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Hirano et al.

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(54) **QUANTUM ENTANGLEMENT GENERATING SYSTEM AND METHOD, AND QUANTUM ENTANGLEMENT GENERATING AND DETECTING SYSTEM AND METHOD**

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(51) **Int. Cl.**
G01B 9/02 (2006.01)

(52) **U.S. Cl.** **356/450**

(58) **Field of Classification Search** 356/450, 356/459–476

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,004,341	A *	4/1991	Grynberg et al.	356/459
5,339,182	A	8/1994	Kimble et al.	
5,982,788	A *	11/1999	Hemmati	372/21
2006/0083376	A1*	4/2006	Kawamoto et al.	380/256

FOREIGN PATENT DOCUMENTS

JP 4-172329 A 6/1992

OTHER PUBLICATIONS

Braunstein et al., "Quantum information with continuous variables", Reviews of Modern Physics, vol. 77, Apr. 2005, pp. 513-577. Mentioned on pp. 2-3 of as-filed specification.

(Continued)

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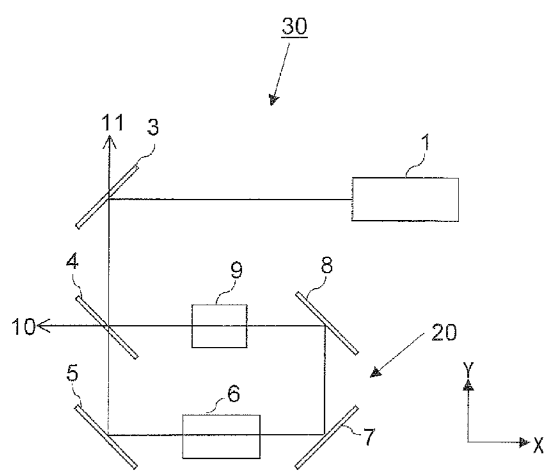
Assistant Examiner — Jonathon Cook
(74) *Attorney, Agent, or Firm* — Chen Yoshimura LLP

(57) **ABSTRACT**

A quantum entanglement generating system includes: a laser light source for producing a light beam of light frequency $2f_0$; a ring interferometer comprising a beam splitter into which the light beam of light frequency $2f_0$ is incident and a plurality of mirrors, the beam splitter and the mirrors forming an optical path in the form of a ring; a parametric amplifier inserted in the optical path of the ring interferometer for producing a beam of light of light frequency f_0 upon receiving the light beam of light frequency $2f_0$ incident into the optical parametric amplifier; and a dispersive medium inserted in the optical path of the ring interferometer for varying relative optical path length for the light beam of light frequency $2f_0$ and the light beam of light frequency f_0.

23 Claims, 8 Drawing Sheets



OTHER PUBLICATIONS

Zhang et al., "Quantum teleportation of light beams", Physical Review A, Mar. 11, 2003, vol. 67, No. 3, pp. 033802-1-033802-16. Cited in ISR below and mentioned on pp. 2-3 of as-filed specification.
Eto et al., "Observation of squeezed light at 1.535 μm using a pulsed homodyne detector", Optics Letters, Jun. 15, 2007, vol. 32, No. 12, pp. 1698-1700. Cited in ISR below and mentioned on pp. 3 and19 of as-filed specification.
Duan et al., "Inseparability Criterion for Continuous Variable Systems", Physical Review Letters, Mar. 20, 2000, vol. 84, No. 12, pp. 2722-2725. Mentioned on pp. 3 and 36 of as-filed specification.
Zhang et al., "Experimental generation of broadband quadrature entanglement using laser pulses", Physical Review A, Jul. 16, 2007, vol. 76, No. 1-A, pp. 012314-1-012314-9. Cited in ISR below.
Matsuoka, "Chokkoisou Sukuizudo Joutai no Hassei to Kensyutsu", Shokabo Text Series—Butsurigaku Ryoshi Kogaku, 6th edition, Kabushiki Kaisha Shokabo, Jun. 20, 2006, pp. 166 to 169. Cited in ISR below as a concise explanation of relevance.
International Search Report (ISR) issued in PCT/JP2008/064436 for Examiner consideration, citing Foreign Patent Document No. 1 and Non-Patent Literature Document Nos. 2-3 and 5-6 listed above.
Written Opinion (PCT/ISA/237) issued in PCT/JP2008/064436. Concise Explanation of Relevance: This Written Opinion considers that the claims are described by or obvious over the references Nos. 1-5 cited in ISR above.
International Preliminary Report on Patentability Chapter II (IPEA/409) issued in PCT/JP2008/064436.
Eto et al., "Continuous-variable entangled state generation using pulsed light at telecommunication wavelength", Meeting Abstracts of the Physical Society of Japan, Hokkaido University, Sapporo Campus, 62th Annual Meeting, Sep. 21-24, 2007, vol. 62, Issue 2, Part 2, pp. 192.
Eto et al., "Continuous-variable entangled state generation using pulsed light at telecommunication wavelength 2", Meeting Abstracts of the Physical Society of Japan, Kinki University, Headquarters Campus, 63rd Annual Meeting, Mar. 22-26, 2008, vol. 63, Issue 1, Part 2, pp. 176.

* cited by examiner

FIG.1

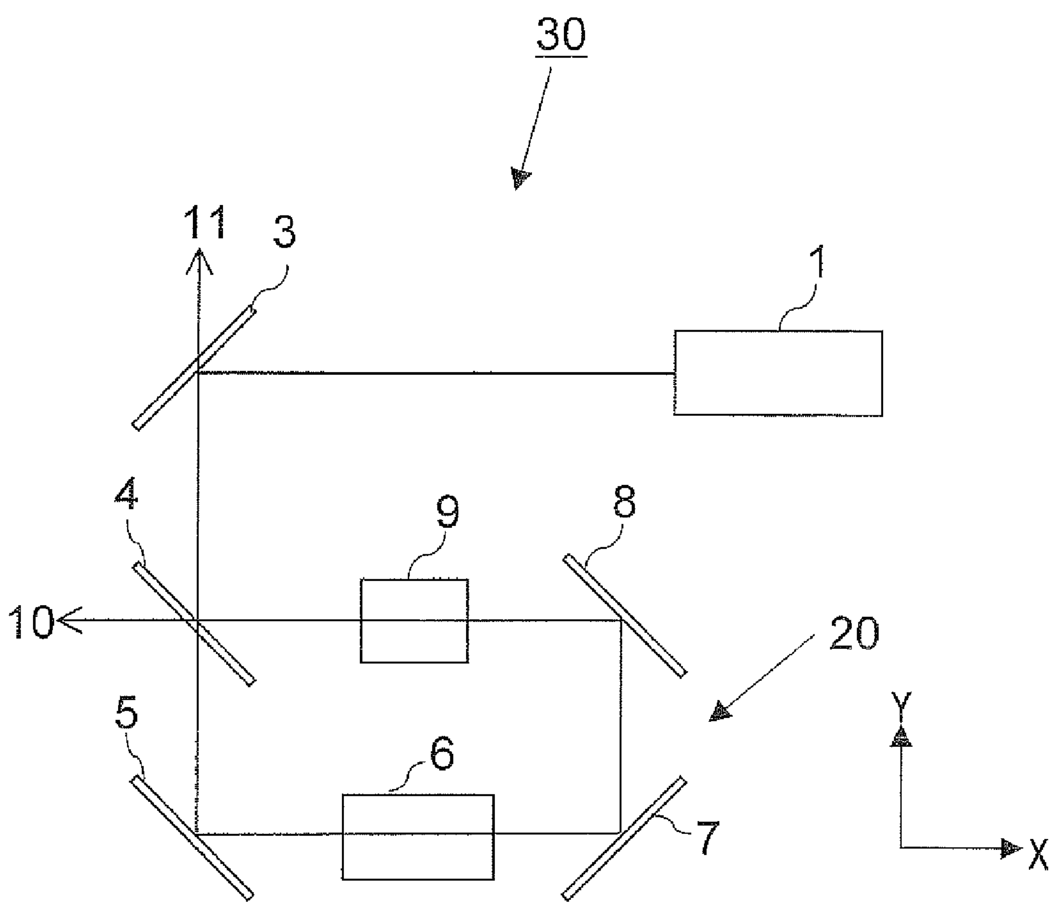


FIG.2

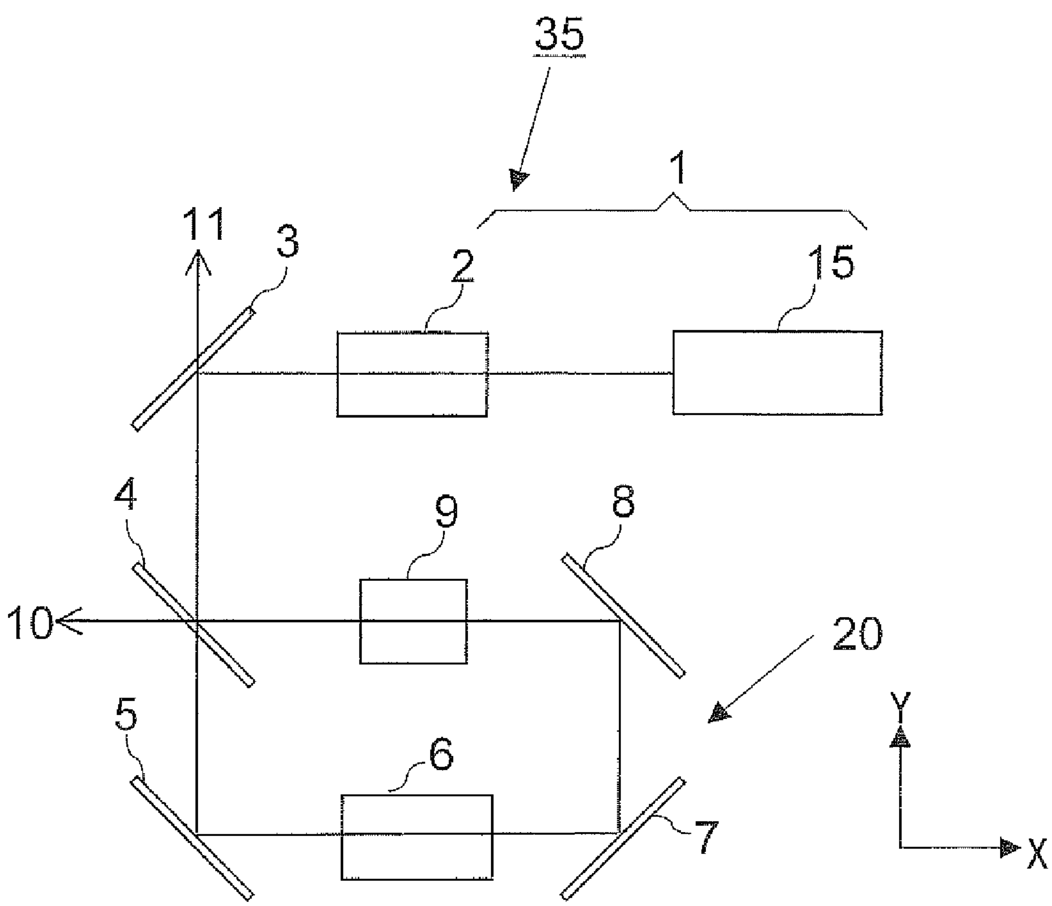


FIG.3

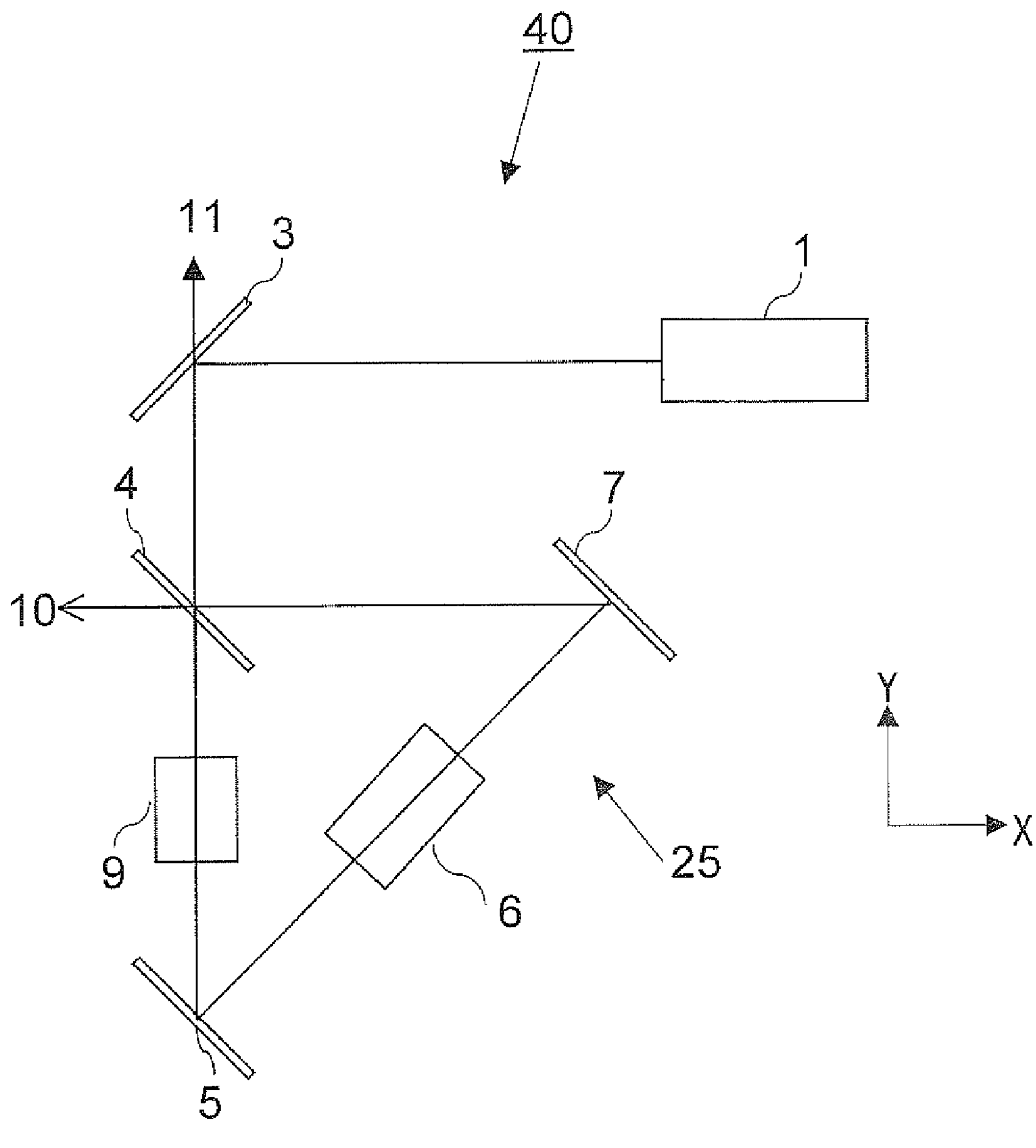


FIG.4

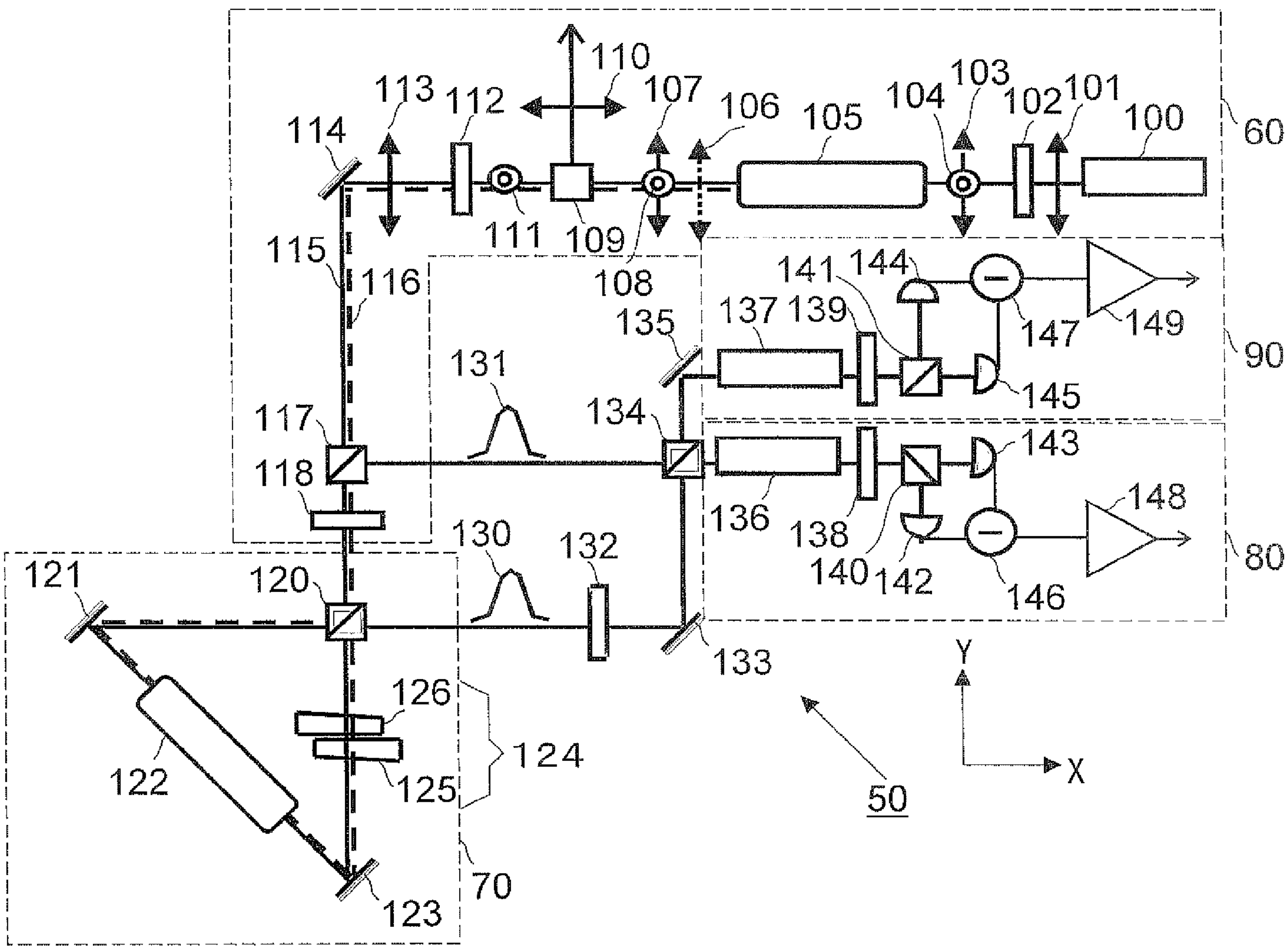

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FIG.5

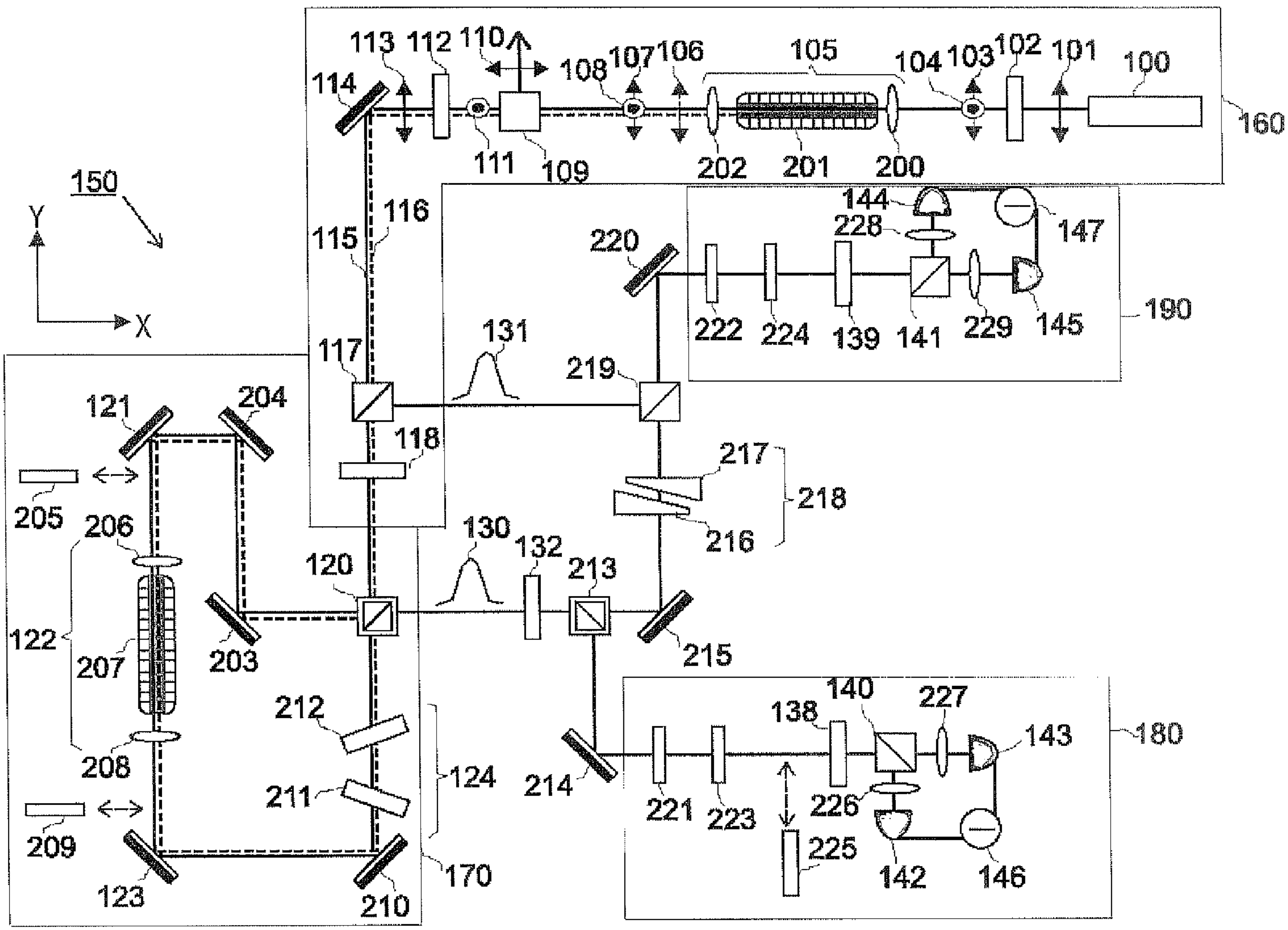
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FIG.6

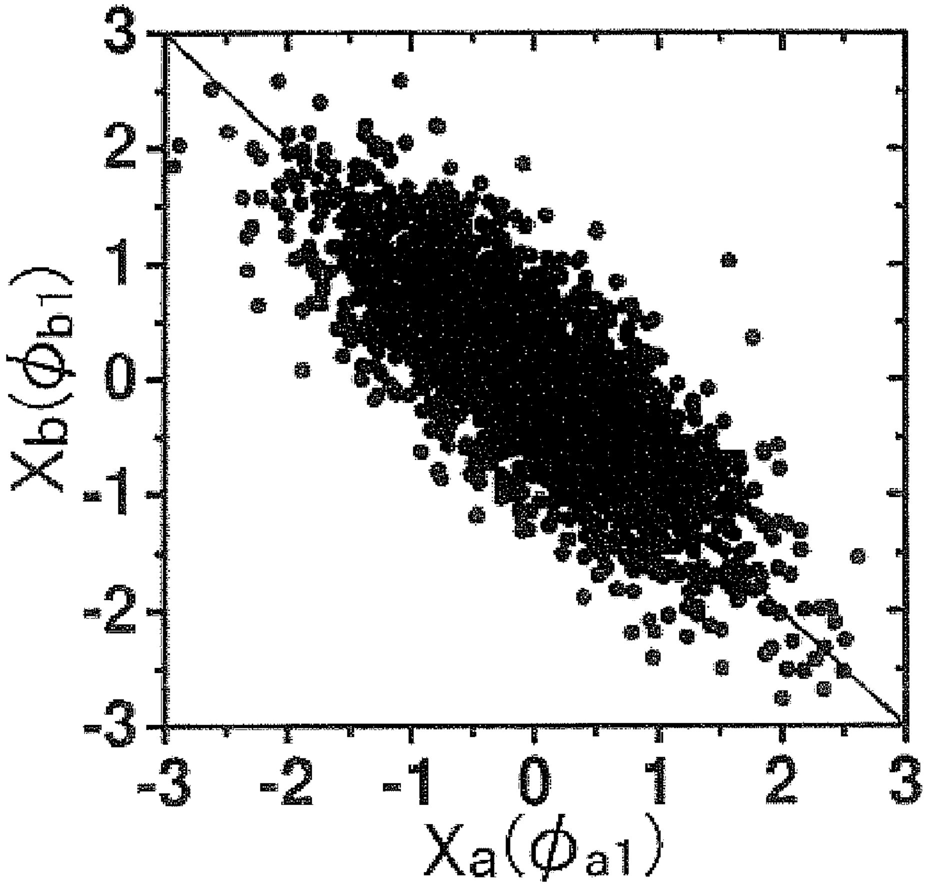


FIG.7

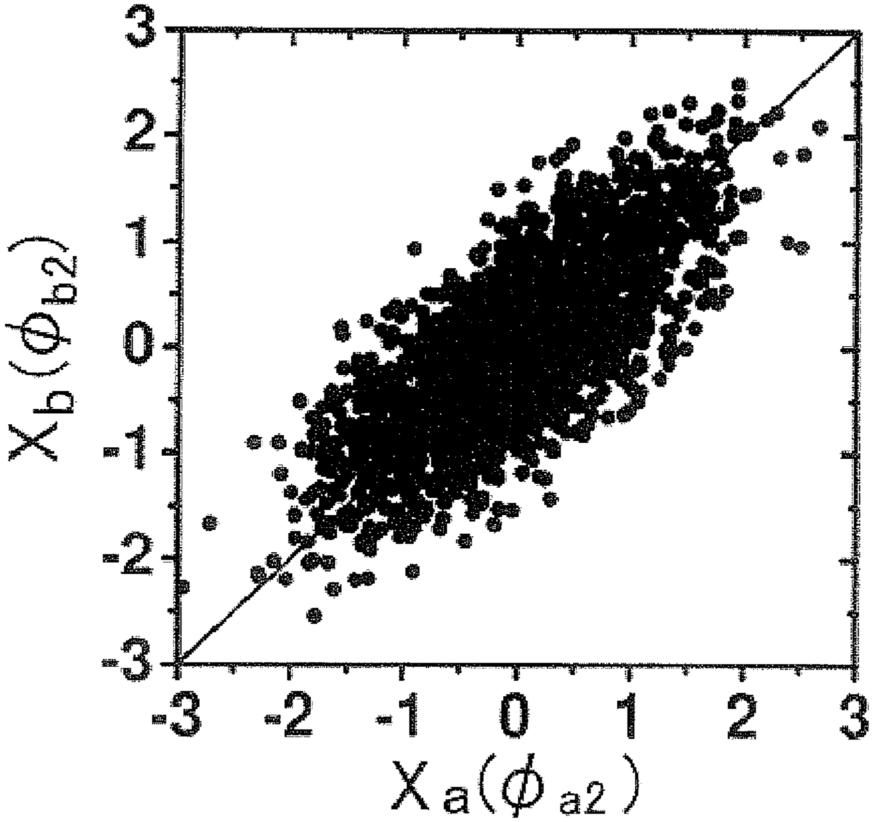
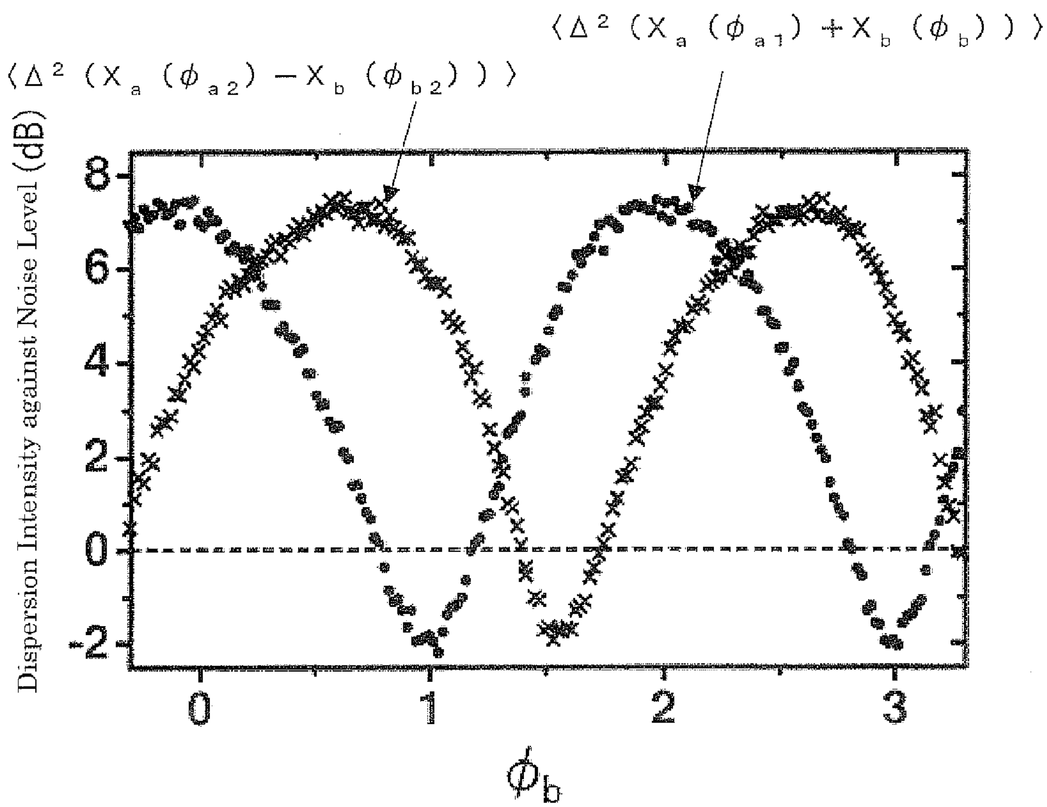


FIG.8


⟨Δ² (X_a (φ_a1) + X_b (φ_b)) ⟩
⟨Δ² (X_a (φ_a2) − X_b (φ_b2)) ⟩
Dispersion Intensity against Noise Level (dB)
8
6
4
2
0
-2
0
1
2
3
φ_b

QUANTUM ENTANGLEMENT GENERATING SYSTEM AND METHOD, AND QUANTUM ENTANGLEMENT GENERATING AND DETECTING SYSTEM AND METHOD

TECHNICAL FIELD

The present invention relates to a quantum entanglement generating system and a quantum enlargement generating and detecting system and to a quantum entanglement generating method and a quantum enlargement generating and detecting method. More specifically, it relates to a system for and a method of generating quantum entanglement of continuous variables using a secondary nonlinear optical effect, and to a system that is capable of detecting generated quantum entangled beams, simultaneously with its generation as well as a method for its detection.

BACKGROUND ART

Quantum information techniques constitute a technology or a field of the technology that utilizes a quantum mechanical effect directly to achieve information processing performance unachievable so far. Quantum entanglement is a most important resource in the quantum information techniques. Utilization of the quantum entanglement permits actualizing absolutely safe communications and computation processing at a speed incommensurably higher than heretofore.

A quantum entangled state is a state that physical systems at a plurality of spatially separated locations are mutually correlated, thus the state that such a plurality of physical systems cannot be treated isolated. If physical systems at two distant locations have a quantum entangled state in common, then measurements conducted at the two locations cause in their results a correlation which cannot be explained in the classical theory.

The term “quantum entanglement” is used in general to refer to a quantum entangled state itself, or a physical phenomenon which the entangled state exhibits and which is brought about peculiar in the quantum theory, or to state the concept that the quantum theory involves an inseparable characteristic. The quantum entanglement is used herein, however, as the term to indicate a quantum entangled state.

Quantum information processing adopts mainly two approaches, one of which uses a discrete physical quantity and the other of which uses a continuous physical quantity (see, e.g., Non-Patent Reference 1). In the case of light, use is generally made of the quadrature amplitude of an electric field as such a physical quantity taking a continuous physical value. The quantum entanglement for continuous physical quantities is termed a continuous variable quantum entanglement.

Mention is made of conventional methods of generating a continuous variable quantum entanglement. The method used most initially uses a non-degenerate parametric amplifier (see, e.g., Patent Reference 1). Patent Reference 1 introduced an experiment in which potassium titanate phosphate (KTP) was used as a nonlinear medium and phase matching of type II was effected to generate a signal and an idler light beams which are in a mutually orthogonal polarized state. The term “non-degenerate” refers to difference in the polarized state. Such signal and idler light beams as generated by parametric amplification using phase matching of type II are quantum correlated and thus capable of generating a continuous variable quantum entanglement.

In a conventional method of using the phase matching of type II, however, a difference in index of reflection of the nonlinear medium to signal and idler light beams made it technically difficult to bring the light resonators into simultaneous resonance with these two light beams. Further, the phase matching of type II in which beams tended in general to work off caused the quantum entanglement to deteriorate in quality.

In the method next performed, two squeezed light beams are generated and combined at a beam splitter with a transmissivity and a reflectance both of 50% to generate quantum entanglement. Then, the two squeezed beams need to be precisely controlled so as to have their relative phase difference of $\pi/2$.

For example, refer to Non-Patent Reference 2 in which a parametric amplifier placed in a ring resonator to effect phase matching of type **1** is used to generate squeezed beams which are traveling clockwise and anticlockwise along a ring and which are combined at a beam splitter laid outside of the ring to generate quantum entanglement. This method has the problem that after leaving the ring resonator and then to be combined at the beam splitter, the two squeezed beams that follow the different paths make it difficult to maintain the relative optical path length between these two paths stably.

Patent Reference 1: H. J. Kimble et al., U.S. Pat. No. 5,339,182, Aug. 16, 1994

Non-Patent Reference 1: S. L. Braunstein and P. van Loock, Rev. Mod. Phys. Vol. 77, p. 513, 2005

Non-Patent Reference 2: T. C. Zhang, et al., Phys. Rev. A. Vol. 67, p. 033802, 2003

Non-Patent Reference 3: Yujiro Eto, et al., Optics Letters, Vol. 32, pp. 1698-1700, 2007

Non-Patent Reference 4: L. M. Duan, et al., Physical Review Letters, Vol. 84, p. 2722, 2000

DISCLOSURE OF THE INVENTION

Problems to be Solved by the Invention

In the conventional method using the two squeezed beams, the difference in optical path length must continually be monitored and be stabilized by feedback control. The problems arise, however, that not only it is achieved to stabilize the relative optical path length with finite accuracy, but the equipment needed to this end must become complicated.

In view of the problems mentioned above, it is a first object of the problem to provide a quantum entanglement generating system whereby in entanglement generation by combining two squeezed light beams their relative optical path length can stably be controlled. A second object of the present invention is to provide a method of generating a quantum entanglement.

It is a third object of the present invention to provide a system that is capable of detecting a quantum entanglement beam generated in the entanglement generating system, simultaneously with its generation. It is a fourth object of the present invention to provide a method of generating a quantum entanglement beam and further, detecting a so generated quantum entanglement, simultaneously with its generation.

The Invention for Solving the Problems

In order to achieve the first object mentioned above, there is provided in accordance with the present invention a quantum entanglement generating system which comprises: a laser light source for producing a light beam of light frequency $2f_0$; a ring interferometer comprising a beam splitter into which the light beam of light frequency $2f_0$ is incident and a plurality of mirrors, the beam splitter and the mirrors forming an optical path in the form of a ring; an optical parametric amplifier inserted in the optical path of the ring interferometer for producing a light beam of light frequency

f_0 upon receiving a light beam of light frequency $2f_0$ incident into the optical parametric amplifier; and a dispersive medium inserted in the optical path of the ring interferometer for varying relative optical path length for the light beam of light frequency $2f_0$ and the light beam of light frequency f_0, whereby two light beams of light frequency $2f_0$ split into by the beam splitter so as to travel mutually contrariwise in direction of advance in the ring interferometer are injected into the optical parametric amplifier to generate a first and a second squeezed light beam traveling mutually contrariwise in direction of advance in the ring interferometer, and the first and second squeezed light beams upon adjustment of their relative phase at a selected value through the dispersive medium are combined at the beam splitter, thereby generating quantum entangled beams.

In the system described above, the optical path of the ring interferometer is preferably formed of the sides of a polygon of triangle or more angle in the ring interferometer in which the beam splitter is disposed at an apex of the polygon with the mirrors lying at its remaining apexes, respectively.

The optical path of the ring interferometer is preferably a triangular optical path in which the beam splitter and a first and a second of the mirrors are arranged in turn anticlockwise, wherein the dispersive medium is disposed in the optical path between the beam splitter and the first mirror in the ring interferometer, and the optical parametric amplifier is disposed in the optical path between the first and second mirrors in the ring interferometer.

The optical path of the ring interferometer is preferably a rectangular optical path in which the beam splitter and a first, a second and a third of the mirrors are arranged in turn anticlockwise, wherein the optical parametric amplifier is disposed in the optical path between the first and second mirrors in the ring interferometer, and the dispersive medium is disposed in the optical path between the beam splitter and the third mirror in the ring interferometer.

On the optical axis there is preferably disposed a condenser means, each between the optical parametric amplifier and the first mirror and between the optical parametric amplifier and the second mirror. The optical parametric amplifier preferably has an optical waveguide structure consisting of an electrooptic crystal.

The dispersive medium preferably consists of two glass plates.

The laser light source preferably comprises a light source for producing a light beam of light frequency f_0 and a second harmonic generator for converting the incident light beam of light frequency f_0 from the light source into a light beam of light frequency $2f_0$.

The second harmonic generator preferably has an optical waveguide structure consisting of an electrooptic crystal.

The beam splitter preferably has a transmissivity and a reflectance of about 50%, alike to both light beams of light frequency f_0 and light frequency $2f_0$.

The ring interferometer is preferably formed on a plane.

In order to achieve the second object mentioned above, the present invention provides a quantum entanglement generating method which comprises: producing a light beam of light frequency $2f_0$ from a laser light source; injecting the light beam from the laser light source into a ring interferometer comprising an optical path of a beam splitter and mirrors, and an optical parametric interferometer and a dispersive medium which are disposed in the optical path; splitting the injected light beam at the beam splitter into two light beams traveling mutually contrariwise in direction of advance in the ring interferometer; advancing one of the split light beams from the optical parametric amplifier into the dispersive medium to generate a first squeezed light beam of light frequency f_0; advancing the other of the split light beams from the dispersive medium into the optical parametric amplifier to generate a second squeezed light beam of light frequency f_0; setting relative phase between the first and second squeezed light beams at a selected value through the dispersive medium; and combining the first and second squeezed light beams at the beam splitter, thereby generating quantum entangled beams.

In the method mentioned described, the relative phase between the first and second squeezed light beams is preferably set at $\pi/2$. The quantum entangled beams comprises a first quantum entangled beam passing through the beam splitter and a second quantum entangled beam reflecting on the beam splitter.

According to the system and method mentioned above, it is possible to generate a quantum entanglement stably by maintaining the relative phase stably between two squeezed light beams generated in the ring interferometer.

In order to achieve the third object mentioned above, the present invention provides a quantum entanglement generating and detecting system which comprises: a light source part comprising a pulsed laser light source of light frequency f_0 and a second harmonic generator into which the light beam of light frequency f_0 is incident to produce a light beam of light frequency $2f_0$, the light source part emitting a pulsed laser light beam of light frequency f_0 and a pulsed laser light beam of light frequency $2f_0$ on a common axis; a ring interferometer comprising a beam splitter into which the light beam of light frequency $2f_0$ is incident and a plurality of mirrors, the beam splitter and mirrors forming an optical path in the form of a ring; an optical parametric amplifier inserted in the optical path of the ring interferometer for producing a light beam of light frequency f_0 upon receiving a light beam of light frequency $2f_0$ incident into the optical parametric amplifier; a dispersive medium inserted in the optical path of the ring interferometer for varying relative optical path length for the light beam of light frequency $2f_0$ and the light beam of light frequency f_0; and a homodyne detector, whereby two light beams of light frequency $2f_0$ split into by the beam splitter so as to travel mutually contrariwise in direction of advance in the ring interferometer are injected into the optical parametric amplifier to generate a first and a second linearly polarized, squeezed light beam of light frequency f_0 traveling mutually contrariwise in direction of advance in the ring interferometer, relative phase between the first and second squeezed light beams is adjusted at a selected value through the dispersive medium, the first and second squeezed light beams are combined at the beams splitter, thereby generating quantum entangled beams, and as a signal light beam the linearly polarized quantum entangled beam of light frequency f_0, and as a local-oscillator light beam the pulsed laser light beam of light frequency f_0 emitted from the light source part and having a polarization orthogonal to the signal light beam, are both injected into the homodyne detector to detect a quadrature amplitude.

Preferably in the system described above, the quantum entangled beams comprises a first and a second quantum entangled beam and the homodyne detector comprises a first and a second homodyne detector, the first and second quantum entangled beams constituting signal light beams to the first and second homodyne detectors, respectively.

The beam splitter preferably has a transmissivity and a reflectance of about 50%, alike to both a horizontally polarized light beam of light frequency f_0 and a horizontally polarized light beam of light frequency $2f_0$, and has a reflectance of about 100% to a vertically polarized light beam of light frequency f_0.

The homodyne detector preferably comprises: an electrooptic crystal into which the signal light beam and the local-oscillator light beam are incident, a half wave plate for polarizing the light beams incident into the electrooptic crystal, a beam splitter for combining the light beams polarized at the half wave plate to split into a transmitted and a reflected light beam, detectors for sensing the two split light beams, respectively, and a means for providing a differential between outputs from the detectors.

The homodyne detector preferably comprises a filter into which the signal light beam and the local-oscillator light beam are incident for transmitting the light frequency f_0 and light frequency $2f_0$, a quarter wave plate for varying a phase between the light beams from the filter, a beam splitter for combining the light beams from the quarter wave plate to split into a transmitted and a reflected light beam, detectors for sensing the two split light beams, respectively, and a means for providing a differential between outputs from the detectors.

The system preferably further comprises: a dispersive medium disposed between the signal and local-oscillator light beams and the homodyne detector wherein the homodyne detector comprises a filter for transmitting a light beam of light frequency f_0 and a light beam of light frequency $2f_0$ out of light beams passing through the dispersive medium, a beam splitter for combining light beams from the filter to split into a transmitted and a reflected light beam, detectors for sensing the two split light beams, respectively, and a means for providing a differential between outputs from the detectors.

The ring interferometer is preferably formed on a plane.

In order to achieve the fourth object mentioned above, the present invention provides a quantum entanglement generating and detecting method which comprises: producing, on a common optical axis, a light beam of light frequency f_0 from a laser light source and a light beam of light frequency $2f_0$ generated via a second harmonic generator from the laser light source; injecting the light beam of light frequency $2f_0$ from the laser light source into a ring interferometer comprising an optical path in the form of ring comprising a beam splitter and a plurality of mirrors and an optical parametric amplifier and a dispersive medium arranged in the optical path; splitting the injected light beam at the beam splitter into two light beams traveling mutually contrariwise in direction of advance in the ring interferometer; advancing one of the split light beams from the optical parametric amplifier into the dispersive medium to generate a first linearly polarized, squeezed light beam of light frequency f_0; advancing the other of the split light beams from the dispersive medium into the optical parametric amplifier to generate a second linearly polarized, squeezed light beam of light frequency f_0; setting relative phase between the first and second squeezed light beams at a selected value through the dispersive medium; combining the first and second squeezed light beams through the beam splitter, thereby generating a linearly polarized quantum entangled beam of light frequency f_0; deriving from the linearly polarized quantum entangled beam of light frequency f_0, a signal light beam for a homodyne detector; passing the light beam of light frequency f_0 from the laser light source through the ring interferometer via an optical path identical to that for the one split light beam to provide a light beam of a polarization orthogonal to the signal light beam for use as a local oscillator light beam for the homodyne detector; and the homodyne detector detecting a quadrature amplitude of the signal light beam.

In the method described above, a filter for blocking the light beam of light frequency $2f_0$ is preferably inserted on an optical axis, each in front and rear of the optical parametric amplifier to suspend generation of the quantum entangled beams.

According to the system and method described above, it is possible to generate a quantum entanglement stably by maintaining the relative phase stably between two squeezed light beams generated in the ring interferometer. Further, a local-oscillator light beam for the homodyne detector can be furnished coaxially with a light ray into the ring interferometer to make it possible to achieve stable homodyne detection of quantum entangled beams.

Effects of the Invention

According to a quantum entanglement generating system and a quantum entanglement generating method of the present invention, it is possible to generate an quantum entanglement stably by maintaining the relative phase stably between two squeezed light beams advancing mutually contrariwise in the ring interferometer.

According to a quantum entanglement generating and detecting system and a quantum entanglement generating and detecting method of the present invention, it is possible to generate an quantum entanglement stably and to achieve homodyne detection of a quantum entangled beam by maintaining the relative phase stably between two squeezed light beams traveling mutually contrariwise in direction of advance in the ring interferometer. Also, a quantum entangled beam and a local-oscillator light beam can be coaxially furnished to better the stability of homodyne detection.

BRIEF DESCRIPTION OF THE DRAWINGS

In the Drawings:

FIG. **1** is a block diagram illustrating the makeup of a quantum entanglement generating system according to a first embodiment of the present invention;

FIG. **2** is a block diagram illustrating the makeup of a quantum entanglement generating system according to a second embodiment of the present invention;

FIG. **3** is a block diagram illustrating the makeup of a quantum entanglement generating system according to a third embodiment of the present invention;

FIG. **4** is a block diagram illustrating a quantum entanglement generating and detecting system according to its first embodiment of the present invention;

FIG. **5** is a block diagram illustrating a quantum entanglement generating and detecting system according to its second embodiment of the present invention;

FIG. **6** is a diagram illustrating scatter plots of $X_a(\phi_{a1})$ and $X_b(\phi_{b1})$ in a phase $(\phi_b=\phi_{b1})$ in which $\langle\Delta^2(X_a(\phi_{a1})+X_b(\phi_b))\rangle$ becomes the minimum;

FIG. **7** is a diagram illustrating scatter plots of $X_a(\phi_{a2})$ and $X_b(\phi_{b2})$ in a phase $(\phi_b=\phi_{b1})$ which satisfies $\phi_b=\phi_{b2}=\phi_{b1}+\pi/2$; and

FIG. **8** is a graph illustrating dependency on ϕ of the dispersion intensity of sum of and difference between a first quantum entangled beam and a second quantum entangled beam, computed from the $X_a(\phi_a)$ and $X_b(\phi_b)$ measured.

REFERENCE NUMERALS

1: Light source
2, **105**: Second harmonic generator
3: First mirror
4: Beam splitter
5: Second mirror
6, **122**: Optical parametric amplifier
7: Third mirror

8: Fourth mirror
9. **124**, **128**: Dispersive medium
10, **130**: First quantum entangled beam
11, **131**: Second quantum entangled beam
15: Laser light source of light frequency f_0
20, **25**, **70**, **170**: Ring interferometer
30, **35**, **40**: Quantum entanglement generating system
50, **150**: Quantum entanglement generating and detecting system
60, **160**: Light source part
80, **180**: First homodyne detector
90, **190**: Second homodyne detector
100: Pulsed laser light source
101: Light pulse
(light horizontally polarized at light frequency f_0)
102, **132**, **138**, **139**: Zero-order half-wave plate for light frequency f_0
103, **107**, **110**, **113**: Horizontally polarized component of light of light frequency f_0
104, **108**, **111**: Vertically polarized component of light of light frequency f_0
106: Light horizontally polarized at light frequency $2f_0$
109, **117**, **219**: Beam splitter for light polarized at light frequency f_0
112, **118**: Wave plate for 2 wavelengths (half-wavelength wave plate at light frequency f_0, and becoming one-wavelength wave plate at light frequency $2f_0$)
114: Mirror
115: Light ray of light frequency f_0
116: Light ray of light frequency $2f_0$
120, **134**, **213**: Special beam splitter
121, **123**, **203**, **204**, **120**: Mirror (two-wavelength mirror)
125, **216**: First glass plate
126, **217**: Second glass plate
133, **135**, **214**, **215**, **220**: Mirror for light frequency f_0
136: First electro-optic crystal
137: Second electro-optic crystal
140, **141**: Beam splitter for light polarized at light frequency f_0
142: First photodiode
143: Second photodiode
144: Third photodiode
145: Fourth photodiode
146: First RF combiner
147: Second RH combiner
148: First amplifier
149: Second amplifier
200, **202**, **206**, **208**, **226**, **227**, **228**, **229**: Lens
205, **207**, **223**, **224**: Red color filter
211, **212**: Parallel planar glass plate
221, **222**: Band-path filter
225: Quarter wave plate

Best Mode for Carrying Out The Invention

Explanation is hereinafter given of preferred forms of implementation of the present invention with reference to the Drawing Figures.

(First embodiment of the quantum entanglement generating system)

FIG. **1** is a block diagram illustrating in a plan view the makeup of a quantum entanglement generating system **30** according to a first embodiment of the present invention. Optical paths are shown in straight lines. According to the X- and Y-coordinates shown, an explanation of the system is given with the X-direction taken crosswise and the Y-direction taken lengthwise. The quantum entanglement generating system **30** as shown in FIG. **1** comprises a laser light source **1** and a ring interferometer **20**. A beam of light of light frequency $2f_0$ emitted from the laser light source **1** impinges on the ring interferometer **20** via a first mirror **3**.

Second embodiment of the quantum entanglement generating system

FIG. **2** is a block diagram illustrating in a plan view the makeup of a quantum entanglement generating system **35** according to a second embodiment of the present invention. Optical paths are shown in straight lines. The quantum entanglement generating system **35** shown in FIG. **2** differs from the quantum entanglement generating system **30** shown in FIG. **1** in the makeup of the laser light source **1**. The laser light source **1** comprises a laser light source **15** of light frequency f_0 and a second harmonic generator **2**, producing a beam of light of light frequency $2f_0$. The laser light emitted from the laser light source **1** and traveling straight in a direction of –X (leftwards) enters a first mirror **3** and is reflected thereat into a direction of –Y (downwards) to enter a ring interferometer **20**.

The ring interferometer **20** comprises a beam splitter **4**, a second mirror **5**, an optical parametric amplifier **6**, a third mirror **7**, a fourth mirror **8** and a dispersive medium **9**. The second mirror **5** is disposed in the direction of –Y (downwards) of the beam splitter **4**. The third mirror **7** is disposed in a direction of X (rightwards) of the second mirror **5**. Also, the fourth mirror **8** is disposed in a direction of X (rightwards) of the beam splitter **4**.

In the ring interferometer **20**, the beam splitter **4**, and the second to fourth mirrors **5**, **7** and **8** are disposed respectively at the four apexes of a quadrangle, specifically a rectangle, forming an optical path. In other words, in the ring interferometer **20** are arranged in order anticlockwise the beam splitter **4**, and the first to third mirrors **5**, **7** and **8** for the ring interferometer **20**. The optical parametric amplifier **6** is disposed along an axis of the optical path that is formed by the second mirror **5** and the third mirror **7**. The dispersive medium **9** is disposed along an axis of optical path that is formed by the beam splitter **4** and the fourth mirror **8**.

The beam splitter **4** desirably has both a transmissivity and a reflectivity, of 50%, alike to both light rays of light frequency $2f_0$ and light frequency f_0.

The first to fourth mirrors **3**, **5**, **7** and **8** are each a mirror reflecting both a light beam of light frequency $2f_0$ and a light beam of light frequency f_0 and composed of, e.g., of a dielectric.

The optical parametric amplifier **6** is designed to convert a light beam of light frequency $2f_0$ to a light beam of light frequency f_0. The optical parametric amplifier **6** used may be of a crystal having a secondary nonlinear optical effect. For example, it may make use of an optical waveguide made of periodically poled $LiNbO_3$.

The dispersive medium **9** used may be of an optical glass. The optical glass may in material be borosilicate glass such as BK7. If the dispersive medium **9** is composed of an optical glass, then it may finely be moved so that its size in an optical axis of the optical glass can vary whereby changing the distance by which laser light beams pass through the glass allows controlling the relative phase between the laser light rays. The optical glass used may be a wedge-shaped glass plate. And, it may, as will be described later, be two such plates to form the dispersive medium **9**. The dispersive medium **9** used may alternatively be a gas such as air loaded in a vessel, forming a so-called gas cell having windows as an inlet and an outlet for light. If the dispersive medium is constituted by a gas cell, then the pressure of the gas may be varied to allow controlling the relative phase between laser light rays passing through the gas.

The ring interferometer **20** is preferably formed on a plane. The ring interferometer **20** can be formed on a breadboard. The breadboard may also be called an optical table. The breadboard may be a plate or substrate made of a material that is stiff. With the ring interferometer **20** formed on a single breadboard, it is possible to stabilize its optical path length against variations in temperature and vibrations while simplifying the system in its apparatus makeup. The first mirror **3** may be formed on the single breadboard as well. Light from the laser light source **1** may be guided to the single breadboard via an optical fiber to make further stable the optical path length against variations in temperature and vibrations.

Explanation is next given of operations of the quantum entanglement generating system **30**, **35**. A light beam of light frequency $2f_0$ emitted from the laser light source **1** and passing the first mirror **3**, the beam splitter **4** and the second mirror **5** constitutes a pumping light input to the optical parametric amplifier **6** to produce a first squeezed light beam of light frequency f_0. The first squeezed light beam traveling anticlockwise in the ring interferometer **20** is reflected by the third mirror **7** and the fourth mirror **8** and then passes through the dispersive medium **9**, arriving in the beam splitter **4**.

On the other hand, the laser light beam reflected by the beam splitter **4** in the X direction (rightwards) passes through the dispersive medium **9**, reflects on the fourth minor **8** in the —Y direction (downwards) and reflects on the third mirror **3** in the —X direction (leftwards), then impinging on the optical parametric amplifier **6** to produce a second squeezed light beam of light frequency f_0. Thus, the second squeezed light beam travels clockwise in the ring resonator, arriving in the beam splitter **4** upon reflection by the second mirror **5**.

The first and second squeezed light beams produced both in the ring interferometer **20** and traveling mutually contrariwise are combined, or spatially overlapped at the beam splitter **4**. Then, a first quantum entangled beam **10** and a second quantum entangled beam **11** which are quantum correlated can be generated by operating the dispersive medium **9** so as to make the relative phase between the first and second squeezed light beams equal to $\pi/2$. The first quantum entangled beam **10** after passing the beam splitter **4** is emitted, as shown in FIG. **1**, in the −X-direction (leftwards). The second quantum entangled beam **11** is reflected by the beam splitter **4** into the Y direction (upwards) and emitted upon passing through the first mirror **3**.

When the first and second squeezed light beams are combined at the beam splitter **4**, their relative phase can be controlled using the dispersive medium **9** for the following reason: in the path of travel anticlockwise in the ring interferometer **20**, a light beam of light frequency f_0 passes through the dispersive medium **9** whereas in the path of travel clockwise in the ring interferometer **20**, a light beam of light frequency $2f_0$ passes through the dispersive medium **9**. To wit, the relative phase between the first and second squeezed light beams traveling in mutually contrary directions, clockwise and anticlockwise, and different in light frequency in passing through the dispersive medium **9** can be varied by varying the magnitude of dispersion.

Further, the relative phase between the first and second squeezed light beams can be set by the dispersive medium **9** to be equal to a value as desired, e.g. $\pi/2$, thereby generating the first and second quantum entangled beams **10** and **11**.

According to the quantum entanglement generating system **30**,**35** of the first, second embodiment of the present invention, the two, i.e., first and second, squeezed light beams, not following mutually different paths but turning in mutually contrary directions in the same ring interferometer **20**, have a relative phase therebetween mechanically stable. Further, the light wavelength is converted within the ring interferometer **20**. To wit, squeezed light beams of light frequency f_0 can be generated in the optical parametric amplifier **9** by a pumping light beam of light frequency $2f_0$ from the laser light source **1** to control the dispersive medium **9**, thereby varying the relative phase between the first and second squeezed light beams. Thus, according to the quantum entanglement generating system **30**, **35** of the present invention, the relative phase difference between the first and second squeezed light beams can be stably controlled in the entangle generation to combine the first and second squeezed light beams.

Third embodiment of the quantum entanglement generating system

Mention is next made of a quantum entanglement generating system **40** according to a third embodiment of the present invention.

FIG. **3** is a block diagram illustrating in a plan view the makeup of the quantum entanglement generating system **40** according to the third embodiment of the present invention. Optical paths are shown in straight lines. The quantum entanglement generating system **40** shown in FIG. **2** differs from the quantum entanglement generating system **30** shown in FIG. **1** in that a ring interferometer indicated by reference character **25** is used. The makeup elsewhere is identical to that of the quantum entanglement generating system **30** whose repeated description is omitted.

The ring interferometer **25** comprises a beam splitter **4**, a dispersive medium **9**, a second mirror **5**, an optical parametric amplifier **6** and a third mirror **7**. The second mirror **5** is disposed vertically downwards (in the −Y direction) of the beam splitter **4**. The third mirror **7** is disposed in the X direction (rightwards) of the beam splitter **4**.

In the ring interferometer **25**, the beam splitter **4**, the second and third mirrors **5** and **7** are disposed respectively at the three apexes of a triangle to form an optical path. In other words, in the ring interferometer **25** are arranged in order anticlockwise the beam splitter **4**, and the first and second mirrors **5** and **7** for the ring interferometer **25**. The optical parametric amplifier **6** is disposed along an axis of the optical path that is formed by the second mirror **5** and the third mirror **7**. The dispersive medium **9** is disposed along an axis of optical path that is formed by the beam splitter **4** and the second mirror **5**.

The ring interferometer **25** as is the ring interferometer **20** is preferably formed on a substrate. With the ring interferometer **25** formed on a substrate, it is possible to stabilize its optical path length against variations in temperature and vibrations while simplifying the system in its apparatus makeup. The first mirror **3** may be formed on the same substrate as well. Light from the laser light source **1** may be guided to the substrate via an optical fiber to make further stable the optical path length against variations in temperature and vibrations.

Explanation is next given of quantum entanglement generation by the quantum entanglement generating system **40** according to the third form of implementation.

A light beam of light frequency $2f_0$ emitted from the laser light source **1** reflects on the first mirror **3** and passes through the beam splitter **4** and thereafter passes through the dispersive medium **9** and reflects on the second mirror **5**, constituting a pumping light input to the optical parametric amplifier **6**. The optical parametric amplifier **6** generates a first squeezed light beam of light frequency f_0. The first squeezed light beam of light frequency f_0 may be of a horizontally polarized light ray.

The first squeezed light beam traveling anticlockwise in the ring interferometer **25** is reflected by the third mirror **7**, arriving in the beam splitter **4**.

The light beam of light frequency $2f_0$ emitted from the laser light source **1** and reflected on the first minor **3** is incident in the beam splitter **4**. The light beam of light frequency $2f_0$ incident in the beam splitter **4** is reflected in the X-direction, reflected by the third minor **7** downwards off to the left on the sheet and incident into the optical parametric amplifier **6** to generate a second squeezed light beam of light frequency f_0.

Next, the second squeezed light beam of light frequency f_0 after reflecting on the second minor **5** in the Y-direction is passed through the dispersive medium **9**, arriving in the beam splitter **4**. Thus, the second squeezed light ray advances clockwise in the ring interferometer **25**, passing through the dispersive medium **9** and arrives in the beam splitter **4**.

In this way, the first and second squeezed light beams generated in the ring interferometer **25** are combined, or spatially overlapped at the beam splitter **4**. Then, a first quantum entangled beam **10** and a second quantum entangled beam **11** which are quantum correlated can be generated by operating the dispersive medium **9** so as to make the relative phase between the first and second squeezed light beams equal to $\pi/2$. The first quantum entangled beam **10** after passing the beam splitter **4** is emitted, as shown in FIG. **3**, in the −X-direction (leftwards). The second quantum entangled beam **11** is reflected by the beam splitter **4** into the Y direction (upwards) and emitted upon passing through the first mirror **3**.

The relative phase between the first and second squeezed light rays can be set by the dispersive medium **9** to be equal to $\pi/2$, thereby generating the first and second quantum entangled beams **10** and **11**.

(First Embodiment of the quantum entanglement generating and detecting system)

Mention is next made of a quantum entanglement generating and detecting system **50** according to a first embodiment of the present invention.

FIG. **4** is a block diagram illustrating in a plan view the makeup of a quantum entanglement generating and detecting system **50** according to its first embodiment of the present invention. Optical paths are shown in straight lines. The quantum entanglement generating and detecting system **50** is made up of a means for generating a quantum entangled beam and a means for detecting a quantum entangled beam as generated. As shown in FIG. **4**, the quantum entanglement generating and detecting system **50** comprises a light source part **60**, a ring interferometer **70**, a first homodyne detector **80** and a second homodyne detector **90**.

Here, quantum entangled beams are generated by the light source part **60** and the ring interferometer **70**. Signals of quantum entangled beams as generated are detected by the first and second homodyne detectors **80** and **90**. In this case, the light beam from the light source part **60** constitutes local-oscillator light beams. Homodyne detection is detection by mixing a signal light beam and a local-oscillator light beam having an identical light frequency and measures the quadrature amplitude of the signal light beam.

The light source part **60** comprises a pulsed laser light source **100**, and a half wave plate **102**, a second harmonic generator **105**, a polarizing beam splitter **109**, a two-wavelength wave plate **102**, a mirror **114**, a polarizing beam splitter **117** and a two-wavelength wave plate **118**. The laser light passing the two-wavelength wave plate **118** is made incident to the ring interferometer **70**.

The pulsed laser light source **100** produces a light pulse **101** which is of light frequency f_0 and horizontally polarized. The horizontally polarized, pulsed light beam **101** is incident to a zero-order half-wave plate **102** for the light frequency f_0. The half wave plate **102** rotates a plane of polarization of the pulsed light beam **101** and converts it into an obliquely linearly polarized light ray. In other words, the plane of polarization of the pulsed light ray **101** is converted into a horizontally polarized component **103** and a vertically polarized component **104** which are injected into the second harmonic generator **105**. In this case, the intensity of a local-oscillator light beam can be adjusted by the angle of rotation of the plane of polarization.

The horizontally polarized component **103** of the pulsed light ray of light frequency f_0 is in part converted into a pulsed laser light beam **106** which is of light frequency $2f_0$ and horizontally polarized. The pulsed laser light beam horizontally polarized **106** is passed as it is through the polarizing beam splitter **109** and the two-wavelength wave plate **112** without undergoing any change there. The second harmonic generator **105** used may be made of a crystal having a secondary nonlinear optical effect, e.g., of an optical waveguide composed of periodically-poled $LiNbO_3$.

A light beam **107** of light frequency f_0 as the horizontally polarized component of light not converted into light of light frequency $2f_0$ is reflected by the polarizing beam splitter **109** for light frequency f_0 so arranged as to transmit the vertically polarized light and becomes a horizontally polarized component **110** of light of light frequency f_0 which is emitted externally and not used in generating entangled beams. This is due to a disturbance of the temporal waveform of a fundamental wave that remains unconverted if the efficiency of conversion into second harmonics is high (see Non-Patent Reference 3). However, if the efficiency of conversion into second harmonics is not high, then the horizontally polarized component **110** need not necessarily be discarded and can be reused.

On the other hand, the vertically polarized component of a pulsed light beam of light frequency f_0 is passed through the second harmonic generator **105** without undergoing any nonlinear interaction therewith and its output vertically polarized component thus is identical in pulse width and spectrum to pulses output from the original pulsed laser light source **100**. The vertically polarized component **108** of the pulsed light beam of light frequency f_0 passes through the polarizing beam splitter **109** and its resulting vertically polarized light beam **111** is converted by the two-wavelength wave plate **112** into a horizontally polarized light **113** of half wavelength if with light frequency f_0 and of one wavelength if with light frequency $2f_0$.

The mirror **114** used should be one that is high in reflectance for light frequency $2f_0$. For the mirror **114**, a mirror made of a dielectric can be used. A reflectance of the mirror **114** for light frequency f_0 may be chosen depending on an intensity of the local-oscillator light beam as needed for the homodyne detection which will later be described. If the mirror **114** has a reflectance that is low for light frequency f_0, then it can be used as a filter for selectively attenuating the light frequency f_0.

Accordingly, the light beam emitted from the pulsed laser light source **100** comes to be a pulsed light beam **115** of light frequency f_0 and a pulsed light beam **116** of light frequency $2f_0$ which are both horizontally polarized on an identical optical axis. Here, the pulsed light beam **115** of light frequency f_0 and the pulsed light beam **116** of light frequency $2f_0$ as they are on the same optical path are also called the coaxial pulsed light beams **115** and **116** of light frequencies f_0 and $2f_0$, respectively.

A polarizing beam splitter **117** is arranged so as to allow a horizontally polarized component of light frequency f_0 to be passed therethrough. Thus, a pulsed light beam of light frequency f_0 is passed as it is. Next, the pulsed light beam of light frequency f_0 is converted by a two wavelength wave plate **118** into a vertically polarized light ray.

The ring interferometer **70** comprises a beam splitter **120** having a special function as will later be described (i.e., hereinafter, referred to as "special beam splitter"), a mirror **121**, an optical parametric amplifier **122**, a mirror **123** and a dispersive medium **124**. In a plan view, the mirror **121** is disposed in a −X direction (leftwards) of the special beam splitter **120** and the mirror **123** is disposed in a −Y direction (downwards) of the special beam splitter **120**.

In the ring interferometer **70**, the special beam splitter **120** and the mirrors **121** and **123** are disposed to lie at the three apexes of a triangle. The optical parametric amplifier **122** is disposed to lie along an axis of optical path formed by the mirrors **121** and **123**. The dispersive medium **124** is disposed to lie along an axis of optical path formed by the special beam splitter **120** and the mirror **123**. The ring interferometer **70** as is the ring interferometer **20** is preferably formed on a breadboard or substrate. Forming the ring interferometer **70** on a breadboard or substrate allows stabilizing its optical path length against variations in temperature and vibrations while simplifying the system in its apparatus makeup.

The special beam splitter **120** has a transmissivity and a reflectance, of about 50%, equally to horizontally linearly polarized light beams of light frequency f_0 and light frequency $2f_0$, and has a reflectance of about 100% to a vertically linearly polarized light beam of light frequency f_0. A pulsed light beam **116** of light frequency $2f_0$ horizontally polarized is therefore bifurcated by the special beam splitter **120** at a proportion of about 1/1. It is then injected into the ring interferometer **70** to generate a first and a second quantum entangled beam **131** and **132** as will later be described.

The mirrors **121** and **123** are each a mirror which is of a reflectance of about 100% to both light frequencies f_0 and $2f_0$ and composed, e.g., of a dielectric.

The optical parametric amplifier **122** used may be made of a crystal having a secondary nonlinear optical effect and may consist of, e.g., periodically-poled $LiNbO_3$.

The dispersive medium **124** comprises a first glass plate **125** and a second glass plate **126**. The first and second glass plates **125** and **126** can each be a wedged glass plate, an optical part capable of imparting a small difference in optical path length between wavelengths. An example of the wedged glass plate **125**, **126** is formed with one face perpendicular to an optical axis and the other face inclined to the optical axis. The wedged glass when used may be composed of borosilicate glass such as BK7. The first or second wedged glass plate **125**, **126** may be made movable perpendicular to the optical axis. The first or second wedged glass plate **125**, **126** if moved perpendicular to the direction of travel of light is capable of limiting variations in beam position of the light after passing the two wedged glass plates.

In the makeup mentioned above, placing the wedged glass plates **125** and **126** contrariwise to each other in wedge orientation, i.e., with their thinner sides placed contrariwise right and left with respect to the optical axis, allows further limiting variations in the light beam position.

Further, providing both faces of the wedged glass plate **125**, **126** with an anti-reflection coating to light frequency f_0 and light frequency $2f_0$ can impart an increased transmissivity to the wedged glass plates **125** and **126**. Moving the wedged glass plate **125**, **126** perpendicularly to the optical axis to vary the optical path length through the glass plates allows achieving the effect of dispersion. To wit, with the use of the first wedged plate **125** and the second wedged plate **126**, by the effect that their refractive indices changes with change in light frequency, it is possible to vary the relative optical path length between the light frequency f_0 and light frequency $2f_0$. For example, assume that the wedged glass plates **125** and **126** are composed of BK7 and have an angle of inclination of 1 degree. If the wavelength of light of light frequency f_0 is 1535 nm and the wavelength of light of light frequency $2f_0$ is 767 nm, moving the wedged glass plate **125**, **126** by 0.86 mm in a perpendicular direction to the optical axis causes the relative phase between light of light frequency f_0 and light of light frequency $2f_0$ to change by $\pi/2$. A variation then caused in relative position between beams of light of light frequency f_0 and of light of light frequency $2f_0$ is less than 3 nm. Also, the first and second wedged glass plates are preferably positioned so that the light beam is made incident to the first glass plate **125** perpendicularly thereto and emitted out of the second wedged glass plate **126** perpendicularly thereto. Further, the two wedged glass plates **125** and **126** are preferably disposed to be adjacent to each other as much as possible. These make it possible to minimize the variation in beam position between light of light frequency f_0 and light of light frequency $2f_0$.

Explanation is next given of operations of the quantum entanglement generating and detecting system according to the first form of implementation.

Of two light beams of light frequency $2f_0$ split into by the special beam splitter **120** at a ratio of about 1/1, one light beam passes anticlockwise in the ring interferometer **70**, namely the mirror **121**, the optical parametric amplifier **122**, the mirror **123** and the dispersive medium **124** in order. The other light beam passes clockwise in the ring interferometer **70**, namely the dispersive medium **124**, the mirror **123**, the optical parametric amplifier **122** and the mirror **121** in order.

The horizontally polarized light beam of light frequency $2f_0$ advancing anticlockwise is incident into the optical parametric amplifier **122** where the pulsed light beam of light frequency $2f_0$ acts as a pumping light for the parametric amplification to generate a horizontally polarized, squeezed light beam of light frequency f_0. The squeezed light beam traveling anticlockwise is reflected by the mirror **123**, passes through the dispersive medium **124** and is incident again into the special beam splitter **120**.

The horizontally polarized light beam of light frequency $2f_0$ advancing clockwise passes through the dispersive medium **124** and is incident into the optical parametric amplifier **122** where the pulsed light ray of light frequency $2f_0$ acts as a pumping light beam for the parametric amplification to generate a horizontally polarized, squeezed light ray of light frequency f_0. The squeezed light beam traveling clockwise is reflected by the mirror **121** and incident again into the special beam splitter **120**.

The two squeezed light beams incident to the special beam splitter **120** and advancing contrariwise to each other, i.e., the squeezed light beam advancing clockwise and the squeezed light beam advancing anticlockwise are each a horizontally polarized light beam and can be combined in 1 to 1. The relative phase between the two squeezed light beams can be set at a value as desired by relative position of the first and second wedged glass plates in the dispersive medium **124**. If relative phase difference is set to be $\pi/2$, a first and a second quantum entangled beam **130** and **131** can be generated which are quantum correlated.

The special beam splitter **120** has a transmissivity and a reflectance of 50% each to a horizontally polarized light beam of light frequency f_0. The quantum entangled beam generated are: a first quantum entangled beam **130** as the component reflected by the special beam splitter **120** and a second quantum entangled beam **131** as the component passing through the special beam splitter **120**.

As shown, the first quantum entangled beam **130** is incident to a first homodyne detector **80** via a half wave plate **132**, a mirror **133** and a special beam splitter **134**. The wave plate **132** is a zero-order half-wave plate for light frequency f_0 and converts a horizontally, linearly polarized light beam into a vertically polarized light beam. The mirror **133** reflects the light beam of light frequency f_0 and is composed of, e.g., a dielectric. The special beam splitter **134** reflects the vertically polarized light beam. The first quantum entangled beam **130** is thereby converted into a vertically polarized light beam and then incident into the first homodyne detector **80**.

The second quantum entangled beam **131** is converted by the two wavelength wave plate **118** into a vertically polarized light beam, reflected by the polarizing beam splitter **117**, a special beam splitter **134** and a mirror **135** and incident into the second homodyne detector **90**. The mirror **135** reflects the light beam of light frequency f_0 and is composed of, e.g., a dielectric.

Mention is made of light as a local-oscillator light beam for the first, second homodyne detector **80**, **90**. From the light from the light source part **60**, vertically linearly polarized light beams of light frequency f_0 and light frequency $2f_0$ are coaxially formed and incident into the special beam splitter **120**. A pulsed light beam of light frequency $2f_0$ as mentioned above is used to generate quantum entangled beams in the ring interferometer **70**. On the other hand, a vertically linearly polarized light beam of light frequency f_0 constitutes a pulsed light beam as a local-oscillator light beam for the first and second homodyne detectors **80** and **90**. Mention is made of its details below.

The vertically linearly polarized light beam of light frequency f_0 is reflected by the special beam splitter **120** and reflected by the mirror **121** shown disposed at its horizontally left hand side in FIG. **4**, passes through the optical parametric amplifier **122**, and is reflected by the mirror **123** and incident again into the special beam splitter **120**. Here, the special beam splitter **120** reflects the vertically linearly polarized light beam of light frequency f_0. Thus, the horizontally linearly polarized light beam of light frequency f_0 injected into the special beam splitter **120** is reflected thereby, advancing towards the half wave plate **132** of zero order to light frequency f_0. Injected into the half-wave plate **132**, the vertically linearly polarized light beam of light frequency f_0 is caused thereby to rotate by 90° its plane of polarization for the light beam of light frequency f_0 whereby the vertically linearly polarized light beam of light frequency f_0 is converted into a horizontally polarized light beam, which is in turn reflected by the mirror **133** whose reflectance is high to a light beam of light frequency f_0, thus arriving in the special beam splitter **134**.

The special beam splitter **134** has a transmissivity and a reflectance, of about 50%, to the horizontally linearly polarized light beam of light frequency f_0. Therefore, the horizontally polarized light beam of light frequency f_0 injected into the special beam splitter **134** is split into a reflected and a transmitted light beam. The reflected light beam is incident into the first homodyne detector **80** while the transmitted light beam is incident into the second homodyne detector **90**, each of them serving as a local-oscillator light beam for the homodyne detector **80**, **90**.

Mention is next made of the first and second homodyne detectors **80** and **90**.

The first homodyne detector **80** comprises an electrooptic crystal **136**, a half wave plate **138**, a polarizing beam splitter **140**, two photodiode **142** and **143**, a RF combiner **146** and an amplifier **148**. The second homodyne detector **90** like the first homodyne detector **80** comprises an electrooptic crystal **137**, a half wave plate **139**, a polarizing beam splitter **141**, two photodiode **144** and **145**, a RF combiner **147** and an amplifier **149**.

Into the first homodyne detector **80** is injected the first quantum entangle beam **130** as mentioned above, i.e., are injected the vertically polarized pulse light beam of light frequency f_0 as a signal light irradiation and the horizontally linearly polarized pulse light as a local-oscillator light beam. Likewise, into the second homodyne detector **90** is injected the second quantum entangled beam **131** as mentioned above, i.e., are injected the vertically polarized pulse light beam of light frequency f_0 as a signal light irradiation and the horizontally linearly polarized pulse light as a local-oscillator light beam.

The first quantum entangled beam **130** incident into the first homodyne detector **80** is horizontally polarized while the vertically polarized and coherent pulsed light serving as the local-oscillator light beam advances on the same optical axis. To wit, the first quantum entangled beam serving as the signal light beam and the vertically polarized and coherent pulsed light serving as the local-oscillator light beam advance coaxially. Accordingly, since the first quantum entangled beam **130** and the local-oscillator light beam are made to follow an identical path, relative phase between them can be maintained quite stably.

As for the second quantum entangled beam **131** incident into the second homodyne detector **90**, the quantum entangled beam **131** and the local-oscillator light beam which after their splitting at the special beam splitter **120** meet each other at the special beam splitter **134** are made to follow partially different paths. Instability arising from this can be remedied by siting the four optical components of the special beam splitter **120**, the polarizing beam splitter **117**, the dielectric mirror **133** and the special beam splitter **134** on a common breadboard or substrate to keep the beam height low.

In the first homodyne detector **80**, it is possible to vary the relative phase between the horizontally polarized and vertically polarized components by varying the voltage applied to the electrooptic crystal **136**. The half wave plate **138** of zero order to light frequency f_0 is disposed so as to hold its plane of polarization for the linearly polarized light beam rotated by 45°. Its state of polarization is thus held that its plane of polarization is rotated by 45° with the first quantum entangled beam **130** and the local-oscillator light beam having their planes of polarization orthogonal to each other.

Thereupon, with the polarizing beam splitter **140** for light frequency f_0, the first quantum entangled beam **130** and the local-oscillating light beam can be combined together substantially at a ratio of one to one. The light beam reflecting on, and the light beam passing through, the polarizing beam splitter **140**, are incident to the photodiodes **142** and **143**, respectively.

The RF combiner **146** furnishes as its output a difference in photo current between the two photodiodes **142** and **143** which is amplified by the amplifier **148**. By measuring its output voltage, it is made possible to determine a quadrature amplitude for the first quantum entangled beam **130**. The RF combiner **146** is a means for deriving a differential in output between two photodiode sensors **142** and **143**. Instead of using the RF combiner **146**, an anode and cathode of the two photodiodes **142** and **143** can be connected together to take out a differential in current.

As for the second homodyne detector **90** as in the first homodyne detector **80**, the phase relative between the horizontally polarized component and the vertically polarized component can be varied by varying the voltage applied to the electrooptic crystal **137**. The half wave plate **139** of zero order to light frequency f_0 is disposed so as to hold its plane of polarization for the linearly polarized light beam rotated by 45°. As a result, its state of polarization is held that its plane of polarization is rotated by 45° with the first quantum entangled beam **130** and the local-oscillator light beam having their planes of polarization orthogonal to each other.

Thereupon, with the polarizing beam splitter **141** for light frequency fo, the second quantum entangled beam **131** and the local-oscillator light beam can be combined together substantially at a ratio of one to one. The light beam reflecting on, and the light ray passing through, the polarizing beam splitter **141**, are incident to the photodiodes **144** and **145**, respectively.

The RF combiner **147** furnishes as its output a difference in photo current between the two photodiodes **144** and **145** which is amplified by the amplifier **149**. By measuring its output voltage, it is made possible to determine a quadrature amplitude for the second quantum entangled beam **131**. The RF combiner **147** is a means for deriving a differential in output between two photodiode sensors **144** and **145**. Instead of using the RF combiner **147**, an anode and cathode of the two photodiodes **144** and **145** can be connected together to take out a differential in current.

According to the makeup mentioned above, it is possible to generate a quantum entanglement stably by keeping stable the relative phase between two squeezed light rays. It is further possible to output a local-oscillator light beam coaxially with the quantum entanglement and to improve the stability at which the homodyne detection is achieved.

In the present form of implementation, the utilization of a degree of freedom of polarization allows a quantum entangled beam and a local-oscillator light beam for homodyne detection to be produced coaxially, thereby holding stable the relative phase between the entangled beam and the locally oscillating light ray.

(Second Embodiment of the Quantum Entanglement Generating and Detecting System)

Mention is next made of a quantum entanglement generating and detecting system **150** according to a second form of implementation thereof in accordance with the present invention.

FIG. **5** is a block diagram illustrating in a plan view the makeup of the quantum entanglement generating and detecting system **50** according to its first form of implementation in accordance with the present invention. Optical paths are shown in straight lines. As shown in FIG. **5**, the quantum entanglement generating and detecting system **150** is made up of a generating means for generating quantum entangled beams and a detecting means for detecting quantum entangled beams generated. The generating means comprises a light source part **160**, a ring interferometer **170**, and the detecting means comprises a first homodyne detector **180** and a second homodyne detector **190**.

The light source part **160** differs from the light source part **60** in the quantum entanglement generating and detecting system **50** according to the first form of implementation in that the second harmonic generator **105** differs. The second harmonic generator **105** here comprises an optical waveguide **201** constituting a second harmonic generator, and lenses **200** and **202** constituting the condensing means and disposed closer to the pulsed laser light source **100** and disposed at the second harmonic emission side, respectively. To wit, the difference is that the optical waveguide **201** is disposed between the lenses **200** and **202**. The optical waveguide **201** for use may be an optical waveguide composed of $LiNbO_3$ having MgO added thereto and having its polarization periodically inverted. The lenses **200** and **202** used may be each a convex lens. Light condensing from the pulsed laser light source **100** into the optical waveguide **201** can be achieved efficiently by the convex lens **200** Likewise, the second harmonic produced from the optical waveguide **201** can be efficiently emitted by using the lens **202**. The other makeup components in the light source part **60** are identical to those in the quantum entanglement generating and detecting system **50** and their repeated description here is omitted.

The ring interferometer **170** in the quantum entanglement generating and detecting system **150** according to the second form of implementation is made up identically to the ring interferometer **70** in the quantum entanglement generating and detecting system **70** according to the second form of implementation in that it includes the special beam splitter **120**, but differ in that it involves a different optical path shape (a first difference), a different structure of the optical parametric amplifier **122** (a second difference), a different structure of the dispersive medium **124** (a third difference) and a structure that makes it possible for red color filters **205** and **209** to be inserted (a fourth difference). These differences will be described below in detail with reference to FIG. **5**.

Mention is first made of the optical path shape constituting the first difference.

The ring interferometer **170** as shown in FIG. **5** comprises the special beam splitter **120**, mirrors **203** and **204**, the mirror **121**, the optical parametric amplifier **122**, the mirror **123**, a mirror **210** and the dispersive medium **124**. The mirror **203** is disposed in a plan view in the –X direction of the special beam splitter **120**, the mirror **204** in the Y direction of the mirror **3**, the mirror **121** in the –X direction of the mirror **204**, the mirror **123** in the –Y direction of the optical parametric amplifier **122**, and the mirror **210** in the X direction of the mirror **123** and in the –Y direction of the special beam splitter **120**.

Here, the mirrors **203**, **204** and **210** as are the mirrors **121** and **123** are each a mirror which has a reflectance of about 100% to light frequencies f_0 and $2f_0$ and consists, e.g., of a dielectric.

In the ring interferometer **170**, there are disposed the beam splitter **120** and the mirrors **203**, **204**, **121**, **123**, **210** to lie at the six apexes of a hexagon or hex-angle, respectively. The ring interferometer **170** in the second form of implementation differs from the ring interferometer **70** in the first form of implementation in that it has the hexagonal or hex-angular optical path while the ring interferometer **70** has the triangular optical path. This notwithstanding, the ring interferometers **70** and **170** operate basically in the same way.

Mention is next made of the optical parametric amplifier **122** constituting the second difference.

It differs from the ring interferometer **70** according to the first form of implementation in that lenses **206** and **208** are disposed, respectively, in front and rear of the optical waveguide **207** in the direction of its optical axis. The optical parametric amplifier **122** in the ring interferometer **170** is disposed along the axis of an optical path formed between the mirrors **121** and **123** and is made up of the two lenses **206** and **208** and the optical waveguide **207** disposed between them and consisting of MgO added $LiNbO_3$ and having its polarization periodically inverted. The lenses **206** and **208** may each be a convex lens. The light beam of light frequency f_0 and the light beam of light frequency $2f_0$ encircling in the ring interferometer **170** and in passing the optical waveguide **207** are efficiently injected into and emitted from the optical waveguide **207** through the two lenses **206** and **208**.

In comparison with the ring interferometer **70** according to the first form of implementation, the mirrors **203**, **204** and **210** are added to the ring interferometer **170** according to this form of implementation. With the two or more lenses disposed at both sides of the optical waveguide, respectively, it is possible to optimize the efficiency of injection of light pulses into the optical waveguide **207** from its both sides. Also, by equalizing distances between the optical waveguide **207** and the special beam splitter **120** for the light rays traveling clockwise and anticlockwise in the ring interferometer **170**, the concurrence in spatial mode between squeezed light beams formed in the clockwise and anticlockwise directions can be enhanced.

Mention is made of the dispersive medium **124** constituting the third difference.

As the dispersive medium **124** disposed in the ring interferometer **170**, use is made of two planar glass plates **211** and **212**, each having two planes or flat surfaces disposed parallel to each other (such a glass plate is hereinafter referred to as a "parallel planar glass"). This is a distinction from the ring interferometer **70** according to the first form of implementation in which the two wedged glass plates **125** and **126** are used.

The parallel planar glass plates **211** and **212** are disposed so as to incline with an angle of inclination to, and symmetrically with respect to a plane perpendicular to, the optical axis. The angle of inclination to the optical axis is preferably varied while holding its equality between the two parallel planar glasses **211** and **212**. If so, a variation in the angle of inclination of the parallel planar glass plate **211**, **212** will keep the optical axis of a light beam after passing through the parallel planar glass plates **211** and **212** unaltered in position. Varying the angle of inclination of the parallel planar glass plate **211**, **212** to the plane perpendicular to the optical axis causes the optical path for light to pass between the parallel planar glass plates **211** and **212** to vary in length; it is thus possible to achieve the effect of dispersion as with the two wedged glass plates. To wit, with the use of the first and second parallel planar glass plates **211** and **212**, by the effect that their refractivity changes with change in light frequency, it is possible to vary the relative optical path length between the light frequency f_0 and light frequency $2f_0$.

Here, the parallel planar plate **211**, **212** used may be composed of borosilicate glass such as BK7. Further, both surfaces of the parallel planar glass plate **211**, **212** are preferably provided with a coating non-reflective to light frequency f_0 and light frequency $2f_0$ to impart thereto an increased transmissivity for a light beam of light frequency f_0 and a light beam of light frequency $2f_0$.

For example, let it be assumed that the parallel planar glass plate **211**, **212** is composed of BK7 and has a thickness of 5 mm. If the wavelength of light of light frequency f_0 is 1535 nm and the wavelength of light of light frequency $2f_0$ is 762 nm, turning the parallel planar glass plates **211** and **212** symmetrically from 0° to 4.8° causes the relative phase between light of light frequency f_0 and light of light frequency $2f_0$ to change by $\pi/2$.

Mention is next made of the red color filters **205** and **209** constituting the fourth difference.

The ring interferometer **170** is provided on its optical axis with the two red color filters **205** and **209** removably, of which as shown the red color filter **205** is disposed on the optical axis between the mirror **121** and the lens **206** and the red color filter **208** is disposed on the optical axis between the lens **209** and the mirror **123**. The red color filter **205**, **209** is capable in property of transmitting substantially 100% of light frequency f_0 and absorbing substantially 100% of light frequency $2f_0$. Disposing the red color filters **205** and **209** as described above, viz. in front and rear of the optical waveguide **207** sandwiched between the two lenses prevents the light beam of light frequency $2f_0$ from entering the optical waveguide **207**. Since the pulsed light beam of light frequency $2f_0$ for acting as a pumping light beam is thus removed by the red color filters **205** and **206**, no squeezed horizontally polarized light ray of light frequency f_0 is generated in and from the optical waveguide **207** constituting the optical parametric amplifier **122**. It follows, therefore, that no first or second quantum entangled beam **130**, **131** is generated from the ring interferometer **170**.

If the red color filter **205**, **209** is inserted to lie on the optical axis, then no squeezed light beam but only a local-oscillator light beam of light frequency f_0 as a signal light beam is incident into the homodyne detector **180**, **190**. The homodyne detector **180**, **190** thus operates with no signal incident thereto, viz., as a detector of shot noise level.

The quantum entanglement generating and detecting system **150** according to the second form of implementation in which the light source part **160** and the ring interferometer **170** are like those in the quantum entanglement generating and detecting system **50** according to the first form of implementation except that it can incorporate a red color filter **205**, **209**, similarly generates a first and a second quantum entangled beam **130** and **131**.

Mention is made of an optical path for a first quantum entangled beam **130** to propagate into the first homodyne detector **180**.

As shown, a first quantum entangled beam **130** of horizontally linearly polarized light passes the half wave plate **132**, a special beam splitter **213** and a mirror **214** in order and is injected into the first homodyne detector **180**. The half wave plate **132** is a wave plate of zero order to light frequency f_0 and converts a horizontally linearly polarized light beam to a vertically polarized light beam at light frequency f_0. The special beam splitter **213** reflects the vertically polarized light ray and this light beam of light frequency f_0 is reflected by a mirror **214**. The mirror **214** is composed of, e.g., a dielectric.

Thus, the first quantum entangled beam **130** after it is converted to the vertically polarized light beam is injected into the first homodyne detector **180**. This is as it is in the quantum entanglement generating and detecting system **50** according to the first form of implementation.

Mention is made of an optical path for a second quantum entangled beam **131** to propagate into the second homodyne detector **190**.

The second quantum entangled beam **131** is converted by the two wavelength wave plate **118** into a vertically polarized light beam, passed through the polarizing beam splitter **117** and a polarizing beam splitter **219**, reflected by a mirror **220** and injected into the second homodyne detector **190**. The mirror **220** is composed of, e.g., a dielectric and reflects a light ray of light frequency f_0.

Thus, the second quantum entangled beam **131** after it is converted to the vertically polarized light is injected into the second homodyne detector **190**. This is as it is in the quantum entanglement generating and detecting system **50** according to the first form of implementation.

Mention is next made of an optical path for a local-oscillator light beam to propagate.

The vertically polarized light ray of light frequency f_0 from the light source **160** is reflected on the special beam splitter **120** and after encircling the ring interferometer **170** is reflected again on the special beam splitter **120**. The reflected pulsed light beam of light frequency f_0 vertically polarized is converted by the half wave plate **132** and split by the special beam splitter **213** into a reflected light beam of horizontal polarization and a transmitted light beam of horizontal polarization at a ratio in intensity of 50 to 50. Horizontally polarized, the pulsed light beam of light frequency f_0 reflected by the special beam splitter **213** is reflected by the mirror **214** and injected into the first homodyne detector **180** to provide the local-oscillator light beam.

On the other hand, the pulsed light ray beam horizontal polarization passed through the special beam splitter **213** passes through the dispersive medium **218** and the polarizing beam splitter **219** and reflects on the mirror **220** and thereafter is injected into the second homodyne detector **190** for use as the local-oscillator light beam.

In the homodyne detectors **80** and **90** of the quantum entanglement generating and detecting system **50** according to the first form of implementation, the difference in phase between the first quantum entangled beam **130** horizontally polarized and the local-oscillator light beam vertically polarized is adjusted by the first electrooptic crystal **136**. Likewise, the difference in phase between the second quantum entangled beam **131** horizontally polarized and the local-oscillator light beam vertically polarized is adjusted by the second electrooptic crystal **137**.

Of the homodyne detector **180**, **190** in the quantum entanglement generating and detecting system **150** according to the second form of implementation, a structure is adopted which differs from that of the homodyne detector **80**, **90** in the quantum entanglement generating and detecting system **50** according to the first form of implementation.

The first homodyne detector **180** is made up of a bandpass filter **221**, a red color filter **223**, a quarter wave plate **225** that can be removably inserted on an optical axis, a half wave plate **138**, a polarizing beam splitter **144**, a lens **226** for condensing the light beam reflected by the polarizing beam splitter **140**, a photodiode **142** for detecting the condensed, reflected light beam, a lens **227** for condensing the light ray transmitted through the polarizing beam splitter **140**, a photodiode **143** for detecting the condensed, transmitted light beam and a RF combiner **146** that provides an output representing a difference in photocurrent between the light beams detected by the two photodiodes **142** and **143**. The output furnished from the RF combiner **146** may, as in the homodyne detector **80**, be amplified by an amplifier **148** not shown.

The first homodyne detector **180** is identical in makeup to the first homodyne detector **80** except that on the optical axis for the mirror **214** and the half wave plate **138** there are arranged the bandpass filter **221**, the red color filter **223**, the quarter wave plate **225** that can be removably disposed on the optical axis, and the lenses **226** and **227**.

The bandpass filter **221** has a light transmission property which is the highest in transmissivity to light frequency f_0. Consequently, components of the light frequency not interfering with the local-oscillator light beam of light frequency f_0 are removed as much as possible.

The red color filter **223** as is the red color filter **205**, **209** used in the ring interferometer **170** is of a transmissivity of about 100%, having the optical property with a transmissivity of nearly **0** to light frequency f_0. The red color filter **223** thus prevents light pulses of light frequency $2f_0$ from entering the photodiode **142**, **143**.

If the quarter wave plate **225** is inserted in the optical path, then the difference in phase between the horizontally and vertically polarized components of light pulses of light frequency f_0 can be shifted by $\pi/2$. Disposing the quarter wave plate **225** in the measurement allows the phase difference between the first quantum entangled beam **130** of vertical polarization and the local-oscillator light beam of horizontal polarization to be shifted from that if the quarter wave plate **225** is not used. It is thus possible to adjust the phase difference between a first quantum entangled beam **130** of vertical polarization and a local-oscillating light beam of horizontal polarization here as well as in the first homodyne detector **80** with the electrooptic crystal **137**.

The lens **226**, **227** disposed between the polarizing beam splitter **140** and the photodiode **142**, **143** is provided for condensing, which may be, e.g., a convex lens.

The functions of the polarizing beam splitter **140**, the photodiodes **142** and **143** and the RF combiner **146** which are shown disposed at the right hand side of the half wave plate **138** in the first homodyne detector **180** are identical to those in the first homodyne detector **80**, and their repeated explanation is omitted.

Including the bandpass filter **221**, the red color filter **223** and the condensing lens **226**, **227** in the first homodyne detector **180** increases its sensitivity from that of the first homodyne detector **80**.

Mention is next made of the second homodyne detector **190**.

The second homodyne detector **190** is made up of a bandpass filter **222**, a red color filter **224**, a half wave plate **139**, a polarizing beam splitter **141**, a lens **226** for condensing the light beam reflected by the polarizing beam splitter **141**, a photodiode **144** for detecting the condensed, reflected light beam, a lens **227** for condensing the light beam transmitted through the polarizing beam splitter **141**, a photodiode **145** for detecting the condensed, transmitted light beam and a RF combiner **147** that provides an output representing a difference in photocurrent between the light beams detected by the two photodiodes **144** and **145**. The output furnished from the RF combiner **147** may, as in the homodyne detector **90**, be amplified by an amplifier **149** not shown.

The second homodyne detector **190** differs from the first homodyne detector **180** in that there is omitted a quarter wave plate **225** that can be removable disposed on the optical axis. To wits, a dispersive medium **218** is used in lieu of the quarter wave plate **225** in the first homodyne detector **180**. The dispersive medium **218** is disposed on an optical axis between the beam splitter **219** and the mirror **215** reflecting horizontally polarized light pulses transmitted through the special beam splitter **213** as mentioned before.

The dispersive medium **218** comprises a pair of glass plates **216** and **217**. The two glass plates **216** and **217** used may each be a wedged glass plate as an optical component that is capable of imparting a small difference in optical path length between wavelengths. As mentioned before, the wedged glass plates **216** and **217** are such that the glass plate **216** or glass plate **217** can be moved in a direction perpendicular to the optical axis. Moving the glass plate **216** or **217** perpendicularly to the optical axis allows the difference in phase between the second quantum entangled beam **131** and the local-oscillator light beam to be varied in the second homodyne detector **190**.

Including the bandpass filter **222**, the red color filter **224** and the condensing lens **228**, **229** in the second homodyne detector **190** as in the first homodyne detector **180** increases its sensitivity from that of the second homodyne detector **90**.

(Criterion for Judging an Entanglement)

Mention is next made of the criterion for judging an entanglement of a first and a second entangled beam **130**,**131**.

Let it be assumed that the quadrature amplitudes of a first and a second entangled beam **130**,**131** are $X_a(\phi_a)$, $X_b(\phi_b)$, respectively, where ϕ_a and ϕ_b represent differences in phase between the first and second quantum entangled beams **130** and **131** and their corresponding local-oscillator light beams, respectively.

Assume, also, that the quadrature amplitudes in two vacuum states are represented by $X_{a,\ vac}$ and $X_{b,\ vac}$, respectively.

A sufficient conditions for generated states to be entangled is expressed by equation (1) below (see Non-Patent Reference 4).

[Formula 1]

$$\langle\Delta^2(X_a(\phi_{a1})+X_b(\phi_{b1}))\rangle+\langle\Delta^2(X_a(\phi_{a2})-X_b(\phi_{b2}))\rangle<\langle\Delta^2(X_{a,\ vac}+X_{b,\ vac})\rangle+\langle\Delta^2(X_{a,\ vac}-X_{b,\ vac})\rangle=2\langle\Delta^2X_{a,\ vac}\rangle+2\langle\Delta^2X_{b,\ vac}\rangle=1 \quad (1)$$

where ϕ_{a1}, ϕ_{a2}, ϕ_{b1} and ϕ_{b2} need to satisfy relations: $\phi_{a2}-\phi_{a1}=\pi/2$ and $\phi_{b2}-\phi_{b1}=\pi/2$.

If the first and second (assumptively) entangled beams **130** and **131** generated satisfy inequality (1) above, then it is proven that they are actually entangled.

Since the first entangled beam **130** and the local-oscillator light beam in the homodyne detector **180** are coaxial, ϕ_a is fixed at a certain specific value. Assuming here that the phase difference in the absence of the quarter wave plate **225** is defined as $\phi_a=\phi_{a1}$, the phase difference in the presence of the quarter wave plate **225** inserted becomes: $\phi_a=\phi_{a2}=\phi_{a1}+\pi/2$. ϕ_b can be varied to a value as desired by way of the dispersive medium **218**.

In the measurement procedure, $X_a(\phi_{a1})$ and $X_b(\phi_b)$ are measured by the homodyne detectors **180** and **190**, respectively, while ϕ_b is being discontinuously scanned in the absence of the quarter wave plate **225** on the optical axis.

Next, the quarter wave plate **225** is placed and $X_a(\phi_{a2})$ and $X_b(\phi_b)$ are measured while ϕ_b is being discontinuously scanned. Next, the red color filters **205** and **209** are placed into the ring interferometer **170**. the homodyne detectors **180** and **190** are irradiated only with the local-oscillator light beam, and $X_{a,\ vac}$ and $X_{b,\ vac}$ are measured.

From $X_a(\phi_{a1})$, $X_b(\phi_b)$, $X_a(\phi_{a2})$, $X_b(\phi_b)$, $X_{a,\ vac}$ and $X_{b,\ vac}$ thus found, values for equation (2) below can be obtained.

[Formula 2]

$$\langle\Delta^2(X_{a,\ vac}+X_{b,\ vac})\rangle+\langle\Delta^2(X_{a,\ vac}-X_{b,\ vac})\rangle=2\langle\Delta^2X_{a,\ vac}\rangle+2\langle\Delta^2X_{b,\ vac}\rangle \quad (2)$$

Example of Measurement in Second Embodiment Quantum Entanglement Generating and detecting System

Mention is made of the prime part in the makeup of the quantum entanglement generating and detection system **150**.

As the pulsed laser light source **100**, use was made of a passively Q-switched erbium (Er) doped glass laser (Tango laser made by Cobolt AB) providing a pulsed laser light beam of a wavelength of 1535 nm, a pulse duration of 3.7 ns and a pulse repetition rate of 2.7 kHz. As the second harmonic generator **105** was used an optical waveguide **201** consisting of MgO added $LiNbO_3$ and having its polarization periodically inverted. Likewise, an optical waveguide **207** consisting of MgO added $LiNbO_3$ and having its polarization periodically inverted was used to form the optical parametric amplifier **122** in the ring interferometer **170**. Thus, the light frequency f_0 corresponds to the wavelength of 1535 nm and the light frequency $2f_0$ to the wavelength of about 767 nm.

First and second quantum entangled beams **130** and **131** were generated by the quantum entanglement generating and detecting system **150** and their respective quadrature amplitudes were measured by the first and second homodyne detectors **180** and **190**. The procedure described above in connection with the criterion for judging the entanglement was followed to determine the quadrature amplitudes of the first and second quantum entangled beams: $X_a(\phi_a)$ and $X_b(\phi_b)$, ϕ_a, ϕ_b, and their quadrature amplitudes in two vacuum states: $X_{a,\ vac}$ and $X_{b,\ vac}$.

Mention is next made of results obtained in the measurement above.

FIG. **6** is a diagram illustrating scatter plots of $X_a(\phi_{a1})$ and $X_b(\phi_b)$ in a phase ($\phi_b=\phi_{b1}$) in which $\langle\Delta^2(X_a(\phi_{a1})+X_b(\phi_b))\rangle$ becomes the minimum.

As is apparent from FIG. **6**, it is seen that $X_a(\phi_{a1})$ and $X_b(\phi_{b1})$ have a correlation of sum; they yielded the value: $\langle\Delta^2(X_a(\phi_{a1})+X_b(\phi_{b1}))\rangle=0.31$. This value in turn yields −2.0 dB for a vacuum noise.

FIG. **7** is a diagram illustrating scatter plots of $X_a(\phi_{a2})$ and $X_b(\phi_{b2})$ in a phase ($\phi_b=\phi_{b1}$) which satisfies $\phi_b=\phi_{b2}=\phi_{b1}+\pi/2$.

As is apparent from FIG. **7**, it is seen that $X_a(\phi_{a2})$ and $X_b(\phi_{b2})$ have a correlation of difference; they yielded the value: $\langle\Delta^2(X_a(\phi_{a2})-X_b(\phi_{b2}))\rangle=0.33$. This value in turn yields −1.9 dB for a vacuum noise.

FIG. **8** is a graph illustrating dependency on ϕ_b of the variance of sum of and difference between a first quantum entangled beam and a second quantum entangled beam, computed from the $X_a(\phi_a)$ and $X_b(\phi_b)$ measured. In FIG. **8**, the abscissa axis represents ϕ_b (π radian) and the ordinate axis represents the magnitude of variance (dB) in comparison with the corresponding vacuum noise. In the graph, marks of black circle (●) and marks of small crosses (×) correspond to $\langle\Delta^2(X_a(\phi_{a1})+X_b(\phi_b))\rangle$ and $\langle\Delta^2(X_a(\phi_{a2})-X_b(\phi_b))\rangle$, respectively. To wits, the circled data represent scatters of the sum computed from the measured $X_a(\phi_{a1})$ and $X_b(\phi_b)$. And, the crossed data represent scatters of the difference computed from the measured $X_a(\phi_{a2})$ and $X_b(\phi_b)$.

As is apparent from FIG. **8**, it is seen that $\langle\Delta^2(X_a(\phi_{a1})+X_b(\phi_b))\rangle$ becomes the minimum when ϕ_b is π radian and 3π radian and the maximum when ϕ_b is 2π radian. It is also seen that $\langle\Delta^2(X_a(\phi_{a2})-X_b(\phi_b))\rangle$ becomes the minimum when ϕ_b is about 1.6π radian and the maximum when ϕ_b is about 2.7π radian.

Computing the equation (1) from the values obtained for $\langle\Delta^2(X_a(\phi_{a1}+X_b(\phi_b))\rangle$ and $\langle\Delta^2(X_a(\phi_{a2})-X_b(\phi_{b2}))\rangle$ yields the inequity (3) shown below.

[Formula 3]

$$\langle\Delta^2(X_a(\phi_{a1})+X_b(\phi_{b1}))\rangle+\langle\Delta^2(X_a(\phi_{a2})-X_b(\phi_{b2}))\rangle=0.64<1 \quad (3)$$

That is to say, since the value of the left side of the equation (3) is 0.64 which is smaller than 1, a sufficient condition for the entanglement is evidently satisfied. To wits, it has been ascertained that the first quantum entangled beam **130** and the second quantum entangled beam **131** are actually entangle.

INDUSTRIAL APPLICABILITY

A quantum entanglement generated in a quantum entanglement generating system and a quantum entanglement generating and detecting system can be utilized to achieve absolutely safe communications as well as computation processing at a speed incommensurably higher than heretofore.

The invention claimed is:

1. A quantum entanglement generating system comprising:

a laser light source for producing a light beam of light frequency $2f_0$;

a ring interferometer comprising a beam splitter and a plurality of mirrors, the beam splitter and the minors forming an optical path in the form of a ring;

an optical parametric amplifier inserted in the optical path of the ring interferometer for producing a light beam of light frequency f_0 upon receiving a light beam of light frequency $2f_0$ incident into the optical parametric amplifier; and

a dispersive medium inserted in the optical path of the ring interferometer,

wherein the light beam of light frequency $2f_0$ from the laser light source injects into the beam splitter,

the beam splitter splits the light beam of light frequency $2f_0$ into two light beams travelling mutually contrariwise in direction of advance in the ring interferometer, the two light beams injected into the optical parametric amplifier to generate a first and a second squeezed light beams traveling mutually contrariwise in direction of advance in the ring interferometer,

the dispersive medium adjusts the relative phase between the first and second squeezed light beams at a selected value, and

the beam splitter combines the first and second squeezed light beams, thereby generating quantum entangled beams.

2. A quantum entanglement generating system as set forth in claim **1** wherein the optical path of the ring interferometer is formed of the sides of a polygon of triangle or more angle in the ring interferometer in which the beam splitter is disposed at an apex of the polygon with the minors lying at its remaining apexes, respectively.

3. A quantum entanglement generating system as set forth in claim **1** wherein

the optical path of the ring interferometer is a triangular optical path in which the beam splitter and a first and a second of the mirrors are arranged in turn anticlockwise, and wherein

the dispersive medium is disposed in the optical path between the beam splitter and the first minor in the ring interferometer, and

the optical parametric amplifier is disposed in the optical path between the first and second minors in the ring interferometer.

4. A quantum entanglement generating system as set forth in claim **1** wherein the optical path of the ring interferometer is a rectangular optical path in which the beam splitter and a first, a second and a third of the mirrors are arranged in turn anticlockwise, and wherein

the optical parametric amplifier is disposed in the optical path between the first and second minors in the ring interferometer, and

the dispersive medium is disposed in the optical path between the beam splitter and the third minor in the ring interferometer.

5. A quantum entanglement generating system as set forth in claim **3** or claim **4** wherein on the optical axis there is disposed a condenser means, each between the optical parametric amplifier and the first minor and between the optical parametric amplifier and the second minor.

6. A quantum entanglement generating system as set forth in claim **1** wherein the optical parametric amplifier has an optical waveguide structure consisting of an electrooptic crystal.

7. A quantum entanglement generating system as set forth in claim **1** wherein the dispersive medium consists of two glass plates.

8. A quantum entanglement generating system as set forth in claim **1** wherein the laser light source comprises a light source for producing a light beam of light frequency f_0 and a second harmonic generator for converting the incident light beam of light frequency f_0 from the light source into a light beam of light frequency $2f_0$.

9. A quantum entanglement generating system as set forth in claim **8** wherein the second harmonic generator has an optical waveguide structure consisting of an electrooptic crystal.

10. A quantum entanglement generating system as set forth in claim **1** wherein the beam splitter has a transmissivity and a reflectance of about 50%, alike to both light beams of light frequency f_0 and light frequency $2f_0$.

11. A quantum entanglement generating system as set forth in claim **1** wherein the ring interferometer is formed on a plane.

12. A quantum entanglement generating method comprising:

producing a light beam of light frequency $2f_0$ from a laser light source;

injecting the light beam from the laser light source into a ring interferometer comprising a beam splitter and a plurality of mirrors, the beam splitter and mirrors forming an optical path in the form of a ring;

splitting the injected light beam at the beam splitter into two light beams traveling mutually contrariwise in direction of advance in the ring interferometer;

advancing one of the split light beams from an optical parametric amplifier disposed in the optical path of the ring interferometer into a dispersive medium disposed in the optical path of the ring interferometer, to generate a first squeezed light beam of light frequency f_0; advancing the other of the split light beams from the dispersive medium into the optical parametric amplifier to generate a second squeezed light beam of light frequency f_0; and

setting relative phase between the first and second squeezed light beams at a selected value through the dispersive medium, and

combining the first and second squeezed light beams at the beam splitter, thereby generating quantum entangled beams.

13. A quantum entanglement generating method as set forth in claim **12** wherein the relative phase between the first and second squeezed light rays is set at $\pi/2$.

14. A quantum entanglement generating method as set forth in claim **12** wherein the quantum entangled beams comprises a first quantum entangled beam passing through the beam splitter and a second quantum entangled beam reflecting on the beam splitter.

15. A quantum entanglement generating and detecting system comprising:

a light source part comprising a pulsed laser light source of light frequency f_0 and a second harmonic generator into which the light beam of light frequency f_0 is incident to produce a light beam of light frequency $2f_0$, the light source part emitting a pulsed laser light beam of light frequency f_0 and a pulsed laser light beam of light frequency $2f_0$ on a common axis;

a ring interferometer comprising a beam splitter and a plurality of mirrors, the beam splitter and mirrors forming an optical path in the form of a ring;

an optical parametric amplifier inserted in the optical path of the ring interferometer for producing a light beam of light frequency f_0 upon receiving a light beam of light frequency $2f_0$ incident into the optical parametric amplifier;

a dispersive medium inserted in the optical path of the ring interferometer ; and

a homodyne detector,

wherein the light beam of light frequency $2f_0$ from the laser light source injects into the beam splitter,

the beam splitter splits the light beam of light frequency $2f_0$ into two light beams travelling mutually contrariwise in direction of advance in the ring interferometer, the two light beams injected into the optical parametric amplifier to generate a first and a second linearly polarized, squeezed light beam of light frequency f_0 traveling mutually contrariwise in direction of advance in the ring interferometer,

the dispersive medium adjusts the relative phase between the first and second squeezed light beams at a selected value,

the beam splitter combines the first and second squeezed light beams to generate a linearly polarized quantum entangled beam of light frequency f_0,

as a signal light beam the linearly polarized quantum entangled beam of light frequency f_0, and as a local-oscillator light beam the pulsed laser light beam of light frequency f_0 emitted from the light source part and having a polarization orthogonal to the signal light beam, are both incident into the homodyne detector to detect a quadrature amplitude.

16. A quantum entanglement generating and detecting system as set forth in claim **15** wherein the quantum entangled beams comprises a first and a second quantum entangled beam and the homodyne detector comprises a first and a second homodyne detector, the first and second quantum entangled beams constituting signal light beams to the first and second homodyne detectors, respectively.

17. A quantum entanglement generating and detecting system as set forth in claim **15** wherein the beam splitter has a transmissivity and a reflectance of about 50%, alike to both a horizontally polarized light beam of light frequency f_0 and a horizontally polarized light beam of light frequency $2f_0$, and has a reflectance of about 100% to a vertically polarized light ray of light frequency f_0.

18. A quantum entanglement generating and detecting system as set forth in claim **15** wherein the homodyne detector comprises:

an electrooptic crystal into which the signal light beam and the local-oscillator light beam are incident, a half wave plate for polarizing the light beams incident into the electrooptic crystal, a beam splitter for combining the light beams polarized at the half wave plate to split into a transmitted and a reflected light beam, detectors for sensing the two light beams split into by the beam splitter, respectively, and a means for providing a differential between outputs from the detectors.

19. A quantum entanglement generating and detecting system as set forth in claim **15** wherein the homodyne detector comprises a filter into which the signal light beam and the local-oscillator light beam are incident for transmitting the light frequency f_0 and light frequency $2f_0$, a quarter wave plate for varying a phase between the light beams from the filter, a beam splitter for combining the light beams from the quarter wave plate and for splitting into a transmitted and a reflected light beam, detectors for sensing the two light beams split into by the beam splitter, respectively, and a means for providing a differential between outputs from the detectors.

20. A quantum entanglement generating and detecting system as set forth in claim **15**, further comprising a dispersive medium disposed between the signal and local-oscillator light beams and the homodyne detector wherein the homodyne detector comprises a filter for transmitting a light beam of light frequency f_0 and a light beam of light frequency $2f_0$ out of light beams passing through the dispersive medium, a beam splitter for combining light beams from the filter to split into a transmitted and a reflected light beam, detectors for sensing the two light beams split into by the beam splitter, respectively, and a means for providing a differential between outputs from the detectors.

21. A quantum entanglement generating and detecting system as set forth in claim **15** wherein the ring interferometer is formed on a plane.

22. A quantum entanglement generating and detecting method comprising:

producing, on a common optical axis, a light beam of light frequency f_0 from a laser light source and a light beam of light frequency $2f_0$ generated via a second harmonic generator from the laser light source;

injecting the light beam of light frequency $2f_0$ from the laser light source into a ring interferometer comprising a beam splitter and a plurality of mirrors ,the beam splitter and minors forming an optical path in the form of ring;

splitting the injected light beam at the beam splitter into two light beams traveling mutually contrariwise in direction of advance in the ring interferometer;

advancing one of the split light beams from an optical parametric amplifier disposed in the optical path of the ring interferometer into a dispersive medium disposed in the optical path of the ring interferometer, to generate a first linearly polarized, squeezed light beam of light frequency f_0;

advancing the other of the split light beams from the dispersive medium into the optical parametric amplifier to generate a second linearly polarized, squeezed light beam of light frequency f_0;

setting relative phase between the first and second squeezed light beams at a selected value through the dispersive medium; and

combining the first and second squeezed light beams at the beam splitter, thereby generating linearly polarized quantum entangled beams of light frequency f_0;

deriving from the horizontally polarized quantum entangled beams of light frequency f_0, a signal light beam for a homodyne detector;

passing the light beam of light frequency f_0 from the laser light source through the ring interferometer via an optical path identical to that for the one light beam split into by the beam splitter, to provide a light beam of a polarization orthogonal to the signal light beam for use as a local-oscillator light beam for the homodyne detector; and

the homodyne detector detecting a quadrature amplitude of the signal light beam.

23. A quantum entanglement generating and detecting method as set forth in claim **22** wherein a filter for blocking the light beam of light frequency $2f_0$ is inserted on an optical axis, each in front and rear of the optical parametric amplifier to suspend generation of the quantum entangled beams.

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