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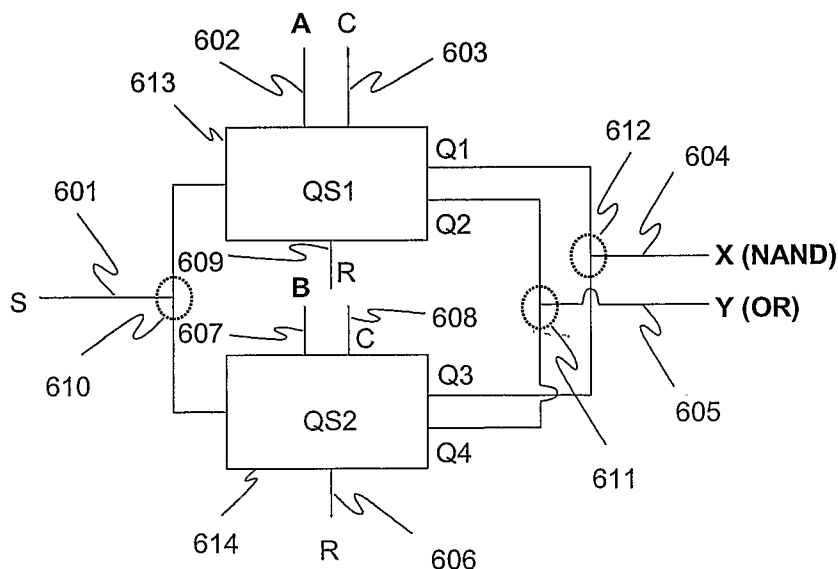
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(57) Abstract: A system, method, and apparatus for photon logic gates based on quantum switch, where a single or multiple quantum switches are utilized for dark resonance interactions in which three-color lasers interact with a four-level or five-level nonlinear optical medium composed of three ground states and one or two excited states through nondegenerate four-wave mixing processes. The photon logic mechanism is based on combination of single or multiple dark resonance-induced two-photon coherence swapping among the three closely spaced ground states through optical transitions via a common excited state. The two-photon coherence induced on the ground states is optically detected via

nondegenerate four-wave mixing processes. The nondegenerate four-wave mixing generation is enhanced owing to dark resonance or electromagnetically induced transparency. The gating time and bandwidth of the present photon logic gate method is not limited by population relaxation time or carrier's lifetime, but phase decay time, where the phase decay time in general much faster than the population decay time in solids or semiconductors.

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PHOTON LOGIC GATES

Technical Field

The present invention relates to a method and apparatus for photon logic gates using quantum switch(es).

5 Background Art

A logic gate is generally used for logical operations in data processing using one more logic inputs to produce a single output. The logic is normally referred to Boolean logic such as NOT, OR, NOR, XOR, XNOR, AND, and NAND. For an
10 electronic central processing unit (CPU) the logic is used as a basic unit to perform computing operations. Due to increasing demand for faster processing ability, there have been exponentially evolved up to now 3.7GHz according to the Moore's law since mid 1970s. However, there
15 have been fundamental limitations in electronic transistors in terms of size-dependent switching time and electric-field-limited operational bandwidth. To overcome such fundamental limitations, optical logic gates have been studied for last several decades. On the
20 contrary, as a counterpart of electronic carriers, optical signals are free from the electromagnetic interference and the size-dependent speed limitation. Moreover parallel processing is an intrinsic benefit. Recently, various types of high-speed all-optical logic gates for Boolean NOT, OR,
25 NOR, AND, XOR, and NAND have been demonstrated using

semiconductor-optical-amplifiers (SOAs) and erbium doped fiber amplifiers (EDFAs). A computing device, however, must satisfy certain requirements of practicality such as lower power consumption, smaller device size, and higher speed. Since 1980's several types of Boolean algebra-based optical logic gates have been proposed and demonstrated. A bulky optical logic gate using linear optics such as mirrors and beam splitters has been applied. The linear optics based optical gate is of course lacks efficiency due to bulky size.

Recently nonlinear optics-based optical logic gates have been intensively studied. In this area, SOA is the most useful component to form the optical logic gate. By introducing SOAs to optical logic gates the device size and power consumption has been extremely reduced. The physics of the SOA-based optical logic gate is based on the refractive index change occurred by electric current. In conventional optical switching technologies, the time delay for the refractive index change is an absolute constraint to the device performance. In SOA-based optical logic gates, the refractive index change is limited by the carrier redistribution time. Therefore, the carrier redistribution time should be fundamentally limited by the carriers' lifetime, where it is sub-nanosecond. Even though a SOA offers relatively low power consumption such as ~100 mW (Optics Letters, Vol. 23, pp. 1271-3 (1997)), total estimated power and size for a potential optical CPU composed of just million units of SOA reaches at several ~100 kW and several square meters, respectively, which is never practical. Here it should be noted that the up-to-date electronic CPU reaches at 3.7 GHz

in clock speed, contains near 300 million transistors, and needs about 100W power consumption: www.intel.com/research/silicon/micron.htm

On the other hand, optical switching effect can be obtained by using a nonlinear quantum phenomenon, electromagnetically induced transparency (EIT), which uses two-color electromagnetic fields for rapid refractive index change owing to quantum interference in an optically resonant medium composed of three energy levels or more: Harris, Physics Today, Vol. 50, p. 36 (1995). The energy level structure of the resonant optical medium satisfies two-closely spaced ground states and an excited state, two-closely spaced excited states and a ground state, or an arbitrarily spaced cascade-type system. The quantum interference-based refractive index change can be induced by strong spin coherence excitation on the close states and absorption cancellation. Due to the absorption spectrum change, a slow light phenomenon is induced due to the steep dispersion slope across the resonance. Lukhin et al., Physical Review Letters (2002).

the time needed for the refractive index change is not limited by the carriers' lifetime or population relaxation time, but dependent on the phase decay time, where the phase decay time is normally much shorter than the population relaxation time in solids. Specifically, the phase decay time is hundreds times faster than the carrier's lifetime in most ion-doped crystals such as Pr³⁺-doped Y₂SiO₅, so that ultrahigh-speed optical processing can be obtained: quantum switching (Ham, Applied Physics

Letters, Vol. 85, pp. 893-5 (2004)). The two-photon coherence excitation between the closely spaced ground states is optically detected by using nondegenerate four-wave mixing processes. The resulting intensity of the nondegenerate four-wave mixing signal can be stronger than that of the original input signal: Hemmer *et al.*, Optics Letters, Vol. 20, pp. 982-4 (1995)).

When the two-closely-spaced ground states are replaced by three-closely-spaced states and three-color optical fields are resonantly applied to the common excited state, a quantum switching phenomenon is obtained: Ham, Physical Review Letters, Vol. 84, pp. 4080-3 (2000). The physics of the quantum switch is the optically controllable spin-coherence swapping, and the optical switching time is much faster than conventional refractive index-based switch. This fact was experimentally demonstrated in Pr³⁺-doped Y₂SiO₅ (Pr:YSO) for 100 fold decrease switching time: Ham, Applied Physics Letters, Vol. 85, pp. 893-5 (2004).

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The primary object of the present invention is to provide a method and an apparatus of photon logic gates based on quantum switching phenomenon. The photon logic gates should overcome limitations of the conventional optical logic gates in operational speed and size. The main feature of the photon logic gates is using quantum optics of EIT and quantum switch for multiple gate function in one

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physical gate composed of three (four) -color lasers interacting with a nonlinear optical medium via optical waveguides or free space. As shown in the quantum switch (Ham, US patent No. 6628453), the operational bandwidth of the present photon logic gates is not limited by the population relaxation time or carrier's lifetime. Main advantage of the present invention is not only for all-optical digital processing but also for quantum interface in a quantum network composed of quantum computers. Briefly described, a system of the photon logic gates of the present invention is provided by a single or multiply connected quantum switches composed of nonlinear optical medium and at least four coherent laser beams. The nonlinear optical medium of the quantum switch is composed of at least four-energy levels. Three of them should be closely spaced ground states, and the last one should be an excited state. The frequencies of the laser beams of A, C, and D are resonant respectively to the transitions from the ground states $|1\rangle$, $|2\rangle$, and $|3\rangle$ to the excited state $|4\rangle$ of the nonlinear optical medium: see Figs. 1 and 2. The laser beam A is used for nondegenerate four-wave mixing process to generate the outputs Q1 or Q2. The nondegenerate four-wave mixing output Q1 and/or Q2 can be used as an input(s) to the second/third nonlinear medium to configure a photon logic gate. The output direction of the Q1 and Q2 is physically separated, so that the quantum switch acts as an optical router: Ham, Applied Physics Letters Vol. 85, pp.893-895 (2004). Each laser beam can be guided by an optical waveguide made of hetero-structured quantum wells, photonic bandgap crystals, silicon on

insulator, or surface plasmon. The optical waveguide is not part of the current invention. By connecting two quantum switches in series or in parallel it performs the Boolean logic: NOT, NAND, AND, OR, XOR, and NOR. The photon logic gates can be extended for scalability purposes by an optical waveguide, and the traveling time between two photon logic gates is negligible.

10 Brief Description of the Drawings

The accompanying figures illustrate several embodiments of the present invention, and together with the descriptions, serve to explain the principles of the invention. The drawings are for only for the purpose of illustrating a preferred embodiment of the invention and are not to be construed as limiting the invention.

FIG. 1 illustrates a block diagram of a photon logic gate, NOT, of the present invention. FIG. 1 is very similar to the block diagram of the NOT gate in U.S. Patent No. 6628453.

FIG. 1 is a four energy level diagram of the nonlinear optical system shown in FIG. 1, where the frequency difference among the ground states are much smaller than the transition frequency between the ground states and the excited states. The excited energy state $|5\rangle$ can be virtual, real, or the same as the state $|4\rangle$ depending on the value of the frequency detuning Δ . Letters R, S, C, A, Q1, and Q2 stand for laser beams at different frequencies of ω_R , ω_S , ω_C , ω_A , ω_{Q1} , and ω_{Q2} , respectively.

FIG. 3 shows both experimental (a, b) and theoretical (c, d) data of FIG. 2: Quantum switching (routing). The spatial direction of the output beams Q1 and Q2 are determined by the phase matching conditions of the laser beams, in which the direction is either the same each other or different.

FIG. 4 illustrates a schematic diagram of a photon logic gate, NOR, of the present invention. Letter QS stands for the quantum switch comprised of a nonlinear optical medium 107, which is connected by optical waveguides used for the laser beams R, S, C, A, Q1 (or X), and Q2 (or Y) in FIG. 1, and also satisfies FIG. 2.

FIG. 5 illustrates a schematic diagram of a photon logic gate, AND, of the present invention. Letter QS stands for the quantum switch comprised of a nonlinear optical medium 107 which is connected by optical waveguides use laser beams R, S, C, A, Q1 (or X), and Q2 (or Y) and also satisfies FIG. 2.

FIG. 6 illustrates a schematic diagram of a photon logic gate, NAND/OR, of the present invention. Letter QS stands for the quantum switch it is comprised of a nonlinear optical medium 107 which is connected by optical waveguides used for the laser beams R, S, C, A, Q1, Q2, Q3, Q4, X, and Y.

FIG. 7 illustrates a schematic diagram of a photon logic gate, NOR/XOR/AND, of the present invention. Letter QS stands for quantum switch comprised of a nonlinear optical medium connected by optical waveguides used for the laser beams R, S, C, A, B, Q1, Q2, X, Y, and Z.

Best Mode for Carrying Out the Invention

To gain a better understanding reference is now made to the drawings which illustrate the preferred embodiments of the invention. Figure 1 describes a photon logic gate, NOT, where a single quantum switch is used. Letters R, S, C, A, Q1, and Q2 stand for laser beams at different frequencies of ω_R , ω_S , ω_C , ω_A , ω_{Q1} , and ω_{Q2} , respectively. The numbers from 101 to 106 stand for both laser beams and optical waveguide used for the laser beams. The number 107 stands for a nonlinear optical medium. According to the quantum switch theory (Physical Review Letters. Vol. 84, pp. 4080-4083 (2000), and Applied Physics Letters, Vol. 78, pp. 3382-3384 (2001); Applied Physics Letters, Vol. 85, pp. 893-895 (2004); US patent No. 6628453 (2003)), the output Q1 (104) is always OFF whenever the logical input beam A is switched ON, and vice versa. Here it should be noted that the laser beams C and R may be continuous if the detuning is not zero: the detuning Δ is shown in FIG. 1. When the detuning Δ is equal to zero, then the laser beams C (105) and S (103) continues but must be pulsed and synchronized with beam C (102). TABLE 1 shows the results of the NOT of FIG. 1.

TABLE 1

S	A	Q1 (NOT)	Q2
1	0	1	0
1	1	0	1

Here the excited energy state $|5\rangle$ is either virtual or real. For the real state of $|5\rangle$ with nonzero detuning Δ , the pulsed nondegenerate four-wave mixing processes have been

demonstrated: Ham, Optics Letters, Vol. 24, pp. 86-88 (1999).

FIG. 2 shows an energy level diagram of the nonlinear optical medium 107 of FIG. 1. In general this kind of energy level structure is typical in a rare-earth doped crystal such as Pr^{3+} doped Y_2SiO_5 (YSO). Here, the lower three energy levels are resulted from the hyperfine splitting in rare-earth doped crystals. The energy level structure of FIG. 2 can also be obtained artificially by multiply coupling semiconductor quantum wells or quantum dots. The nonlinear optical medium 107 of FIG. 1 has either four energy states; $|1\rangle$, $|2\rangle$, $|3\rangle$ and $|4\rangle$ or five energy states; $|1\rangle$, $|2\rangle$, $|3\rangle$, $|4\rangle$ and $|5\rangle$. The state $|4\rangle$ of FIG. 2 is higher than $|1\rangle$, $|2\rangle$ and $|3\rangle$ in energy. In fact the nonlinear optical medium 107 of FIG. 1 may have more than five energy levels, the mentioned energy levels shown in FIG. 2 contain the photon logic mechanism of the present invention. The detuning Δ of FIG. 2 is an offset of the laser ω_R from the resonance frequency from the state $|3\rangle$ to $|4\rangle$, i.e. $\Delta = \omega_4 - \omega_3$. The laser output beam Q1 at frequency ω_{Q1} is generated by nondegenerate four-wave mixing processes involving three laser interactions of C, S, and R are involved at frequencies ω_C , ω_S , and ω_R , respectively, with the nonlinear optical medium. Similarly, the laser output Q2 at frequency ω_{Q2} is generated by nondegenerate four-wave mixing processes involving three laser interactions of A, S, and R at ω_A , ω_S , and ω_R , respectively. The propagation directions \mathbf{k}_{Q1} and \mathbf{k}_{Q2} of the nondegenerate four-wave mixing signals Q1 and Q2 of FIG. 2 are determined by the phase

matching conditions, respectively: $k_{Q2}=k_A-k_S+k_R$; $k_{Q1}=k_C-k_S+k_R$. Here, the nondegenerate four-wave mixing generation is strongly enhanced owing to dark resonance or EIT. To understand the enhancement of the nondegenerate four-wave
5 mixing processes, more detail explanation is presented below.

Enhancement of nondegenerate four-wave mixing processes was suggested by Harris in Physical Review Letters, Vol. 64, pp. 1107-1110 (1991) and were demonstrated
10 experimentally in atomic gases by Jain *et al.* in Optics Letters Vol. 18, pp. 98-101 (1993) and in ion-doped solid by Ham *et al.* in Optics Letters, Vol. 22, pp. 1138-1140 (1997). Signal amplifications and high-conversion efficiency using atomic gases for nondegenerate four-wave mixing processes
15 were also experimentally demonstrated by Hemmer in Optics Letters, Vol. 20, pp. 982-984 (1995) and Ja in Physical Review Letters, Vol. 77, pp. 4326-4328 (1996) respectively. The high-conversion efficiency of nondegenerate four-wave mixing processes was also
20 experimentally demonstrated in ion-doped solids by Ham *et al.* in Physical Review Letters, Vol. 59, pp. R2583-2586 (1999). The enhancement of nondegenerate four-wave mixing processes is based on reduced first-order linear susceptibility and enhanced third-order nonlinear susceptibility owing to
25 destructive and constructive quantum interference, respectively.

To show more detail relations between the laser inputs and the nondegenerate four-wave mixing output signals, coherence swapping should be understood. To see the

coherence excitation in FIG. 2, density matrix ρ must be discussed. The density matrix has been a useful tool to show a system's macroscopic ensemble; *Quantum optics*, Cambridge University Press, New York, N.Y. (1997), Edited by Scully and Zubairy. In FIG. 2, two laser beams C and S can induce two-photon coherence ρ_{23} on the transition $|2\rangle - |3\rangle$ via the excited state $|4\rangle$. Similarly two lasers beams A and S can also induce two-photon coherence ρ_{13} on the ground state transition $|1\rangle - |3\rangle$ via the excited state $|4\rangle$. Especially, the two-photon coherence is strongly enhanced if dark resonance or EIT involves. Here, dark resonance or EIT is the same physical phenomenon, but the term EIT roots in the absorption cancellation so that a resonant electromagnetic field can pass through an optically thick medium without experiencing any absorption.

FIG. 3 shows both theoretical and experimental data of the quantum switching (routing) using $\text{Pr}^{3+}:\text{YSO}$ base for the detuning $\Delta=0$: The δ stands for the detuning of laser beam A from the resonance frequency of the transition $|1\rangle - |3\rangle$. In FIG. 3, the intensity of the two-photon coherence ρ_{13} and $\text{Re}\rho_{23}$ is swapped each other according to the detuning of A: The two-photon coherence can be optically detected using the laser beam R resulting in generation of nondegenerate four-wave mixing signal Q1 or Q2. The experimental data of the nondegenerate four-wave mixing signals in FIGs. 3a and 3b match well the two-photon coherence intensity $[\text{Re}\rho_{12}]^2$, which has been calculated theoretically: Ham et al. in *Physical Review A*, Vol. 59, R2583-R2586 (1999), *Physical Review Letters*. Vol. 84, pp. 4080-4083 (2000), and *Applied Physics Letters*, Vol. 78, pp.

3382-3384 (2001); Applied Physics Letters, Vol. 85, pp. 893-895 (2004); US patent No. 6628453 (2003).

FIG. 4 describes a photon logic gate, NOR, where two quantum switches are connected in series. Here, the output Q1 (410) of the left (first) quantum switch QS1 (412) is fed into the right (second) quantum switch QS2 (413) as an input (see S in FIG. 1). Two logical input laser beams A (402) from QS1 and B (404) from QS2 perform optical logic inputs and result in Boolean algebra NOR at the output X (406). As mentioned above the laser beams R (408, 411) applied to each quantum switch can be continues wave if $\Delta \neq 0$. If $\Delta = 0$, R muse be pulsed and synchronized to the input logic laser A (402). Both input laser beams A (402) and B (404) must be synchronized, too. TABLE 2 shows the Boolean algebra of NOR resulted in the outputs X (406) by the combinatic logic inputs A (402) and B (404).

TABLE 2

S	A	B	Q1	Q2	X (NOR)	-
1	0	1	1	0	1	0
			1	0	0	1
			0	1	0	0
			0	1	0	0

FIG. 5 shows a photon logic gate AND, where the logic gate is composed of two quantum switches connected in series. Here, the output Q2 (509) of the left quantum switch QS1 (512) is fed into the right quantum switch QS2 (513) as an input S (see S in FIG. 1). The combination of two logic input beams A (502) from QS1 and B (504) from QS2 result in Boolean algebra AND to the output Y (507). As mentioned

above the laser beam R (511, 508) applied to each quantum switch can be continues wave if $\Delta \neq 0$. If $\Delta = 0$, however, R must be pulsed and synchronized to the input laser A (502). Both input laser beams A (502) and B (504) must be synchronized, too. TABLE 3 shows a resulting Boolean algebra AND appeared in the output Y (507) according to two logic inputs A (502) and B (504).

TABLE 3

S	A	B	Q1	Q2	X	Y (AND)
1	0	1	1	0	0	0
1	0	0	1	0	0	0
1	1	1	0	1	1	0
1	1	0	0	1	0	1

10

FIG. 6 shows a photon logic gate, NAND/OR. The system is composed of two quantum switches connected in where the source laser S (601) is shared. The output the top quantum switch QS1 and Q3 from the botto switch QS2 is combined together to lead the logic (604). The output Q2 and Q4 are combined to lead the logic outp laser beams R (609, 606) are either cw ε ing Δ is not zero or synchronized as δ input laser beams A (602) and B (607) if the detuning Δ is zero. The source laser beam S (601) is split into two components through an optical splitter/combiner (610, 611, 612) such as a Y branch or a beam splitter. Under the action of two inputs A (602) and B (607), the output logic laser beams X (604) and Y (605) perform Boolean logic operations NAND and OR, respectively: see TABLE 4.

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TABLE 4

S	A	B	Q1	Q2	Q3	Q4	X (NAND)	Y (OR)
1	0	0	1	0	1	0	1	0
1	0	1	1	0	0	1	1	1
1	1	0	0	1	1	0	1	1
1	1	1	0	1	0	1	0	1

FIG. 7 shows a photon logic gate, NOR/XOR/AND. The system is composed of three quantum switches, where two of them are connected to the last one. Each output Q1 (712) and Q2 (710) of the quantum switch QS1 (716) are used as an input to the quantum switches QS2 (718) and QS3 (717), respectively. The output P1 (706) is used as a logic output X. The outputs P2 and P3 are combined together (719) to lead the logic output Z (707). The output P4 (708) is used as a logic output Y. There are two logic inputs A (702) and B (704, 715), where A is for the QS1 and B is for bot QS3. The functions of R (711, 713, 709) and C (714) are the same as discussed above. As seen in the two logic inputs A and B performs Boolean algebra the output X, XOR at Z, and AND at Y, simultaneously.

S							2	P3	P4	X (NOR)	Y (AND)	Z (XOR)
1								0	0	1	0	0
1	0	1	1	0	0	1	0	0	0	0	1	
1	1	0	0	1	0	0	1	0	0	0	1	
1	1	1	0	1	0	0	0	1	0	1	0	

Claims

1. A method of photon logic gates using a single or multiple quantum switches whose nonlinear optical medium is comprised of three closely spaced ground states $|1\rangle$, $|2\rangle$ and $|3\rangle$ such that the transition among the said ground states is dipole forbidden, and an excited state $|4\rangle$ and $|5\rangle$ such that two-photon transitions between said ground state $|1\rangle$ and said $|3\rangle$, said $|2\rangle$ and said $|3\rangle$, and said $|1\rangle$ and said $|2\rangle$ via said excited state $|4\rangle$ (and said excited state $|5\rangle$ if said $|5\rangle$ is real energy state) are allowed, said method comprising following steps:

a) applying to said nonlinear optical medium a first laser beam as an input beam A through an optical waveguide or free space at a frequency of ω_A corresponding to transition between said ground state $|1\rangle$ and said state $|4\rangle$;

b) applying a second laser beam C through a waveguide or free space at a frequency of ω_C corresponding to a transition between said ground state $|2\rangle$ and said

excited state $|4\rangle$;

c) applying a third laser beam S through an optical waveguide or free space at a frequency of ω_S corresponding to a third transition between said ground state $|3\rangle$ and said excited state $|4\rangle$;

d) applying a fourth laser beam R through an optical waveguide or free space at a frequency of ω_R corresponding to a third transition between said ground state $|3\rangle$ and said excited state $|5\rangle$;

e) adjusting the intensities of said first laser beam A, said second laser beam C, said third laser beam S, and said fourth laser beam R to produce nondegenerate four-wave mixing signals Q1 at a frequency ω_{Q1} , or Q2 at a frequency ω_{Q2} corresponding to the two-photon coherence induction $[Rep_{23}]^2$ or $[Rep_{13}]^2$, respectively;

f) connecting said nondegenerate four-wave mixing signals Q1 and Q2 to optical waveguides physically separated;

g) connecting two quantum switches in a way to share said S and combine each said Q1 or Q2 together, respectively, via optical waveguides or free space;

h) connecting two quantum switches in a way to combine nondegenerate four-wave mixing signals Q1 from one quantum switch and Q2 from the other quantum switch;

i) connecting said Q1 or Q2 of the first quantum switch to said S of the second quantum switch via a waveguide or free space;

j) connecting each said Q1 and Q2 of the first quantum switch to the second and third quantum switch via waveguides or free space.

2. The method of claim 1 wherein said excited state $|4\rangle$ is selected such that its energy level is higher than the energy level of said ground state $|1\rangle$, said $|2\rangle$, and said $|3\rangle$.

3. The method of claim 1 wherein said excited state $|5\rangle$ is selected such that its energy level is separated from

said excited state $|4\rangle$ by detuning Δ , where Δ is 0 or near optical Rabi frequency of said R or A.

4. The method of claim 1 wherein Rabi frequency Ω_A of
5 said first laser beam A is greater than that of said second
laser beam C, and said third laser beam S.

5. The method of claim 1 wherein said first laser beam
A, said second laser beam C, said third laser beam S, and
10 said fourth laser beam R are synchronized satisfying said
laser beams A, C, and S are overlapped one another
temporally, and said fourth laser beam R is time delayed by
 τ shorter than phase decay time T_2 among the said three
ground states $|1\rangle$, $|2\rangle$, and $|3\rangle$ if $\Delta=0$.

15

6. The method of claim 1 wherein said sec
beam C and said fourth laser beam R are always sw:
and said first laser beam A and said third laser k
temporally synchronized, if $\Delta \neq 0$.

20

claim 1 wherein the detuning Δ ,
ener said energy states $|4\rangle$ and $|5\rangle$ is
greater than or similar to the Rabi frequency of said first
laser A for the applications of optical router of the
25 quantum switch.

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8. The method of claim 1 wherein a single quantum
switch is used for Boolean NOT algebra, where said first
laser beam controls said third laser beam S to invert it and
30 to produce it into said output Q1.

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9. The method of claim 1 wherein serial two quantum switches are used for Boolean NOR algebra, where said output Q1 of the first said nonlinear medium is used as said laser beam S to said second nonlinear medium, and the relation between two said first laser beams A's and said output Q1 of the second said nonlinear medium satisfies Boolean algebra NOR.

10. The method of claim 1 wherein serial two quantum switches are used for Boolean algebra AND, where said output Q2 of the first said nonlinear medium is used as said laser beam S to said second nonlinear medium, and the relation between two said first laser beams A's and said output Q2 of the second said nonlinear medium satisfies Boolean AND.

11. The method of claim 1 wherein parallel two quantum switches are used for Boolean NAND/OR algebra, where said laser beam S is used for two said nonlinear media and each said laser beam A's are combined, respectively, so that two said first laser beams A's are applied to each said nonlinear medium and each said combined outputs Q1's and Q2's satisfies Boolean algebra NAND and OR, respectively.

12. The method of claim 1 wherein three quantum switches are connected one another to satisfy Boolean NOR/XOR/AND algebra, where said Q1 and Q2 of the first quantum switch is used for said S for both parallel quantum

switches, and each said output Q2 and Q1 from the parallel quantum switches are combined for Z, respectively, so that the relation between three laser beams said A's applying to each said nonlinear media and said outputs Q1, Q2, and Z satisfies Boolean algebra NOR, AND, and XOR, respectively.

13. An apparatus for photon logic gates using a single or multiple nonlinear optical medium composing three ground states $|1\rangle$, $|2\rangle$, $|3\rangle$ such that the transition between said ground states $|1\rangle$ and $|2\rangle$, $|1\rangle$ and $|3\rangle$, and $|2\rangle$ and $|3\rangle$ are dipole forbidden, and an excited state $|4\rangle$ such that two-photon transition between said ground states $|1\rangle$ and $|2\rangle$, $|1\rangle$ and $|3\rangle$, and $|2\rangle$ and $|3\rangle$ via said excited state $|4\rangle$ is allowed, said apparatus comprising:

- 15 a) a first laser beam source for applying nonlinear optical medium said first laser beam frequency of ω_A corresponding to a first transition said ground state $|1\rangle$ and said excited state $|4\rangle$;
- 20 b) a second laser beam source for applying to said nonlinear optical medium a second beam C at a frequency of ω_C corresponding to a second transition between said ground state $|2\rangle$ and said excited state $|4\rangle$;
- 25 c) a third laser beam source for applying to said nonlinear optical medium a third beam S at a frequency of ω_S corresponding to a third transition between said ground state $|3\rangle$ and said excited state $|4\rangle$;
- d) a fourth laser beam source for applying to said nonlinear optical medium a fourth beam R at a frequency of ω_R corresponding to a fourth transition between said ground

state $|3\rangle$ and said excited state $|5\rangle$, either said excited state $|5\rangle$ is real or virtual;

e) a means for splitting a third laser beam S from said third laser beam into two or multiple beams for applying to each said nonlinear optical medium at a frequency of ω_s corresponding to a third transition between said ground state $|3\rangle$ and said excited state $|4\rangle$;

f) a means for combining said nondegenerate four-wave mixing signals Q1 and Q2 from multiple nonlinear optical media into corresponding optical channels, respectively.

g) a means for adjusting the intensities and the frequencies of said first beam, said second beam, said third beam, and said fourth beam to produce coherent superposition state of said ground state $|1\rangle$ and said $|2\rangle$, said $|1\rangle$ and said $|3\rangle$, and said $|2\rangle$ and $|3\rangle$;

h) a means for synchronizing or delaying a first laser beam A, a third laser beam S, and a fourth laser beam B with another.

i) A means for spatially overlapping a first laser beam A, a second laser beam C, a third laser beam S, and a fourth laser beam B with a nonlinear optical medium.

14. The apparatus of claim 13 wherein said nonlinear optical medium is a solid

15. The apparatus of claim 13 wherein said nonlinear optical medium is multiply coupled semiconductors.

16. The apparatus of claim 15 in which said three ground states $|1\rangle$, $|2\rangle$ and $|3\rangle$, and said excited states $|4\rangle$

and $|5\rangle$ are selected in conduction band of said multiply coupled semiconductor.

17. The apparatus of claim 13 in which said nonlinear
5 optical medium is connected via optical waveguides, free space, or plasmon waveguides to guide said laser beams A, C, S, R, Q1, and/or Q2.\

18. The apparatus of claim 13, where said first laser
10 beam A acts on said third laser beam S to produce said output Q1 for the Boolean NOT algebra.

19. The apparatus of claim 13, where said nonlinear
15 medium is connected in which said output Q1 of the first nonlinear medium to be fed into said second nonlinear as a said third laser beam S, and the relation between first laser beams A's applying to each said nonlinear and said output Q1 of said second nonlinear medium the Boolean algebra NOR.

20

of claim 13, where said nonlinear
medi which said output Q2 of the first
nonlinear medium to be fed into said second nonlinear medium
as a said third laser beam S, and the relation between two
25 first laser beams A's applying to each said nonlinear medium and said output Q2 of said second nonlinear medium satisfies the Boolean algebra AND.

21. The apparatus of claim 13, where said third laser
30 S is shared by two nonlinear media each said outputs Q1 and

Q2 are combined together, and results satisfy the Boolean algebra NAND and OR, respectively, for two said first laser beams A of each nonlinear media.

5 22. The apparatus of claim 13, where three said nonlinear media are connected in a way that said both outputs Q1 and Q2 from said one nonlinear medium used for the third laser S of the said rest two nonlinear media, said
10 outputs Q1 and Q2 are combined together, so that three outputs satisfy the Boolean algebra NOR, XOR, and AND, respectively.

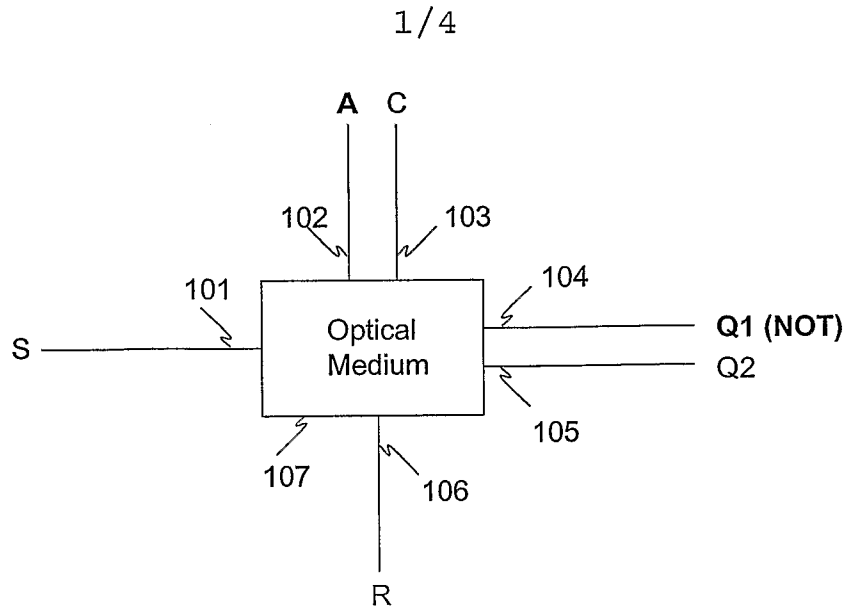


FIG. 1

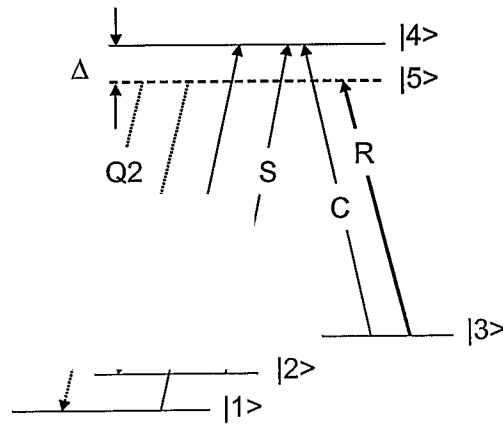


FIG. 2

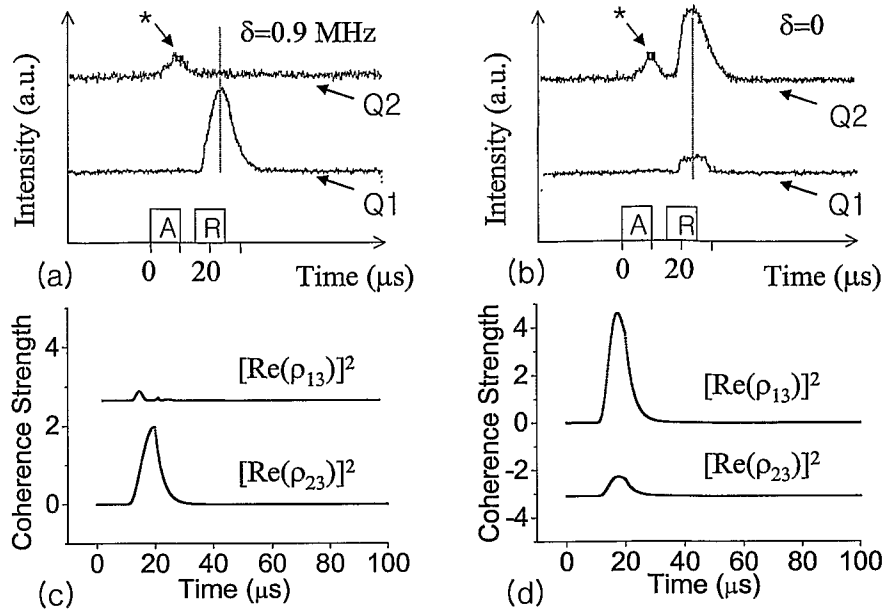


FIG. 3

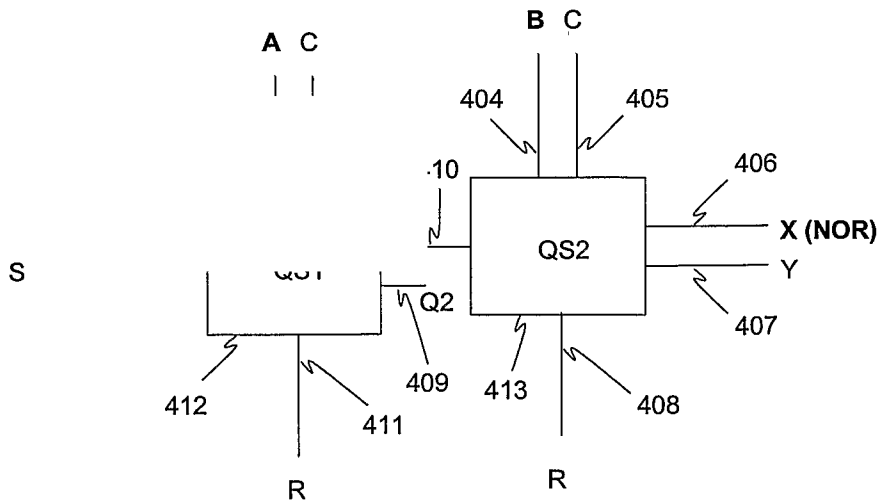


FIG. 4

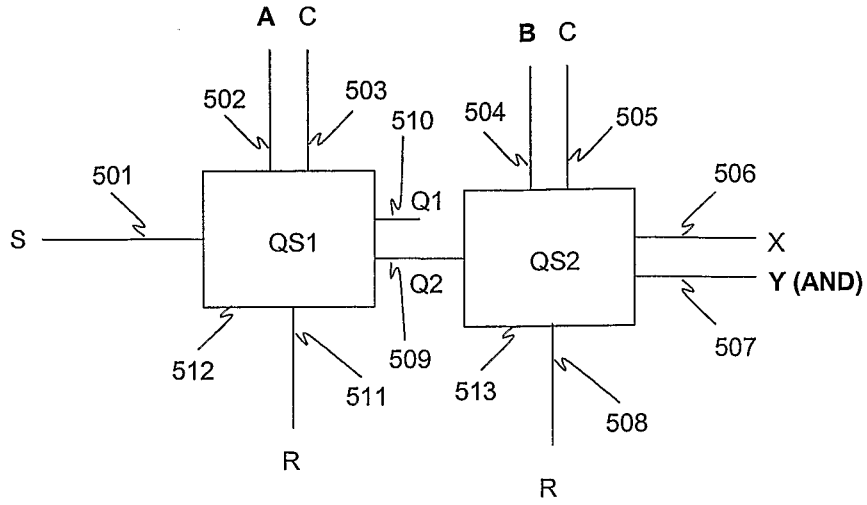


FIG. 5

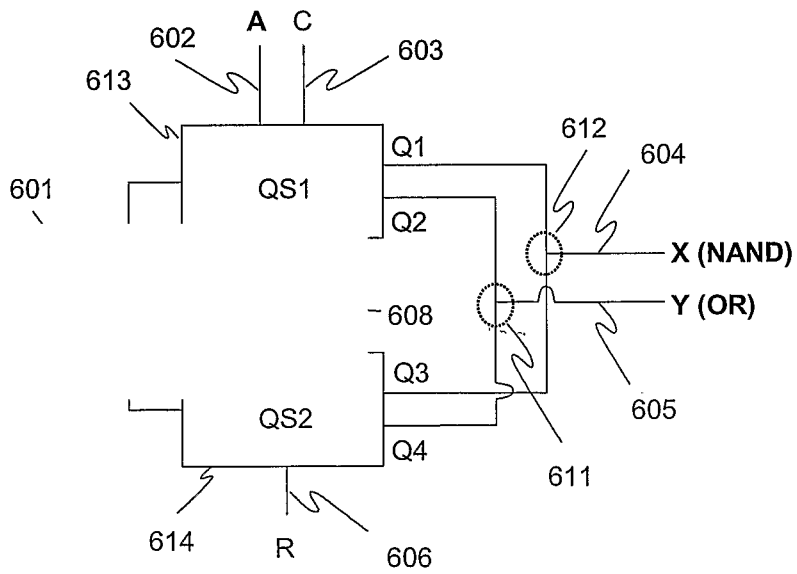


FIG. 6

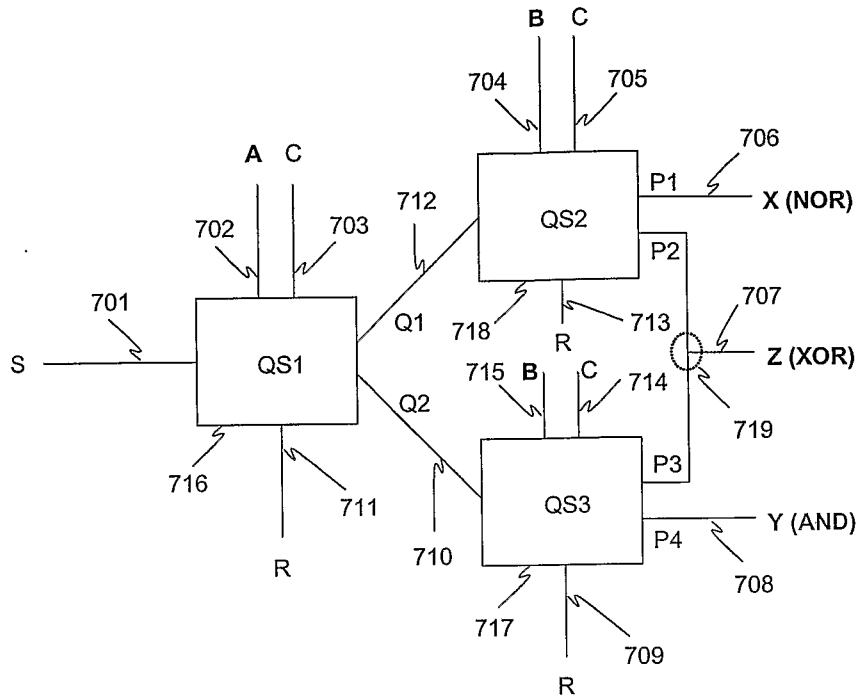


FIG. 7

A. CLASSIFICATION OF SUBJECT MATTER**G02B 6/35(2006.01)i**

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 8 G02

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

Korean Utility Models and applications for Utility Models since 1975 : IPC as above
Japanese Utility Models and applications for Utility Models since 1975 : IPC as above

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

eKIPASS(KIPO internal) "Keywords : photon, quantum, logic, gate, switch, computer and similar terms"

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KR 10-2001-0113407 A (HAM, BYOUNG-SEUNG) 28 DEC 2001 See pages 3- 5 & Figures 1-5	1, 13
A	US 6298180 B1 (HO, SENG-TIONG) 2 OCT 2001 See column 9, line 11 - column 15, line 56 & Figures 2-7	1, 13
A	US5005933 (SHIMUZU, AKIRA) 9 APR 1991 See column 3, line 34 - column 6, line 15 & Figures 2-8	1, 13
A	JP 2005-165123 A (NIPPON TELEGRAM & TELEPHONE CORPORATION) 23 JUN 2005 See paragraphs 14 - 36 & Figures 1-6	1, 13
A	JP 09-096845 A (MITSUBISHI ELECTRIC CORPORATION) 8 APR 1997 See paragraphs 5 - 73 & Figures 1-6	1, 13

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

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Date of the actual completion of the international search

05 JULY 2007 (05.07.2007)

Date of mailing of the international search report

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/KR2007/001130

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
KR 10-2001-0113407 A	28.12.2001	US 06628453 B2 US 2002-0015205 A1	30.09.2003 07.02.2002
US 06298180 B1	02.10.2001	AU 20007-009836 A1 CA 2385600 AA EP 1238299 A1 TW 546496 B US 2003-053785 A2 US 6788838 B2 WO 01-20379 A1 WO 01-20379 C2	17.04.2001 22.03.2001 11.09.2002 11.08.2003 20.03.2003 07.09.2004 22.03.2001 28.11.2002
US 05005933	09.04.1991	DE 68924949 T2 EP 0361508 A2 EP 0361508 B1 JP 02-093523 A JP 2698394 B2	23.05.1996 04.04.1990 29.11.1995 04.04.1990 19.01.1998
JP 2005-165123 A	23.06.2005	None	
JP 09-096845 A	08.04.1997	None	