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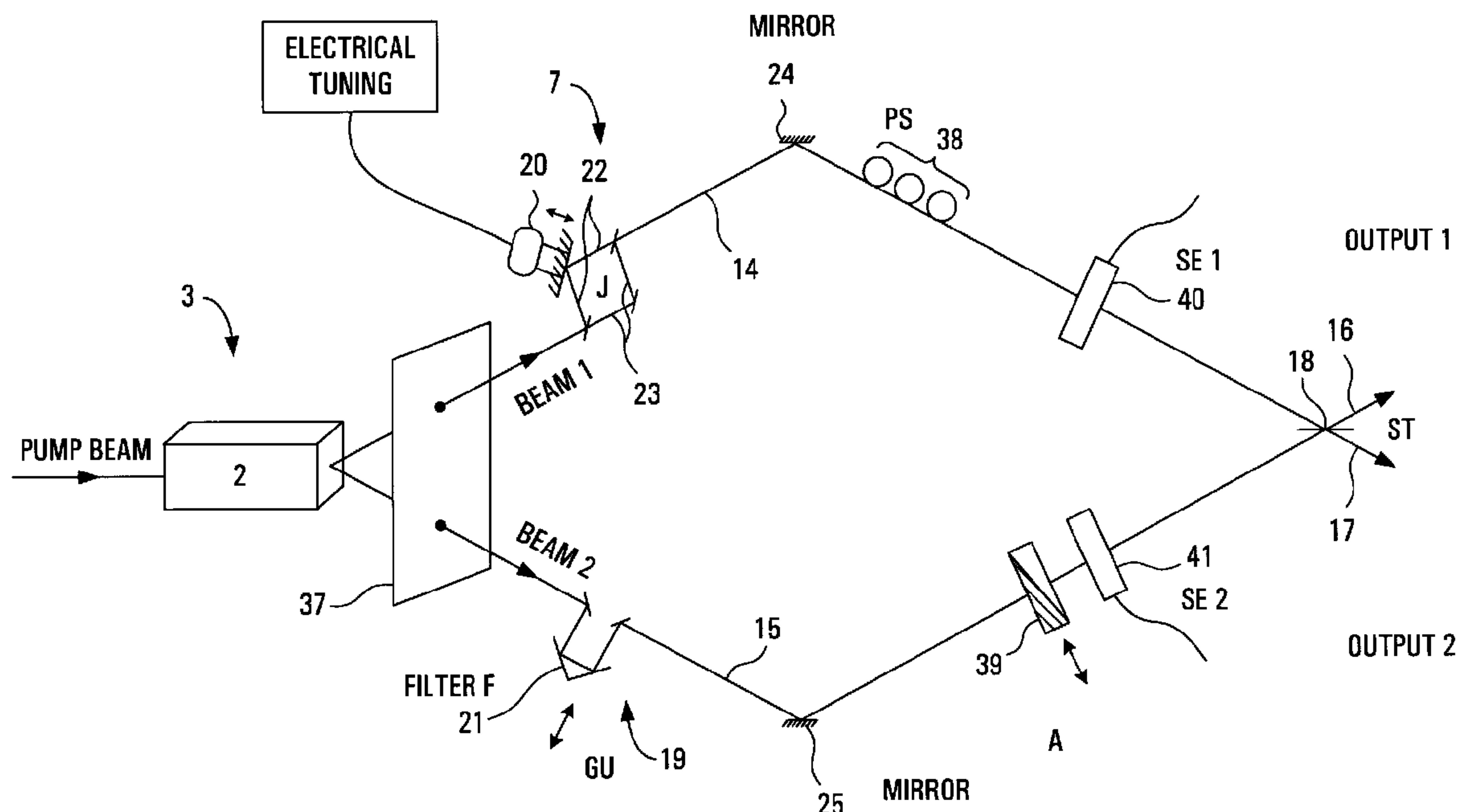
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(54) Titre : PROCEDE ET DISPOSITIF POUR LA PRODUCTION AU CHOIX DE PHOTONS INDIVIDUELS OU DE
PAIRES DE PHOTONS DANS UN CANAL OPTIQUE

(54) Title: METHOD AND APPARATUS FOR THE SELECTIVE GENERATION OF INDIVIDUAL PHOTONS OR PAIRS
OF PHOTONS IN AN OPTICAL CHANNEL



(57) Abrégé/Abstract:

Method for selective generation of individual photons or photon pairs in an optical channel (16, 17) with the following steps: - generation of a two-photons (photon pair); - spatial separation of the photon pair whilst retaining the quantum mechanical correlation in the event that the photons are emitted linearly; - injection of each photon into an optical channel (14, 14', 14''), one channel (15, 15', 15'') incorporating an interferometer (7-13) with a variable optical path lengths difference $\delta 1_F - \delta 1_S$ and the other channel incorporating an optical delay section (19) of optical lengths $\delta 1$; - spatial merging of both channels by means of a beam splitter (18, 31-36); - co-ordination of the values $\delta 1_F$, $\delta 1_S$, and $\delta 1$ such that the probability K for coincidences between the outputs (16, 17) of the beam splitter amounts selectively to $K=0$ or $K=1$ or to a predetermined intermediate value, $K=0$ corresponding to a



(57) Abrégé(suite)/Abstract(continued):

photon pair in one of the outputs channels (16, 17) of the beam splitter, and $K=1$ corresponding to two individual photons in both outputs channels of the beam splitter. Using the present invention, it is possible to realize an optical switch or gate for one or two photon states, as desired, which can be used in quantum cryptography and as a basic element for a quantum-optical computer.

Abstract

Method for selective generation of individual photons or photon pairs in an optical channel (16, 17) with the following steps:

- generation of a two-photons (photon pair);
- spatial separation of the photon pair whilst retaining the quantum mechanical correlation in the event that the photons are emitted linearly;
- injection of each photon into an optical channel (14, 14', 14''), one channel (15, 15', 15'') incorporating an interferometer (7-13) with a variable optical path lengths difference $\delta l_F - \delta l_S$ and the other channel incorporating an optical delay section (19) of optical lengths δl ;
- spatial merging of both channels by means of a beam splitter (18, 31-36);
- co-ordination of the values δl_F , δl_S , and δl such that the probability K for coincidences between the outputs (16, 17) of the beam splitter amounts selectively to $K=0$ or $K=1$ or to a predetermined intermediate value, $K=0$ corresponding to a photon pair in one of the outputs channels (16, 17) of the

beam splitter, and $K=1$ corresponding to two individual photons in both outputs channels of the beam splitter.

Using the present invention, it is possible to realize an optical switch or gate for one or two photon states, as desired, which can be used in quantum cryptography and as a basic element for a quantum-optical computer.

Method and Apparatus for the Selective Generation of Individual Photons or Pairs of Photons in an Optical Channel

The present invention relates to a method for selective generation of single photons or photon pairs in an optical channel. The present invention also relates to an apparatus for carrying out the method that can, in particular, be used as a controllable light source for single or double photon states and/or as a controllable switch or control gate for quantum states. The present invention also relates to a network that is formed from a plurality of such apparatuses.

Prior Art:

The phenomenon of parametric fluorescence occurs in optically non-linear crystals. Under certain circumstances, with a specific probability, an individual energy quantum (photon) of an intensive optical pump-light source, mostly laser light, decays into two energy quanta or photons of approximately half energy (H. Paul, *Non-Linear Optics*, Vol. 2, pp. 94 et seq., Berlin, 1973). In the case of monochromatic or narrow band excitation, it does not necessarily follow that the spectral distribution of the fluorescence photons will also be narrow band although, because of the conservation of energy, the sum of the energies of

the two fluorescence photons must equal the energy of the excitation photon. The same applies to impulse conservation. For this reason, parametric fluorescence occurs only with specific excitation geometries, i.e., at a specific orientation of the pump beam relative to the optical axes of the non-linear crystal and at specific, matched refraction indices. This leads to the fact that the fluorescence light is emitted at two main frequencies or wavelengths, depending on the excitation geometries, in a defined spatial direction relative to the direction of propagation of the pump beam. For all practical purposes, the two fluorescence photons are emitted simultaneously, i.e., within a time frame of approximately 10 femtoseconds and in the same or in different spatial directions, depending on the type of non-linear crystal and the excitation geometries that are involved. Their direction of polarization is similarly established. The physical properties of the two photons of parametric fluorescence are linked to each other by a series of secondary conditions. From the stand point of quantum mechanics, they are in an entangled state. In the case of the entangled photons, from the standpoint of quantum mechanics, this involves a single state in which two photons are inseparable, measurements made with respect to one of the photons making it possible to make accurate statements with respect to the physical properties of the other photon in each case. Two photon states

such as these are of critical importance as the starting state for quantum cryptography, the optical random-number generator, or for the quantum computer.

At the present time, only two classic methods are known for separating the photons within a swarm from each other or for injecting them into a single optical channel, e.g., a glass fibre, together. One known classic possibility for separating a plurality of photons and injecting them into two different channels is the conventional beam splitter, a partially mirrored glass plate in which the mirror coating is partially transparent at the wave lengths that are used, or which incorporates small holes. The partial mirroring can also be in the form of thin vapour-deposited layers. These beam splitters are usually set at an angle α in the beam path, so that one part of the light falling on the beam splitter is deflected from the original direction of the beam. Another possibility for extracting some of the photons of a swarm involves using a polarizing beam splitter, the properties of which are based on the principle of reflection on dielectric layers of crystal-optical prisms, e.g., the Nicol prism.

For the event that the individual photons are coherent relative to each other, it is also possible to use interference methods

for beam splitting. The best known of these are the Michelson interferometer, which transmits constructively interfering photons and reflects destructively interfering photons, and the Mach-Zehnder interferometer that sorts constructively and destructively interfering photons into two different output channels. In addition, the deflection grating is numbered among the beam splitters that operate interferometrically.

One characteristic of all these beam splitters is the fact that the division of the individual photons into the individual outputs channels at the beam splitters can only be predicted with reference to their distribution probability. A pair of photons will be split at a 1:1 dividing beam splitter with a probability of $1/2$, regardless of whether this involves two photons that can be differentiated or two photons that cannot be differentiated. It is, however, impossible to make exact statements as to whether an existing pair of photons will actually be separated or will remain together. At present, the deliberate transition from a two-photon state to two individual photons is not possible. The deliberate generation of individual photons or pairs of photons in an optical channel is, however, of importance when improving quantum cryptography methods, in measurement technology, and for the development of a quantum computer.

Technical domain:

For this reason, it is the objective of the present invention to describe a method for selectively generating single photons or pairs of photons in an optical channel. In addition, an apparatus is to be described which, while carrying out the method, can be used as a controllable light source for one and two photon states in quantum cryptography and in measurement technology, as well as a controllable switch or gate for quantum states in information and computer networks.

Disclosure of the invention and its advantages:

This objective has been achieved by a method that involves the following steps:

In a first step, a two photon state is generated, which is to say a pair of quantum mechanically correlated photons that are in an entangled state. It is preferred that the photon pair be generated in a suitable excitation geometry in the known manner by parametric fluorescence while using an optically non-linear crystal of suitable excitation geometry, a laser being used as the source of the pump light. Depending on the excitation geometry and the type of the non-linear crystal, the fluorescence

photons leave the crystal in the same or different directions, at a defined angle to the direction of the excitation beam, the fluorescence photons being either identically polarized or linearly, orthogonally. polarized. If the frequency of the pump light is $2\omega_0$, the individual photons of the photo pair will be of frequency ω_1 or ω_2 , with $\omega_1 + \omega_2 = 2\omega_0$

In the next step, in the event that the photons are emitted collinearly, the photon pair is spatially separated whilst retaining the quantum mechanical correlation. This takes place, for example, because of the polarization of the fluorescence photons, provided these are different, or because of the wavelengths, e.g., by means of a wavelength selective mirror.

In the next step, in each instance one, one photon is inserted into one optical channel. One of the channels contains a two or multi-beam interferometer with an a variable optical wavelength differential $\delta l_F - \delta l_S$ and the other channel incorporates an optical delay section of optical length δl . Both channels are recombined by a beam splitter. The optical channels have the same basic length, which is understood to be the optical distance from the place at which the photons of the photon pair are spatially separated to the beam splitters or to the detectors on passing along the particular part beam paths, in the case of beam paths

with interferometers, the length determined by the interferometer arms. When determining the basic length, the optical paths travelled in the interferometer or in the optical delay section must be taken into account.

The interferometer that is used in one of the optical channels is a two-beam interferometer, e.g., a Mach-Zehnder or a Michelson interferometer, or a multibeam interferometer, e.g., a Fabry-Perot interferometer or an echelon. What is important is that the optical path difference $\delta l_F - \delta l_S$ can be adjusted over at least one-half of the mean wavelength λ of the fluorescence photons. In addition, the interferometer can be a linear, double refracting crystal plate, in particular a quartz plate, the optical path difference of which can be so expanded by an additional compensator that the path difference can be adjusted by more than a half wavelength λ_1 of those photons that pass through the interferometer.

It is preferred that the optical delay section that is arranged in the other channel be variable in the same way as the optical path length difference in the interferometer. The optical delay section is preferably implemented in the form of an optical trombone [wave stretcher] or by an electro optical element, the refractive index of which is variable so that a variable phase

difference can be induced. In addition, this delay section can comprise a delay section of fixed length and an adjusting element that can introduce a variable phase difference corresponding more or less to a half mean.wavelength. However, the optical delay section does not necessarily have to be variable.

Finally, in the next step, the values δl_F , δl_s , and δl are so coordinated that the probability K for coincidences between the outputs of the beam splitters can amount to approximately $K=0$ or $K=1$, or some predetermined intermediate value. The probability K is proportional to the coincidence rates, which can be easily determined by arranging a detector at each output of the beam splitters and determining the coincidences rates between both outputs in the known manner by evaluating the counter events. A coincidence probability of 0 then corresponds to the case that both photons of the originally generated photon pair are emitted in a common output channel of the beam splitter, which is to say, collinearly. In this connection, it is not determined which of the two outputs channels the photon pair takes. The probability for a specific channel amounts, in each instance, to 50%. A maximal coincidences rate, corresponding to $K \approx 1$ is obtained for the event that both photons move into different output channels of the beam splitter, so that there is only one photon per output channel.

One or a plurality of mechanical and/or electro optical adjuster elements are provided to change the optical path lengths δl_F , δl_s and/or δl ; it is preferred that these be remotely controlled. The mechanical adjuster elements are, for example, mirrors, which can be moved by means of a motor. However, electrically controllable liquid-crystal cells and/or electro-optical crystal modulators are advantageous, in particular, for the adjusting the phase in the interferometer. Adjustment of the phase is effected in microseconds if liquid crystals are used, and in nanoseconds with the aid of electro-optical crystal modulators. Rapid and precise adjustment of the phase between two predetermined values is of interest, in particular, in the event that switching is to be effected rapidly between one or two photons in the output channel.

It is preferred that the optical path-length difference in the interferometer ($\delta l_F - \delta l_s$) be so adjusted that it amounts to an integer multiple of the half mean wavelength λ_0 of the photons of the photon pair, which is to say

$$|\delta l_F - \delta l_s| = n/2\lambda_0, \text{ with } n=0,1,2\dots$$

At the same time, the optical length δl of the delay section is matched to the mean path difference $1/2(\delta l_F + \delta l_s)$ of the interferometer. Depending on whether the optical path length

28030-61

difference in the interferometer is an integer or non-integer multiple of the half wavelength λ_0 , only photon pairs or single photons will be generated in the output channel. The transition from n to $n+1$ corresponds to the transition
5 from $K=0$ to $K=1$, or vice versa. Since matching the apparatus for Type I or II non-linear crystals differs somewhat from each other, adjustment of the optical lengths δl_F , δl_S , and δl is preferably checked out experimentally, by measuring the coincidence rates.

10 The device can also be tuned completely by experiment by determining the probability K for coincidences between the outputs of the beam splitter as a function of the values δl_F , δl_S , and/or δl . The settings of the optical lengths that lead to $K=0$ and/or to $K=1$ and/or to a
15 predetermined intermediate value are recorded in each instance so that it is possible to switch between individual photons and pairs of photons in the output channel by switching between recorded values for the corresponding lengths or between the corresponding settings of the
20 adjuster elements.

In accordance with one aspect of this invention, there is provided a method for generating a choice of one of individual photons and photon pairs in at least one of a first optical channel and a second optical channel,
25 comprising the steps of: generating a two-photon state corresponding to a photon pair; spatially separating the photon pair while preserving a quantum-mechanical correlation if photons of the photon pair are emitted in a collinear manner; coupling one of the photons of the photon
30 pair into one of the first optical channel and the second optical channel and another one of the photons of the photon

28030-61

pair into another one of the first optical channel and the second optical channel, wherein one of the first optical channel and the second optical channel includes an interferometer providing a variable optical path-length difference $\delta l_F - \delta l_S$, and the other one of the first optical channel and the second optical channel includes an optical delay section having an optical length δl ; spatially reuniting both the first optical channel and the second optical channel through a beam splitter; and adjusting quantities δl_F , δl_S , and δl such that a probability K for coincidences between outputs of the beam splitter is a choice corresponding to one of $K=0$, approximately $K=1$, and K corresponding approximately to a predetermined intermediate value, wherein $K=0$ corresponds to the photon pair being present in one of the outputs of the beam splitter, and $K=1$ corresponds to one of the photons of the photon pair being present in one of the outputs of the beam splitter and another one of the photons of the photon pair being present in another one of the outputs of the beam splitter.

In accordance with another aspect of this invention, there is provided a device, comprising: a light source for a quantum-optically correlated photon pair; an arrangement for separating the photon pair if photons of the photon pair are emitted in a collinear manner; a plurality of beam-component paths arranged such that each one of the photons is coupled into a corresponding one of the plurality of beam-component paths; a beam splitter; an arrangement for reuniting the plurality of beam-component paths at the beam splitter to superimpose and transfer the plurality of beam components into a plurality of shared output channels; an interferometer arranged in one of the plurality of beam-component paths and including a first interferometer arm

28030-61

corresponding to optical path length δl_F and a second interferometer arm corresponding to optical path length δl_S ; an optical delay section corresponding to optical length δl and arranged in another one of the plurality of beam-
5 component paths; and an arrangement for changing at least one of optical path lengths δl_F , δl_S , and δl .

Brief description of the drawings

The drawings appended hereto show the following:

Figures 1a, 1b: Generation of a pair of photons by parametric
 fluorescence in a non-linear crystal of Type
 I or II;

Figure 2: A schematic representation of an apparatus according to
 the present invention that serves as a controllable
 light source for one- or two-photon states;

Figure 3: Two such devices connected in series;

Figure 4: Four apparatuses connected so as to form a network.

Figure 1 is a schematic representation showing the generation of
a quantum-mechanically correlated photon pair by parametric
fluorescence. To this end, a non-linear crystal 1 that is of Type
I or a crystal 1' that is of Type II is pumped with a high
intensity laser beam. The crystal must be so cut and oriented
relative to the excitation beam that so-called phase matching
conditions are fulfilled and parametric fluorescence is not
precluded because of energy- and pulse-conservation. In the case
of the Type I non-linear crystal, a pump photon decays with a
specific probability into two fluorescence photons of parallel
linear polarization P_1 or P_2 that are emitted in spatial
directions that depend on the excitation geometries. In the case

of non-linear crystals of Type II, two photons that are polarized orthogonally to each other are generated.

Preferred embodiments:

Figure 2 shows an arrangement for carrying out the method according to the present invention, which can be used as a controllable light source for one- or two-photon states and/or as a controllable switch or controllable gate for quantum states, as well as within the framework of an optical computer network, as shown in Figure 3 and Figure 4. The apparatus incorporates a light source 3 for quantum-optically correlated photon pairs. This light source is a suitably cut and oriented optically non-linear crystal 2, which is pumped by a high intensity laser beam at a suitable frequency. Because of parametric conversion of the pump photons, two fluorescence beams result, and these leave the crystal 2 in different directions relative to the direction of propagation of the pump beam. In each instance, one photon of the one beam is located with another photon of the other beam in a quantum-mechanically entangled state.

The pump light is suppressed by a filter 37. It is preferred that this be an optical bandpass filter that does not permit passage of the pump wavelengths but transmits the fluorescence light of

the fluorescence wavelengths λ_1 or λ_2 . In addition, a filter can be arranged at the output of the light source 3, said filter reducing the intensity of the fluorescence light to the point that in each instance only one photon pair is in the arrangement with a specific probability.

Each of the quantum-mechanically correlated fluorescence photons is injected into a part beam path 14 or 15 of the apparatus. Because of deflection through one or a plurality of mirrors 24, 25, the part beam paths 14, 15 are merged again in a beam splitter 18. The two part beam paths 14, 15 are superimposed and transferred into two separate outputs channels 16, 17 with the beam splitters 18. The merging of the two part beam paths can also be effected with a lens instead of with mirrors 24, 25, as is shown in Figure 3 and Figure 4.

According to the present invention, an interferometer 7 is arranged in one of the part beam paths 14; in the drawing, this is a Mach-Zehnder interferometer that has interferometer arms 22 and 23. The interferometer arm 22 is of optical length δl_F , and this can be varied with an electrically tunable adjuster element 20. The interferometer arm 23 is of a fixed length δl_s . Thus, the optical path length differential $\delta l_F - \delta l_s$ can be varied with the adjuster element 20 in the interferometer 7.

According to the present invention, in the other part beam path 15 there is an optical delay section 19 that, in this instance, is an optical trombone. The optical length δl of the delay section 19 can be varied by means of another adjuster element 21. It is preferred that this be electrically controllable in the same way as the adjuster element 20, by which means the length δl of the delay section 19 can be remotely controlled.

The optical lengths of the part beam paths 14, 15 are preferably equal without taking into consideration the lengths of the interferometer arms 22, 23, respectively. For the event of a photo pair that is generated with a non-linear crystal of Type I of identical polarization, the coincidence rate K for coincidences between the outputs 16, 17 can be described as follows:

$$K = \frac{1}{2} \left\{ 1 - \frac{1}{2} \exp \left[-\frac{1}{c^2 a^2} (\delta l_F - \delta l)^2 \right] - \frac{1}{2} \exp \left[-\frac{1}{c^2 a^2} (\delta l_S - \delta l)^2 \right] + \right. \\ \left. \cos \left[\frac{\omega_0}{c} (\delta l_F - \delta l_S) \right] \left[\exp \left[-\frac{1}{4c^2 a^2} (\delta l_F - \delta l_S)^2 \right] - \exp \left[-\frac{1}{c^2 a^2} \left(\frac{\delta l_F - \delta l_S}{2} - \delta l \right)^2 \right] \right] \right\}$$

wherein δl_F , δl_S , and δl are in each instance the optical paths in the interferometer arms 22, 23 or in the delay section 19; c is the speed of light; and a determines the spectral width of the spectra of the two beams. A Gaussian distribution with the mid-frequency

$$\omega_0 \text{ and } \omega_1 + \omega_2 = 2\omega_0$$

is assumed for both beams.

Hereinbelow, it is assumed that the spectral width of the two photons $1/a$ is so big that the path different $\delta l_F - \delta l_S$ of the interferometer exceeds the coherence length $c \cdot a$ by a multiple. In addition, it is assumed that the optical path lengths δl_F , δl_S are so matched to each other that $\delta l = 1/2(\delta l_F + \delta l_S)$. Of course, this is the same as the case when the overall optical length of the beam path 15 including the optical delay section 19 agrees with the mean optical length of the part beam path 14 including the length of the interferometer arms 22, 23.

For this case, the coincidence rate K becomes

$$K \approx \frac{1}{2} \left\{ 1 - \cos \left[\frac{\omega_0}{c} (\delta l_F - \delta l_S) \right] \right\}$$

Depending on the path difference or the phase difference in the interferometer $\delta l_F - \delta l_S$, the following cases will apply:

a) in the event that .

$$\cos\left[\frac{\omega_0}{c}(\delta l_F - \delta l_S)\right] = +1, \text{ i.e., } \delta l_F - \delta l_S = n \frac{2\pi c}{\omega_0} = n\lambda_0$$

with $n=0, 1, \dots, K=0$.

This means that both photons leave the apparatus at one of the outputs 16, 17 together, as a pair. The output they take remains uncertain.

b) in the event that

$$\cos\left[\frac{\omega_0}{c}(\delta l_F - \delta l_S)\right] = -1, \text{ i.e., } \delta l_F - \delta l_S = \frac{2n+1}{2}\lambda_0,$$

$K=1$. This means that both photons leave the apparatus by way of both outputs 16, 17, which is to say that they are again separated.

In both cases, the quantum relationship of the photo pairs is preserved. This means that the apparatus influences the quantum state of the photon pair in a purposeful manner and can be used as a switch or gate in a quantum computer. A prerequisite for this property of the apparatus are the small coherent lengths of the individual photons from the non-linear crystal, the matching of δl to the mean path difference of the interferometer, and a coherent length of the laser pump light that is greater than $\delta l_F - \delta l_S$. Since adjustment of the phase within the interferometer can be effected with suitable adjuster elements 20, e.g., with liquid crystals in microseconds or, using electro-optical crystal modulators, even in nanoseconds, switching between the values with $K=0$ and $K=1$, or with the minimal or maximal K that has been achieved experimentally, and which corresponds to the theoretical cases $K=0$ or $K=1$, can be effected very rapidly.

In the event that the length δl of the optical delay section 19 is not to be adjusted to the average path difference of the interferometer 7 for every reswitching operation, the optical lengths δl_F , δl_S of the interferometer arms 22, 23 can be reduced or increased individually by means of two suitable adjuster elements 20, in each instance by a quarter wavelength λ_0 . Thus, the average path difference in the interferometer 7 remains

constant, whereas the phase difference changes by $\lambda_0/2$, which corresponds to switching from $K=0$ to $K=1$, or vice versa.

In a further development of the present invention, additional adjuster elements 38, 39, 40, and 41 are incorporated in the three beam paths 14, 15. The absorber 39 serves to match the intensity in the part beam path 15, and the polarization adjuster element 38 serves to match the polarization of the photons passing through the part beam path 14 in the event that the photons at the output are present in another polarization state to the one originally generated. The additional adjuster elements 40, 41 serve to manipulate the photons passing through the one beam path with reference to frequency and/or phase.

The version that is shown in Figure 2 can be implemented either in part or completely in an embodiment with optical fibres. The individual components in the fibre version are known. In addition, the non-linear optical crystal 2 can be replaced by an optical non-linear fibre with a suitable fibre coupler. A fibre version, in particular of the beam splitters 18, entails the advantage that the injection of the photons leaving the apparatus into another fibre can be effected directly by splices or plug-type connectors. Thus, it is also possible to cascade or network

apparatuses of the type described in a very simple manner, as is shown in Figure 3 and Figure 4.

In each of the individual stages, it is possible to effect polarization and phase manipulation in the two-photons state. The individual photons of the photon pairs can be influenced as desired. This is done by means of the adjuster elements 40, 41, which are known as delay plates in the liquid crystal version, or as Kerr cells. In addition, a defined shift of the spectral frequency of one or both photons can be effected at this location with the aid of $\lambda/2$ plates or with their electro optical analogues, as well as optical storage of photons, e.g., in glass-fibre loops or resonators.

If the interferometer in one of the part beam paths 14, 15 is in the form of a polarizing interferometer, e.g., a quartz plate, the tuning of the phase shift for the path difference in the interferometer 7 can also be effected outside the interferometer 7 with the aid of Pancharatnam's phase, e.g., if an additional polarization is incorporated in the beam path.

It is also possible to set the apparatus to the case $K=0$, i.e., one photon pair in one of the outputs 16, 17, so as to produce a defined state in the optical output channel. For this case, it is

possible to dispense with the variable path lengths, i.e., with the adjuster elements, after a single adjustment of the apparatus.

Figure 3 shows two apparatuses 42, 43 that are connected in series. The first apparatus 42 consists of a light source 4 for photon pairs, this being a non-linear optical crystal with suitable excitation. The light source 4 generates a photon pair, the individual photons each being injected in each case into a part beam path 14', 15', of the first apparatus 42. Within the part beam path 14' there is an interferometer 8 as well as an adjuster element SE. There is an additional adjuster element SE within the second part beam path 15'. Both part beams are united by means of a lens 26 to form a beam section 31. The first apparatus 42 is adjusted in the manner described heretofore, it being possible to switch between the cases with $K=0$ or $K=1$ by changing the path difference in interferometer 8 and/or by triggering the adjuster element SE.

The first apparatus 42 is followed by a second, identical apparatus 43. The apparatus 42 serves as a light source for the apparatus 43, the outputs channels 14" or 15" representing the input channels for the second apparatus 43, which is to say that

they make a direct transition to become the part beam paths 14", 15" of the second apparatus 43.

According to the present invention, the apparatus 43 has an interferometer 11 in the part beam path 15". In addition, adjuster elements SE are arranged in the two part beam paths 14", 15". Both of the part beam paths are merged at an additional beam splitter 34. The cascade can be extended as desired by incorporating other apparatuses in series.

Figure 4 shows four apparatuses 44, 45, 46, 47 according to the present invention that are connected to each other in series, the apparatuses 44 and 45 being connected to each other in parallel, the apparatus 46 consisting of an output channel from each of the apparatuses 44 and 45, these being merged at a beam splitter 35; the apparatus 47 is connected in series with the apparatus 46.

The apparatuses 44 and 45 have a non-linear crystal as a light source 5, 6; the light source for apparatus 46 consists of an output channel of the elements 44, 45, the element 46 representing, in its turn, the light source of the following element 47. The part beam paths of the individual elements are passed to the corresponding beam splitter 32, 33, or 36 through lenses 27, 28, or 30, respectively. In the case of element 46

the part beam paths are merged at the beam splitter 35 solely as a result of the geometrical arrangement. In addition, an interferometer 9, 10, 12, 13 located in one of the part beam paths, as well as an adjuster element located in each other part beam path are associated with each of the apparatuses. If necessary, these are arranged in both part beam paths.

In a network of this kind, the path of one or a plurality of photon pairs or of individual photons can be predetermined within specific limits by suitable adjustment of the phase differences in the interferometer source and/or the adjuster elements. Thus, the basic elements of a quantum-optical computer are created because of this cascading or networking and the deliberate access to quantum states of photon pairs.

Commercial applicability:

The present invention can be exploited commercially in many areas of information technology as a basic element for a quantum computer and for cryptography methods.

Reference Numbers used in Drawings

1,1', 2	non-linear crystal
3,4,5,6	light source
7-13	interferometer
14,15,14',14"	
15,15"	part beam path (optical channel)
16,17	output channel
18, 31-36	beam splitter
19	optical delay section (optical trombone)
20,21,SE	adjuster element
22,23	interferometer arm
24,25	mirror
26-30	lens
37	filter
38	polarization adjuster element
39	absorber
40,41	phase and/or frequency-changing adjuster element
42-47	apparatus (optical switch/gate)

28030-61

CLAIMS:

1. A method for generating a choice of one of individual photons and photon pairs in at least one of a first optical channel and a second optical channel,
5 comprising the steps of:

generating a two-photon state corresponding to a photon pair;

spatially separating the photon pair while preserving a quantum-mechanical correlation if photons of
10 the photon pair are emitted in a collinear manner;

coupling one of the photons of the photon pair into one of the first optical channel and the second optical channel and another one of the photons of the photon pair into another one of the first optical channel and the second
15 optical channel, wherein one of the first optical channel and the second optical channel includes an interferometer providing a variable optical path-length difference $\delta l_F - \delta l_S$, and the other one of the first optical channel and the second optical channel includes an optical delay section
20 having an optical length δl ;

spatially reuniting both the first optical channel and the second optical channel through a beam splitter; and

adjusting quantities δl_F , δl_S , and δl such that a probability K for coincidences between outputs of the beam
25 splitter is a choice corresponding to one of $K=0$, approximately $K=1$, and K corresponding approximately to a predetermined intermediate value, wherein $K=0$ corresponds to the photon pair being present in one of the outputs of the beam splitter, and $K=1$ corresponds to one of the photons of

28030-61

the photon pair being present in one of the outputs of the beam splitter and another one of the photons of the photon pair being present in another one of the outputs of the beam splitter.

5 2. The method according to claim 1, wherein:

the two-photon state corresponding to the photon pair is generated by a parametric fluorescence by pumping an optically non-linear crystal with a pumping laser light having a frequency of $2\omega_0$.

10 3. The method according to claim 2, wherein:

the pumping laser light includes a coherence length that is greater than the path-length difference $\delta l_F - \delta l_S$ in the interferometer.

4. The method according to claim 1, further
15 comprising the step of:

setting the path-length difference $\delta l_F - \delta l_S$ in the interferometer to approximately an integral multiple of a half average wavelength λ_0 of the photons of the photon pair to produce a relationship corresponding to $|\delta l_F - \delta l_S| = n/2\lambda_0$,
20 wherein:

$n=0, 1, 2 \dots$,

δl is adjusted to an average path difference $1/2(\delta l_F + \delta l_S)$ of the interferometer to produce a relationship corresponding to $\delta l \approx 1/2(\delta l_F + \delta l_S)$, and

25 a transition from n to $n+1$ corresponds to a transition from one of $K \approx 0$ to $K \approx 1$ and $K \approx 1$ to $K \approx 0$.

28030-61

5. The method according to claim 1, further comprising the step of:

determining the probability K as a function of at least one of quantities δl_F , δl_S , and δl , the step of
5 determining the probability K being performed by mounting a plurality of detectors at the outputs of the beam splitter and measuring a coincidence rate according to an experimental technique, wherein settings for δl_F , δl_S , and δl resulting in at least one of $K \approx 0$, $K \approx 1$, and K corresponding
10 to the predetermined intermediate value are recorded.

6. The method according to claim 5, further comprising the step of:

making a switchover among occurrences of $K \approx 0$, $K \approx 1$, and K corresponding to the predetermined intermediate value
15 by performing a remote-controlled change of at least one of the quantities δl_F , δl_S , and δl .

7. A device, comprising:

a light source for a quantum-optically correlated photon pair;

20 an arrangement for separating the photon pair if photons of the photon pair are emitted in a collinear manner;

a plurality of beam-component paths arranged such that each one of the photons is coupled into a corresponding
25 one of the plurality of beam-component paths;

a beam splitter;

28030-61

an arrangement for reuniting the plurality of beam-component paths at the beam splitter to superimpose and transfer the plurality of beam components into a plurality of shared output channels;

- 5 an interferometer arranged in one of the plurality of beam-component paths and including a first interferometer arm corresponding to optical path length δl_F and a second interferometer arm corresponding to optical path length δl_S ;

10 an optical delay section corresponding to optical length δl and arranged in another one of the plurality of beam-component paths; and

an arrangement for changing at least one of optical path lengths δl_F , δl_S , and δl .

8. The device according to claim 7, wherein the
15 device is configured as at least one of a controllable light source for one of a one-photon state and a two-photon state, and as one of a controllable separating filter and a controllable gate for quantum states.

9. The device according to claim 7, wherein:
20 the light source includes:

 an optically non-linear crystal,

 a pumping light source producing a pump light, and

 an optical filter for suppressing the pump light at an output of the optically non-linear crystal, and
25 the photon pair is generated in the optically non-linear crystal by a parametric conversion of one photon of the pump light.

28030-61

10. The device according to claim 9, wherein:
the pumping light source corresponds to a laser.

11. The device according to claim 7, further
comprising:

5 an optically linear fiber, wherein:

the light source includes:

an optically non-linear fiber corresponding to a
non-linear fiber piece arranged by being one of inserted
into and added onto the optically linear fiber,

10 a pumping light source producing a pump light, and

an optical filter for suppressing the pump light
at an output of at least one of the optically non-linear
fiber and the optically linear fiber, and

the photon pair is generated in at least one of
15 the optically non-linear fiber and the optically linear
fiber by a parametric fluorescence.

12. The device according to claim 11, wherein:
the pumping light source corresponds to a laser.

13. The device according to claim 7, wherein:

20 the light source is formed by one of one output of
at least a further device and by a combination of a
plurality of outputs of a plurality of further devices.

14. The device according to claim 7, wherein:

28030-61

the arrangement for separating the photon pair includes one of a wavelength-selective mirror, a polarizer, and a polarizing beam splitter.

15. The device according to claim 7, wherein:

5 at least one of the optical path lengths δl_F , δl_S , and δl is capable of being varied by at least one of at least one mechanical adjustment element and at least one electro-optical adjustment element.

16. The device according to claim 15, wherein:

10 each one of the at least one mechanical adjustment element and the at least one electro-optical adjustment element is remote-controlled.

17. The device according to claim 15, wherein:

15 each one of the at least one mechanical adjustment element and the at least one electro-optical adjustment element includes one of electronically controllable liquid-crystal cells and electro-optical crystal modulators.

18. The device according to claim 7, wherein:

20 the interferometer includes one of a Mach-Zehnder interferometer, a Michelson interferometer, a Fabry-Perot interferometer, and an Echelon.

19. The device according to claim 7, wherein:

the interferometer includes a linearly birefringent crystal having an optical path difference
25 $\delta l_F - \delta l_S$ that is enlarged by one of an additional compensator and an electrically tunable delay plate corresponding to one of a liquid-crystal cell and a Kerr cell, such that the

28030-61

optical path difference $\delta l_F - \delta l_S$ is variable by more than one half wavelength of the photon coupled into a corresponding one of the plurality of beam-component paths.

20. The device according to claim 19, wherein:

5 the linearly birefringent crystal includes a quartz plate, and

the additional compensator includes a Babinet-Soleil compensator.

21. The device according to claim 7, wherein:

10 the beam splitter includes an optical fiber coupler having a division ratio of 1:1.

22. The device according to claim 7, wherein mounted in at least one of the plurality of beam-component paths are at least one of:

15 at least one intensity-altering absorber for influencing a quantity of the photons,

at least one polarization-altering adjustment element for influencing a polarization of the photons,

20 at least one phase-altering adjustment element for influencing a phase of the photons, and

at least one frequency-altering adjustment element for influencing a frequency of the photons.

23. The device according to claim 7, further comprising:

28030-61

at least one optical storage device inserted into
at least one of the plurality of beam-component paths.

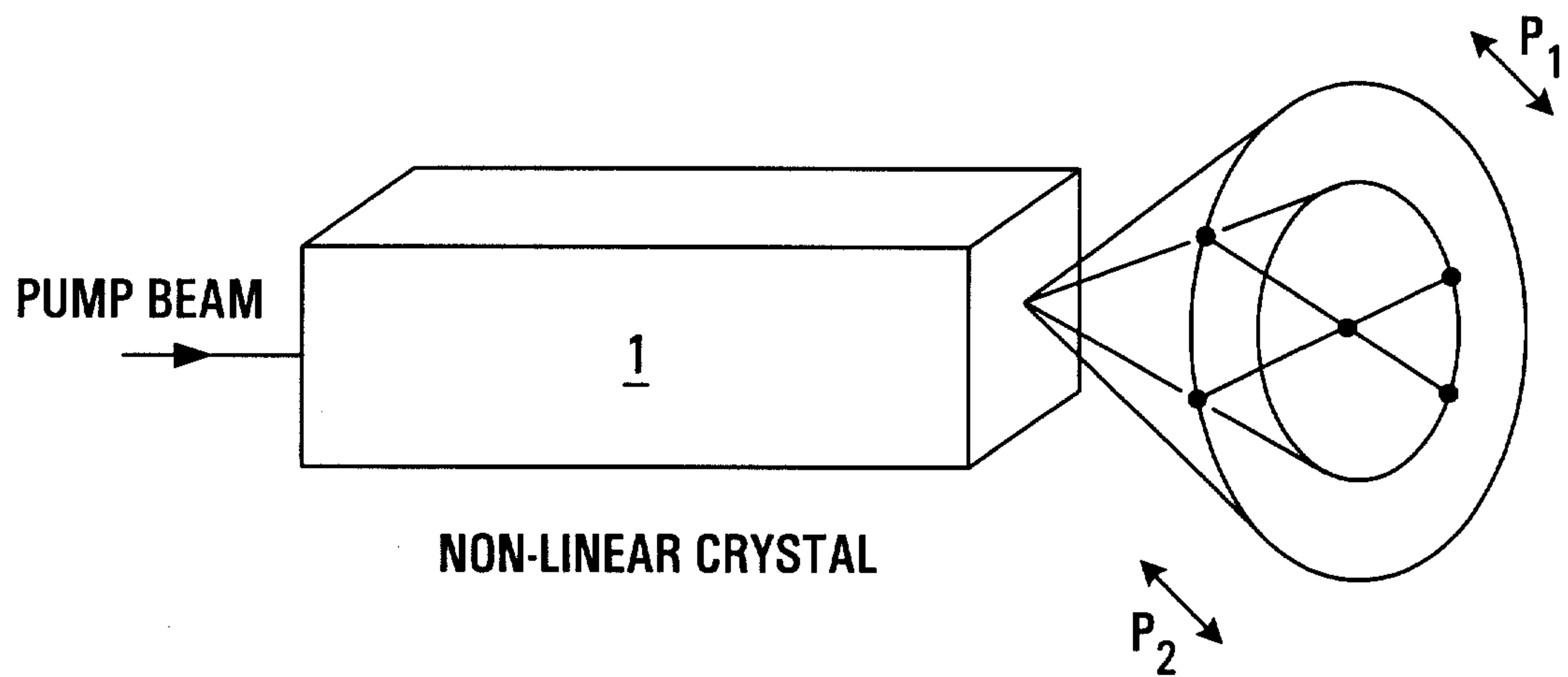
24. The device according to claim 23, wherein the at
least one optical storage device includes one of a glass-
5 fiber loop and a Fabry-Perot resonator.

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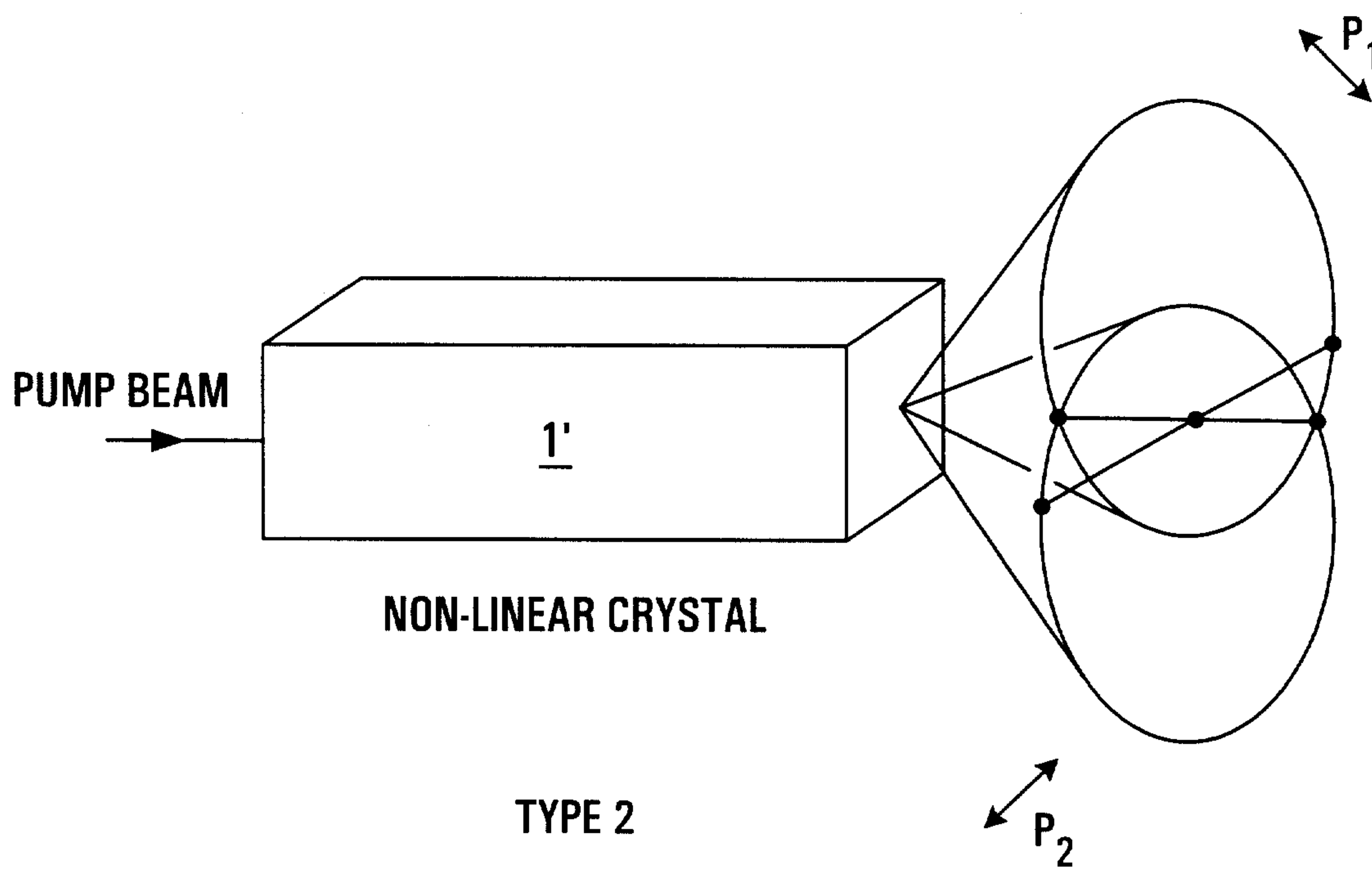
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1/3



TYPE 1

FIG. 1A



TYPE 2

FIG. 1B

2/3

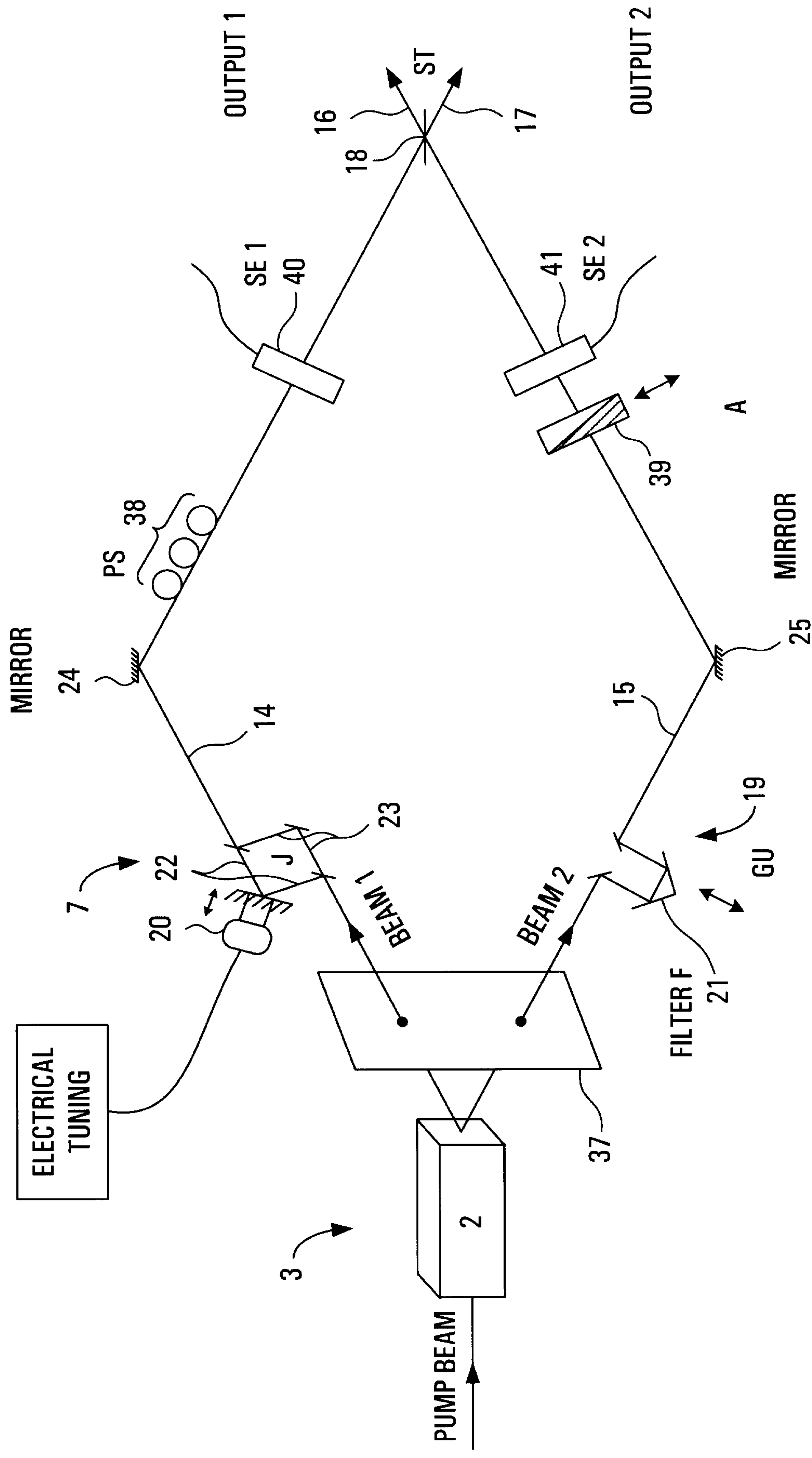


FIG. 2

