer. In contrast, the polariton gyroscope indeed does not depend on the mass and is simply $\phi(t) = 2 l \Omega t$, where l is the angular momentum number. This is because the phase around a vortex is fixed no matter what path one takes around the vortex core. There is no mass dependence, because this is topologically fixed. This is also why there is no area dependence to this formula. This is actually no different from the atomic BEC case, because a vortex exists in either case, and mass does not enter.

[0092] Discussed now are the signal-to noise ratio (SNR) and the sensitivity achievable in such a polariton Sagnac interferometer. The SNR is given by the ratio of the rotational phase shift to the shot noise that depends on the number of photons N arriving at the CCD from the polariton condensate per second, $SNR = \phi_{\Omega}(t) / \sqrt{1/N}$ [52]. The final SNR has a maximum at a certain rate of photon detection, and the sensitivity $\Omega_{\min}$ is calculated by setting $SNR = 1$.

[0093] For the vortex-antivortex superposition we have [51]

$$\Omega_{\min} = 1/(2lt\sqrt{N}). \quad (28)$$

For the ring geometry,

$$\Omega_{\min} = 1/(2k_{\theta}rt\sqrt{N}). \quad (29)$$

[0094] Typical polariton densities are in the region of 10^{10} cm^{-2} , and for a polariton spot size of $100 \text{ } \mu\text{m}^2$ this gives a polariton number in the region of 10^5 . The lifetime of the polaritons is in the region of $\sim \text{ps}$, and hence it can be estimated that the number of signal photons is $N \sim 10^{17} \text{ s}^{-1}$ for polaritons. $\Omega_{\min}$ for the polariton vortex-antivortex superposition is then

$$\Omega_{\min} = 2 \times 10^{-9} \text{ rad s}^{-1} \text{ Hz}^{-1/2} \quad (30)$$

while for ring geometries

$$\Omega_{\min} = 2 \times 10^{-10} \text{ rad s}^{-1} \text{ Hz}^{-1/2}, \quad (31)$$

These are comparable to or exceeding state of the art atomic beam gyroscopes which are at the $10^{-9} \text{ rad s}^{-1} \text{ Hz}^{-1/2}$ level [47].

[0095] With regard to the stability of the polariton Sagnac interferometer described herein, it bypasses the beam drift that is a common cause of instability in the metrology that employs atomic or optical beams, and no complicated atomic beam configurations are required. The technical issues that optical Sagnac interferometers face, such as the short-time rotational sensitivity problem [49], and the change in phase velocity of light [50], are not present for polaritons by construction. Moreover, thermal expansion over atomic beam trajectories is not an issue for polariton BECs, as atomic beams are not needed. Interferometers which use atomic beams usually have beam drifts on the order of $\mu \text{ deg} / h$ after hours of running time [52].

[0096] Disclosed herein is a mechanism for inducing vortex superposition states in a polariton BEC via injection of orbital angular momentum (OAM) of light through a distributed Bragg reflector (DBR) microcavity. The vortex superposition states can also be induced in the polariton BEC via metastable condensation [36]. The transfer of a superposition of OAM of light to vortices, and the respective characteristic interference pattern in polariton BECs has been numerically simulated using the G-FDTD method [42]. Once the vortex superposition state is induced, it follows a free evolution under standard pump-loss dynamics of the polariton BEC. Thus the direct injection provides the initial seed state for the polariton BEC, and thereafter the vortex-antivortex state becomes a metastable state. Based on the numerical results, embodiments demonstrate how the superposition of counter-rotating currents in the polariton BEC could be used for determining the Sagnac phase, or angular velocity of an interferometer, effectively constituting a gyrometer, or seismometer, for example. The system can be used in a variety of applications, including, but not limited to, devices utilizing navigational systems, for example, mobile phones, drones, land and sea vehicles, etc. Some advantages offered by an interferometer based on superpositions of counter-rotating vortex structures include the tunability of the effective de-Broglie wavelength by obtaining room temperature polariton BECs within a DBR microcavity with a lattice permitting infinite effective mass polaritons. In particular, the angular velocity and phase sensitivity can be tuned via the choice of quantized angular momentum of the polaritons.

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[00161] The embodiments illustrated and discussed in this specification are intended only to teach those skilled in the art how to make and use the invention. In describing embodiments of the invention, specific terminology is employed for the sake of clarity. However, the invention is not intended to be limited to the specific terminology so selected. The above-described embodiments of the invention may be modified or varied, without departing from the invention, as appreciated by those skilled in the art in light of the above teachings. It is therefore to be understood that, within the scope of the claims and their equivalents, the invention may be practiced otherwise than as specifically described.

WE CLAIM:

1. A room temperature exciton-polariton Sagnac interferometer, comprising:
 - a light source;
 - an orbital angular momentum superposition state of light component configured to receive light from said light source and output an orbital angular momentum superposition state of light;
 - a microcavity configured to support an exciton-polariton Bose-Einstein condensate (BEC) wherein said orbital angular momentum superposition state of light is transmitted through said microcavity to induce a vortex superposition state in said exciton-polariton BEC;
 - a photodetector configured to detect light emitted from said microcavity; and
 - a processor configured to determine a Sagnac phase based on said detected light.
2. A room temperature exciton-polariton Sagnac interferometer according to claim 1, wherein said exciton-polariton BEC is formed in a potential permitting infinite effective mass polaritons.
3. A room temperature exciton-polariton Sagnac interferometer according to claim 2, wherein said potential permitting infinite effective mass polaritons is a two-dimensional Kagome lattice.
4. A room temperature exciton-polariton Sagnac interferometer according to claim 1, wherein said microcavity is a micropillar microcavity.
5. A room temperature exciton-polariton Sagnac interferometer according to claim 1, wherein said light from said light source is a Gaussian laser beam.
6. A room temperature exciton-polariton Sagnac interferometer according to claim 1, wherein said orbital angular momentum superposition state of light component comprises a spiral phase plate for generating a Laguerre-Gaussian (LG) laser mode from said light from said light source.
7. A room temperature exciton-polariton Sagnac interferometer according to claim 6, wherein said orbital angular momentum superposition state of light component further

comprises a Mach-Zehnder Interferometer with a Dove prism for generating an orbital angular momentum superposition state from said Laguerre-Gaussian (LG) laser mode.

8. A room temperature exciton-polariton Sagnac interferometer according to claim 1, wherein said orbital angular momentum superposition state of light component comprises a cylindrical lens mode converter for generating a Laguerre-Gaussian (LG) laser mode from said light from said light source.

9. A room temperature exciton-polariton Sagnac interferometer according to claim 1, wherein said orbital angular momentum superposition state of light component comprises a computer generated hologram for generating a Laguerre-Gaussian (LG) laser mode from said light from said light source.

10. A room temperature exciton-polariton Sagnac interferometer according to claim 1, wherein said microcavity is a distributed Bragg reflector (DBR) microcavity.

11. A room temperature exciton-polariton Sagnac interferometer according to claim 1, wherein said microcavity is a Fabry-Perot optical cavity.

12. A room temperature exciton-polariton Sagnac interferometer according to claim 1, wherein said microcavity is a semiconductor microcavity.

13. A room temperature exciton-polariton Sagnac interferometer according to claim 1, wherein said processor is configured to determine a ground velocity of said microcavity based on said Sagnac phase.

14. A room temperature exciton-polariton Sagnac interferometer according to claim 1, wherein said processor is configured to determine said Sagnac phase based on an interference pattern of said detected light.

15. A room temperature exciton-polariton Sagnac interferometer according to claim 14, wherein said processor is configured to determine said Sagnac phase based on an angle of rotation of said interference pattern.

16. A room temperature exciton-polariton Sagnac interferometer according to claim 1, further comprising a second light source, wherein light from said second light source maintains said exciton-polariton BEC in said microcavity.

17. A room temperature exciton-polariton Sagnac interferometer according to claim 1, further comprising:

- a second microcavity configured to support a second exciton-polariton Bose-Einstein condensate (BEC) wherein said orbital angular momentum superposition state of light is transmitted through said second microcavity to induce an interference state in said second exciton-polariton BEC; and

- a second photodetector configured to detect light emitted from said second microcavity, wherein said second microcavity is orthogonal to said first microcavity, and wherein said processor is configured to determine a second Sagnac phase based on said light detected by said second photodetector.

18. A room temperature exciton-polariton Sagnac interferometer according to claim 17, wherein said processor is configured to determine a rotation of the first and second microcavities in two dimensions based on said first and second Sagnac phases.

19. A method for performing Sagnac interferometry using a room temperature exciton-polariton Bose-Einstein condensate (BEC), comprising:

- creating an orbital angular momentum superposition state of light;
- inducing an vortex superposition state in an exciton-polariton BEC using said orbital angular momentum superposition state of light;
- detecting light emitted from said exciton-polariton BEC; and
- determining a Sagnac phase based on said detected light.

20. A method for performing Sagnac interferometry using a room temperature exciton-polariton BEC according to claim 19, further comprising:

- inducing a vortex superposition state in a second room temperature exciton-polariton BEC positioned orthogonally to said first room temperature exciton-polariton BEC using said orbital angular momentum superposition state of light;

detecting light emitted from said second room temperature exciton-polariton BEC; and
determining a second Sagnac phase based on said detected light.

21. A method for performing Sagnac interferometry using a room temperature exciton-polariton BEC according to claim 20, further comprising determining a rotation of the first and second exciton-polariton BECs in two dimensions based on said first and second Sagnac phase.

22. A method for performing Sagnac interferometry using a room temperature exciton-polariton Bose-Einstein condensate (BEC), comprising:

inducing an vortex superposition state in an exciton-polariton BEC;
detecting light emitted from said exciton-polariton BEC; and
determining a Sagnac phase based on said detected light.

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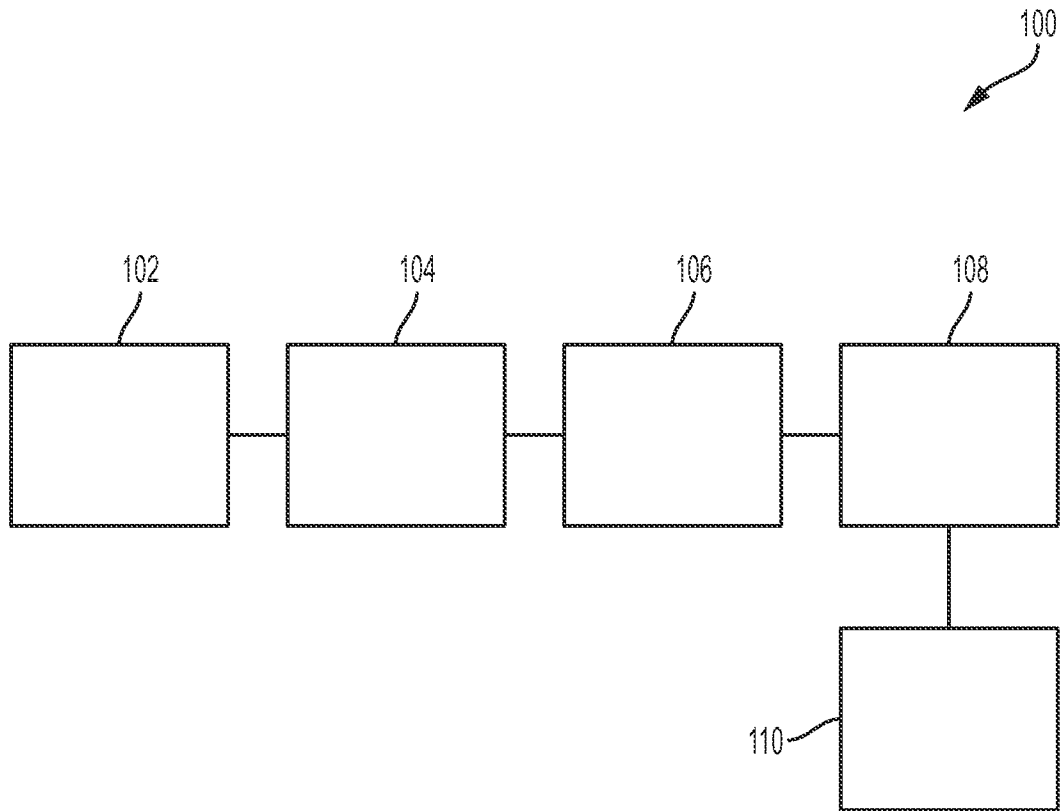


FIG. 1

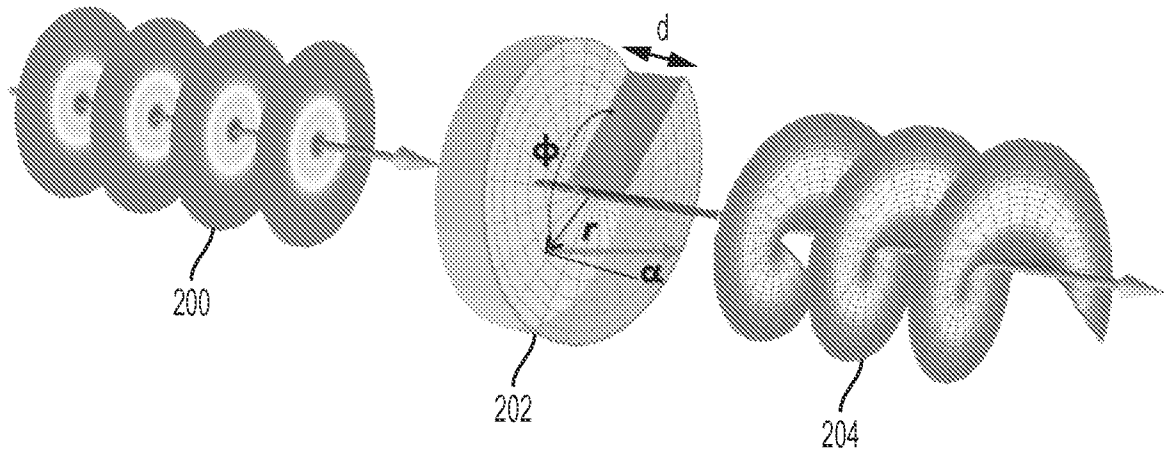


FIG. 2

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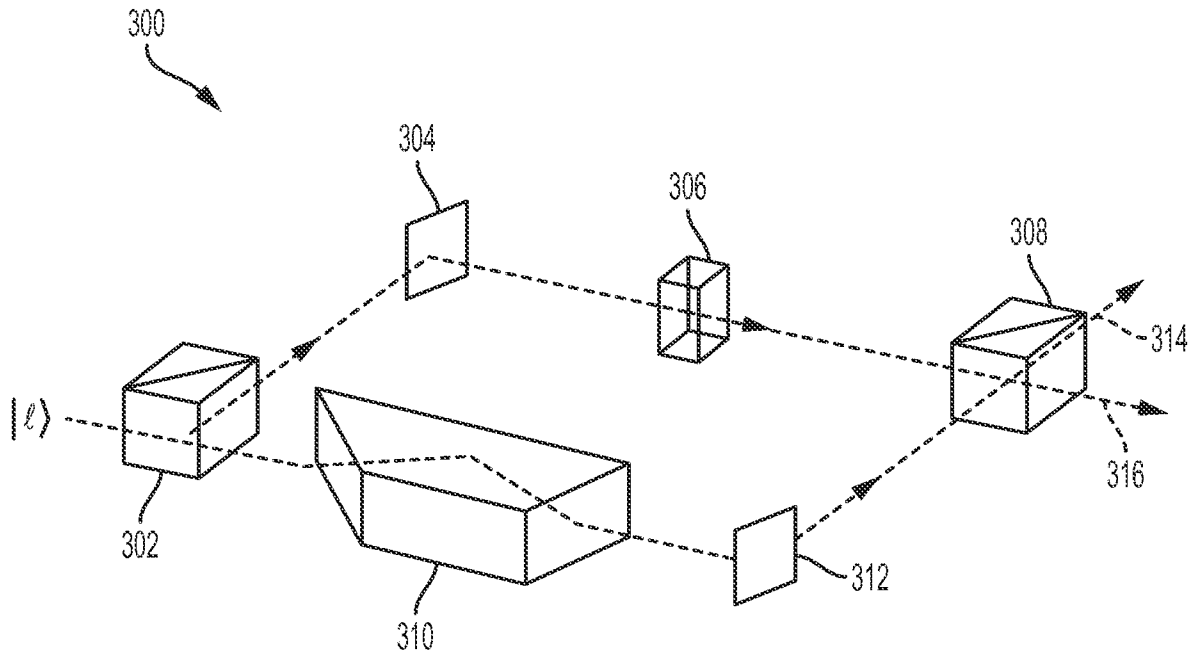


FIG. 3

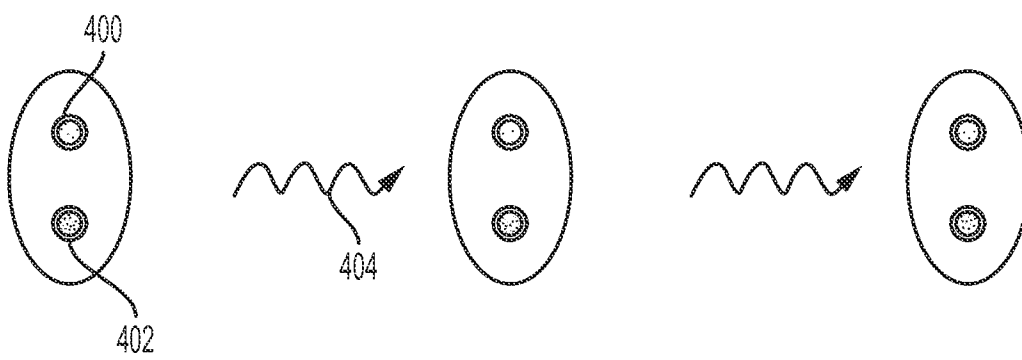


FIG. 4

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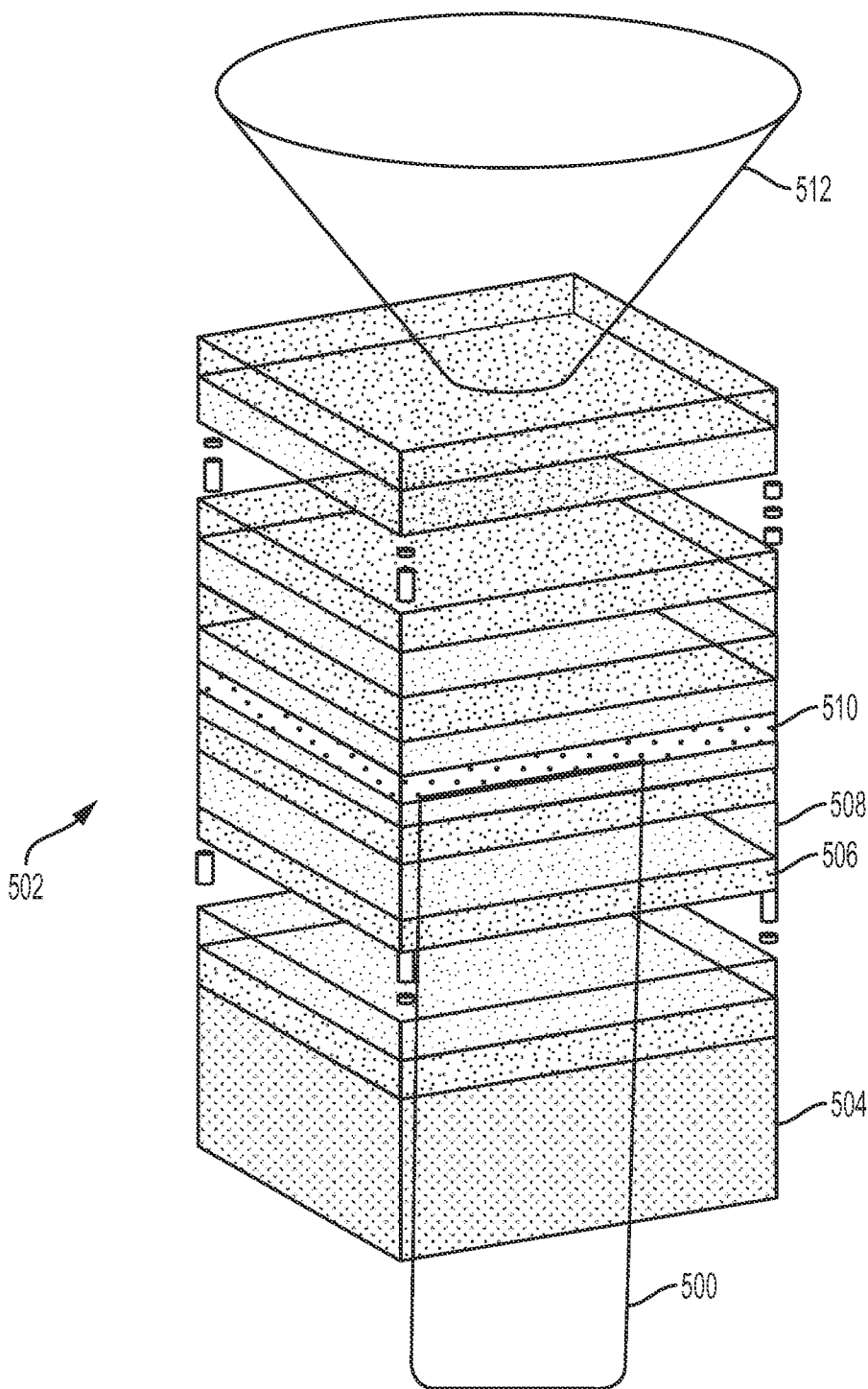
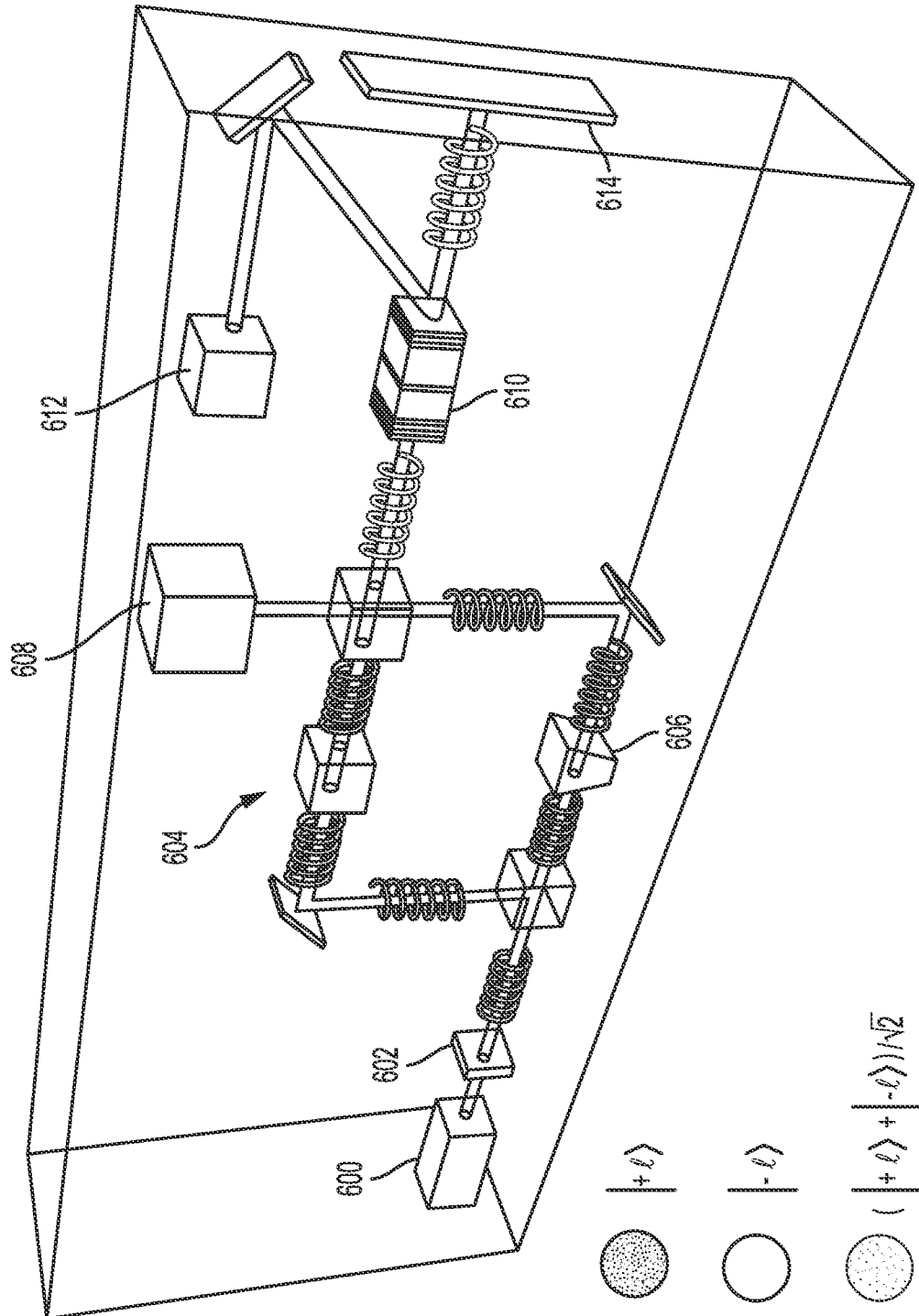


FIG. 5

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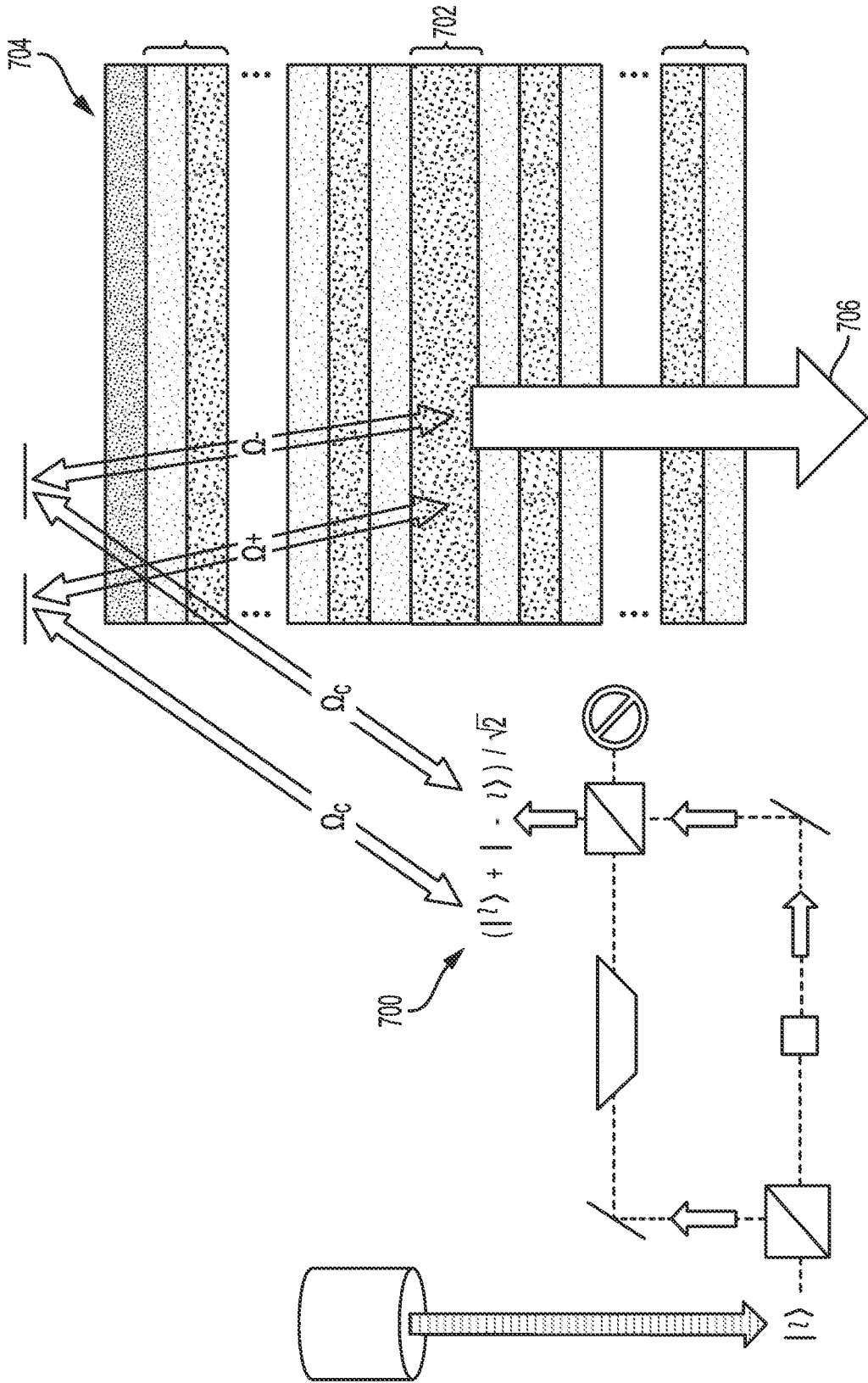


FIG. 7

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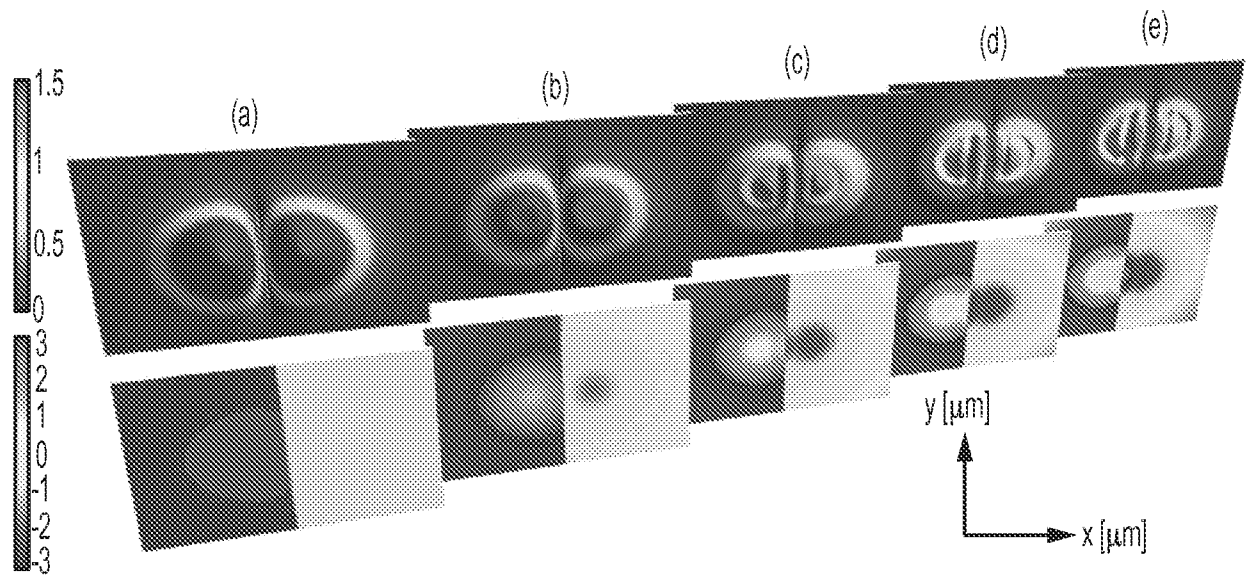


FIG. 8A-8E

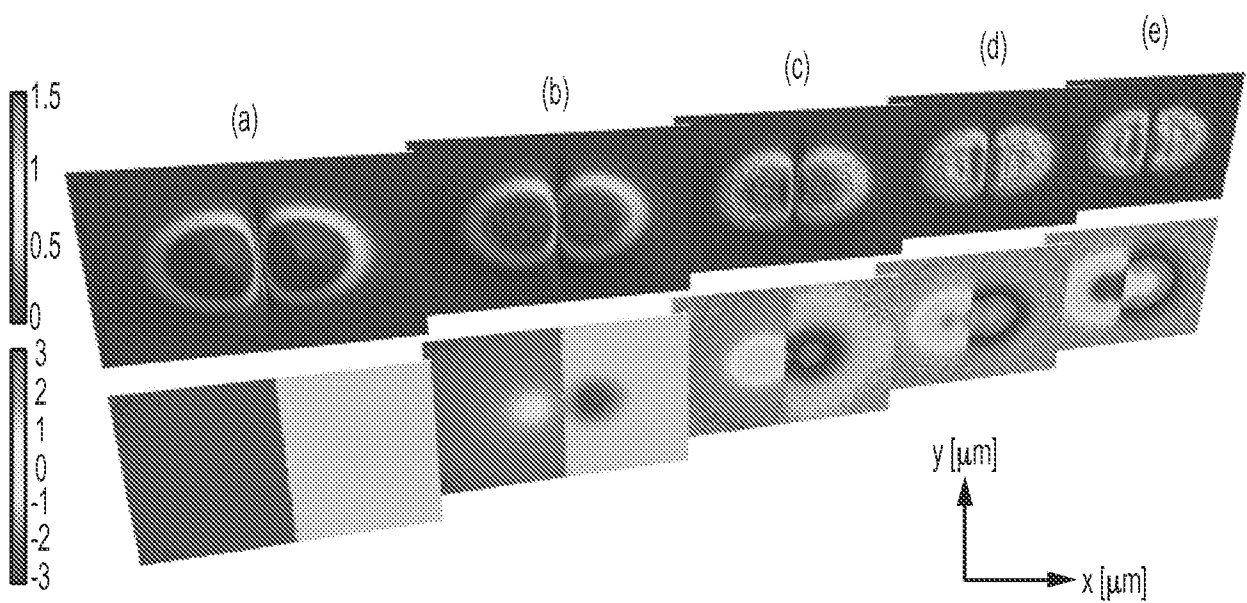


FIG. 9A-9E

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