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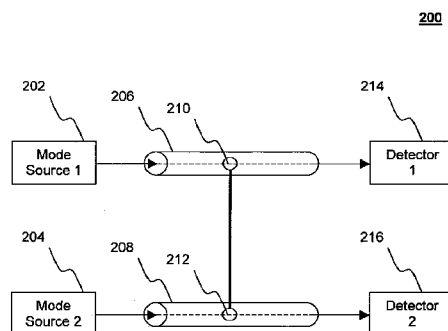


FIG. 2

(57) Abstract: A device (200) and method (100) to develop a linear atomic quantum coupler comprising a plurality of mode sources and a plurality of waveguides, characterized in that the plurality of waveguides are placed in close proximity to allow exchanging of energy via evanescent waves and the plurality of waveguides comprises at least one localized and/or trapped atom, wherein the plurality of mode sources comprises means for generating a plurality of modes, and the plurality of waveguides comprises means for propagating the plurality of modes through the plurality of waveguides.

LINEAR ATOMIC QUANTUM COUPLER

FIELD OF INVENTION

- 5 The present invention relates to a device and method to develop a linear atomic quantum coupler.

BACKGROUND ART

- 10 Quantum couplers have attracted much attention in the framework of the optics communication and quantum computing networks, which require data transmission and ultra-high-speed data processing. Furthermore, directional couplers have been experimentally implemented, e.g. in planar structures, dual optical fibres and certain organic polymers.

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- The interaction between radiation field and matter (i.e. atom), namely, Jaynes-Cummings model (JCM), is important in quantum optics and quantum information theories. The simplest form of the JCM is the two-level atom interacting with the single-mode of the radiation field. The JCM is a rich source for the nonclassical effects, e.g. the revival-collapse phenomenon (RCP), sub-Poissonian statistics and squeezing. Furthermore, the JCM has been experimentally implemented by various means, e.g. one-atom mazer, the NMR refocusing, a Rydberg atom in a superconducting cavity, the trapped ion and the micromaser. Various extensions to the JCM have been reported including the two two-level atoms interacting with the radiation field(s).

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The trapped atoms or molecules are promising systems for quantum information processing and communications. They can serve as convenient and robust quantum memories for

photons, providing thereby an interface between static and flying qubits. The subject of coupling cold atoms to the radiation field sustained by an optical waveguide has already appeared in various contexts. For example, hollow optical glass fibers were used to guide atoms over long distances, especially, employing red detuned light field filling out the hollow core. Substrate based atom waveguide can also be realized by using guided two-color evanescent light fields.

Moreover, the coupling of atomic dipoles to the evanescent field of tapered optical fibers has been previously demonstrated. In this respect the optical nanofibers can manipulate and probe singleatom fluorescence. Moreover, it has been suggested that using a two-color evanescent light field around a subwavelength-diameter fiber traps and guides atoms. The optical fiber carries a red-detuned light and a blue-detuned light, with both modes far from resonance. When both input light fields are circularly polarized, a set of trapping minima of the total potential in the transverse plane appears as a ring around the fiber. This design allows confinement of atoms to a cylindrical shell around the fiber.

Additionally, it has been shown that sub-wavelength diameter optical fibers can be used to detect, spectroscopically investigate, and mechanically manipulate extremely small samples of cold atoms. In particular, on resonance, as little as two atoms on average, coupled to the evanescent field surrounding the fiber, already absorbed the total power transmitted through the fiber. By optically trapping one or more atoms around such fibers, it should become possible to deterministically couple the atoms to the guided fiber mode and to even mediate a coupling between two simultaneously trapped atoms. This leads to a number of applications, e.g., in the context of quantum information processing, high precision measurements, single-photon generation in optical fiber or EIT-based parametric four-wave mixing using a few atoms around optical nanofibers.

SUMMARY OF INVENTION

In one embodiment of the present invention is a device for a linear atomic quantum coupler. The device comprises a plurality of mode sources and a plurality of waveguides, characterized in that the plurality of waveguides are placed in close proximity to allow exchanging of energy via evanescent waves and the plurality of waveguides comprises at least one localized and/or trapped atom, wherein the plurality of mode sources comprises means for generating a plurality of modes, and the plurality of waveguides comprises means for propagating the plurality of modes through the plurality of waveguides.

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In another embodiment of the present invention is a method for constructing a linear atomic quantum coupler. The method comprises generating a plurality of modes, placing a plurality of waveguides in close proximity to allow exchanging of energy via evanescent waves, localizing and/or trapping at least one atom in the plurality of waveguides and propagating the plurality of modes through the plurality of waveguides.

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The present invention consists of features and a combination of parts hereinafter fully described and illustrated in the accompanying drawings, it being understood that various changes in the details may be made without departing from the scope of the invention or sacrificing any of the advantages of the present invention.

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BRIEF DESCRIPTION OF THE ACCOMPANYING DRAWINGS

To further clarify various aspects of some embodiments of the present invention, a more particular description of the invention will be rendered by references to specific embodiments thereof, which are illustrated, in the appended drawings. It is appreciated that these drawings depict only typical embodiments of the invention and are therefore not to be considered limiting of its scope. The invention will be described and explained with additional specificity and detail through the accompanying drawings in which:

FIG. 1 illustrates a flowchart of a method for constructing a linear atomic quantum coupler.

FIG. 2 illustrates a device for a linear atomic quantum coupler.

FIG. 3 illustrates the evolution of the $\langle \hat{\sigma}_z^{(1)}(t) \rangle$ against the interaction time $T = \lambda_1 t$ with

$(\alpha, \beta) = (5, 5)$ for $(\lambda_2, \lambda_3) = (1, 0)$ (a), $(1, 0.6)$ (b), $(2, 3)$ (c) and $(1, 1)$ (d).

FIG. 4 illustrates the evolution of the single-mode second order correlation function as indicated against the interaction time $T = \lambda_1 t$ with $(\lambda_2, \lambda_3) = (1, 0)$ (a), $(1, 0.6)$ (b), $(2, 3)$ (c)- (d).

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention relates to a device and method for a linear atomic quantum coupler. Hereinafter, this specification will describe the present invention according to the preferred
5 embodiments of the present invention. However, it is to be understood that limiting the description to the preferred embodiments of the invention is merely to facilitate discussion of the present invention and it is envisioned that those skilled in the art may devise various modifications and equivalents without departing from the scope of the appended claims.

10 Reference is first made to FIGs. 1 and 2 collectively. FIG. 1 illustrates a flowchart of the method for constructing the linear atomic quantum coupler. FIG. 2 illustrates the device for the linear atomic quantum coupler.

The device (200) for a linear atomic quantum coupler comprises a plurality of mode sources
15 and a plurality of waveguides, characterized in that the plurality of waveguides are placed in close proximity to allow exchanging of energy via evanescent waves and the plurality of waveguides comprises at least one localized and/or trapped atom, wherein the plurality of mode sources comprises means for generating a plurality of modes, and the plurality of waveguides comprises means for propagating the plurality of modes through the plurality of
20 waveguides.

The method (100) for constructing a linear atomic quantum coupler according to the embodiments of the present invention comprises generating a plurality of modes (102), placing a plurality of waveguides in close proximity (104) to allow exchanging of energy via
25 evanescent waves, localizing and/or trapping at least one atom in the plurality of waveguides (106) and propagating the plurality of modes through the plurality of waveguides (108).

The description and illustration herein is provided such that the plurality of mode sources further comprises at least two mode sources (202, 204) and the plurality of waveguides further comprises at least two waveguides (206, 208) for ease of explanation.

- 5 The linear atomic quantum coupler of the present invention consists of two waveguides (206, 208), each of which includes a localized and/or a trapped atom (210, 212). The waveguides (206, 208) are placed close enough to each other to allow interchanging energy between them. In each waveguide one mode propagates along and interacts with the atom inside in a standard way as the Jaynes-Cummings model (JCM). The atom-mode in each waveguide
10 interacts with the other one via the evanescent wave.

According to the embodiments of the present invention, the waveguides are placed in close proximity to allow exchanging of energy via evanescent waves and the rate of the exchanging of energy is controlled by a flux intensity of the mode sources.

15

In the framework of the rotating wave approximation (RWA) the Hamiltonian describing the linear atomic quantum coupler can be expressed as:

$$\frac{\hat{H}}{\hbar} = \hat{H}_0 + \hat{H}_I,$$

$$\hat{H}_0 = \sum_{j=0}^2 \omega_j \hat{a}_j^\dagger \hat{a}_j + \frac{\omega_a}{2} (\hat{\sigma}_z^{(1)} + \hat{\sigma}_z^{(2)}), \quad \hat{H}_I = \sum_{j=1}^2 \lambda_j (\hat{a}_j \hat{\sigma}_+^{(j)} + \hat{a}_j^\dagger \hat{\sigma}_-^{(j)}) + \lambda_3 (\hat{a}_1 \hat{a}_2^\dagger \hat{\sigma}_+^{(1)} \hat{\sigma}_-^{(2)} + \hat{a}_1^\dagger \hat{a}_2 \hat{\sigma}_-^{(1)} \hat{\sigma}_+^{(2)}), \quad (1)$$

- where $\hat{H}_0$ and $\hat{H}_I$ are the free and interaction parts of the Hamiltonian, $\hat{\sigma}_\pm^{(j)}$ and $\hat{\sigma}_z^{(j)}$ are
20 the Pauli spin operators of the j th atom ($j = 1, 2$); $\hat{a}_j$ ($\hat{a}_j^\dagger$) is the annihilation (creation) operator of the j th-mode with the frequency ω_j and ω_a is the atomic transition frequency (considering that the frequencies of the two atoms are equal) and λ_1 (λ_2) is the atom-field coupling constant in the first (second) waveguide.

The interaction between the modes in the two waveguides occurs through the evanescent wave with the coupling constant λ_3 . This constant is responsible for the switching mechanism between the waveguides and hence it plays an essential role in the behavior of the linear atomic quantum coupler.

5

Furthermore, the switching term is obtained by applying the RWA in each individual waveguide. In other words, such type of $\lambda_3(\hat{a}_1\hat{\sigma}_-^{(1)}\hat{a}_2^\dagger\hat{\sigma}_+^{(2)} + \hat{a}_1^\dagger\hat{\sigma}_+^{(1)}\hat{a}_2\hat{\sigma}_-^{(2)})$ is non-conservative and then it is cancelled out. Finally, when the atoms (fields) are treated classically the Hamiltonian (1) tends to that of the linear directional coupler (two-atom interaction).

10

The device for the linear atomic quantum coupler of the present invention further comprises a plurality of detectors (214, 216) comprising means for measuring output field from the plurality of modes propagating through the plurality of waveguides. The fields exited from the coupler can be examined as single or compound modes by means of homodyne detection to observe the squeezing of vacuum fluctuations, or by means a set of photodetectors (214, 216) to measure photon antibunching and sub-Poissonian photon statistics in the standard ways. The linear atomic quantum coupler of the present invention generates nonclassical effect and reduces noise in the output field.

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20 The wave function for the Hamiltonian (1) is further evaluated. According to one embodiment of the present invention, the description herein is provided such that the two modes and atoms are initially prepared in the coherent states $|\alpha, \beta\rangle$ and in the excited atomic states $|e_1, e_2\rangle$, respectively for ease of explanation. For resonance case $2\omega_a = \omega_1 + \omega_2$ it can easily

proven that $\left[\hat{H}_0, \hat{H}_1\right] = 0$.

25

Under these conditions, the dynamical wave function describing the device can be expressed as:

$$\begin{aligned}
 |\Psi(t)\rangle = & \sum_{n,m=0}^{\infty} C_{n,m} [X_1(t, n, m) |e_1, e_2, n, m\rangle + X_2(t, n, m) |e_1, g_2, n, m+1\rangle \\
 & + X_3(t, n, m) |g_1, e_2, n+1, m\rangle + X_4(t, n, m) |g_1, g_2, n+1, m+1\rangle], \\
 C_{n,m} = & \exp\left(-\frac{1}{2}|\alpha|^2 - \frac{1}{2}|\beta|^2\right) \frac{\alpha^n \beta^m}{\sqrt{n!m!}},
 \end{aligned} \tag{2}$$

where $|g\rangle$ stands for atomic ground state. From the Schrödinger equation we obtain the following system of differential equations:

$$\begin{aligned}
 i\dot{X}_1(t, n, m) &= \lambda_2\sqrt{m+1}X_2(t, n, m) + \lambda_1\sqrt{n+1}X_3(t, n, m), \\
 i\dot{X}_2(t, n, m) &= \lambda_2\sqrt{m+1}X_1(t, n, m) + \lambda_3\sqrt{(n+1)(m+1)}X_3(t, n, m) + \lambda_1\sqrt{n+1}X_4(t, n, m), \\
 i\dot{X}_3(t, n, m) &= \lambda_1\sqrt{n+1}X_1(t, n, m) + \lambda_3\sqrt{(n+1)(m+1)}X_2(t, n, m) + \lambda_2\sqrt{m+1}X_4(t, n, m), \\
 i\dot{X}_4(t, n, m) &= \lambda_1\sqrt{n+1}X_2(t, n, m) + \lambda_2\sqrt{m+1}X_3(t, n, m),
 \end{aligned} \tag{3}$$

where the superscript "." refers differentiation with reference to time. In the following, only details related to the solution of the coefficient $X_1(T, n, m)$ are provided, where the others can be similarly treated. Differentiating the first and last equations in (3) and re-substituting with the others, the following is obtained:

$$\begin{aligned}
 (\hat{D}^2 + A_{n,m})X_1(t, n, m) &= -(i\lambda_3c_2D + c_1)X_4(t, n, m), \\
 (\hat{D}^2 + A_{n,m})X_4(t, n, m) &= -(i\lambda_3c_2D + c_1)X_1(t, n, m), \\
 \hat{D} = \frac{d}{dt}, A_{n,m} &= \lambda_1^2(n+1) + \lambda_2^2(m+1), c_1 = 2\lambda_1\lambda_2\sqrt{(n+1)(m+1)}, c_2 = \lambda_3\sqrt{(n+1)(m+1)}.
 \end{aligned} \tag{4}$$

From (4) it can be easily obtained that:

$$(\hat{D}^2 + A_{n,m})^2 X_1(t, n, m) = (i\lambda_3c_2D + c_1)^2 X_1(t, n, m). \tag{5}$$

This equation can be easily solved. By means of the initial conditions stated above the exact forms of the coefficients X_j can be expressed as:

$$\begin{aligned}
X_1(t, n, m) &= \frac{1}{2} \exp(i\frac{t}{2}c_2) \left[\cos(t\Omega_-) - i\frac{c_2}{2\Omega_-} \sin(t\Omega_-) \right] + \frac{1}{2} \exp(-i\frac{t}{2}c_2) \left[\cos(t\Omega_+) + i\frac{c_2}{2\Omega_+} \sin(t\Omega_+) \right], \\
X_2(t, n, m) &= \frac{-i\sqrt{n+1}}{2c_2^2[A_{n,m}-4\frac{\lambda_1^2\lambda_3^2}{\lambda_2^2}]} \left\{ \exp(i\frac{t}{2}c_2) \left[(c_2^2 - 2c_1)\lambda_2^3(m+1) + (2A_{n,m} - c_1) \left(\lambda_2c_1 - \frac{\lambda_1\lambda_3}{2}(n+1)c_2 \right) \right] \right. \\
&\quad \times \frac{\sin(t\Omega_-)}{\Omega_-} + \exp(-i\frac{t}{2}c_2) \left[(c_2^2 + 2c_1)\lambda_2^3(m+1) - (2A_{n,m} + c_1) \left(\lambda_2c_1 - \frac{\lambda_1\lambda_3}{2}(n+1)c_2 \right) \right] \frac{\sin(t\Omega_+)}{\Omega_+} \Big\}, \\
X_3(t, n, m) &= \frac{-i\sqrt{n+1}}{2c_2^2[A_{n,m}-4\frac{\lambda_1^2\lambda_3^2}{\lambda_2^2}]} \left\{ \exp(i\frac{t}{2}c_2) \left[(c_2^2 - 2c_1)\lambda_1^3(n+1) + (2A_{n,m} - c_1) \left(\lambda_1c_1 - \frac{\lambda_2\lambda_3}{2}(m+1)c_2 \right) \right] \right. \\
&\quad \times \frac{\sin(t\Omega_-)}{\Omega_-} + \exp(-i\frac{t}{2}c_2) \left[(c_2^2 + 2c_1)\lambda_1^3(n+1) - (2A_{n,m} + c_1) \left(\lambda_1c_1 - \frac{\lambda_2\lambda_3}{2}(m+1)c_2 \right) \right] \frac{\sin(t\Omega_+)}{\Omega_+} \Big\}, \\
X_4(t, n, m) &= \frac{1}{2} \exp(i\frac{t}{2}c_2) \left[-\cos(t\Omega_-) + i\frac{c_2}{2\Omega_-} \sin(t\Omega_-) \right] + \frac{1}{2} \exp(-i\frac{t}{2}c_2) \left[\cos(t\Omega_+) + i\frac{c_2}{2\Omega_+} \sin(t\Omega_+) \right], \quad (6)
\end{aligned}$$

where

$$\Omega_{\pm} = \frac{1}{2} \sqrt{\lambda_3^2(n+1)(m+1) + 4(\lambda_1\sqrt{n+1} \pm \lambda_2\sqrt{m+1})^2}. \quad (7)$$

- 5 It is obvious that the Rabi oscillation in the linear atomic quantum coupler is more complicated than that of the JCM. From the solution (6) different limits can be checked. For instance, when $(\lambda_2, \lambda_3) \rightarrow (0, 0)$ ($\lambda_3 \rightarrow 0$) the coefficients (6) reduce to those of the standard JCM (two decoupled JCM). Moreover, when $(\lambda_1, \lambda_2) \rightarrow (0, 0)$ the device reduces to a simple form, which is in good correspondence with the conventional coupler. Nevertheless,
- 10 the linear atomic quantum coupler of the present invention, in this case, is a rich source for the nonclassical effects, which depend on the types of initial atomic states.

According to other embodiments of the present invention, further three cases of the two modes and atoms are discussed herein. Firstly, the atoms are initially prepared in $|e_1, e_2\rangle$,

- 15 and in this case the device reduces to the dark state, where $\hat{H}_{\text{int}}|e_1, e_2\rangle = 0$. These states do not evolve in time. This property has been exploited in the quantum clock synchronization.

Secondly, the atoms are initially prepared in $|e_1, g_2\rangle$, wherein the dynamical state of the device takes the form of:

$$|\Psi(t)\rangle = \sum_{n,m=0}^{\infty} C_{n,m} \left[\cos[T\sqrt{(n+1)(m+1)}] |e_1, g_2, n, m+1\rangle - i \sin[T\sqrt{(n+1)(m+1)}] |g_1, e_2, n+1, m\rangle \right], \quad (8)$$

5 where $T = \lambda_3 t$. The expression (8) reveals that the behavior of the radiation fields is typically that of the two-mode single-atom JCM.

Finally, when the two atoms are initially in the Bell state $[|e_1, g_2\rangle + |g_1, e_2\rangle]/\sqrt{2}$, the wavefunction takes the form of:

$$10 \quad |\Psi(t)\rangle = \frac{1}{\sqrt{2}} \sum_{n,m=0}^{\infty} C_{n,m} \exp[-iT\sqrt{(n+1)(m+1)}] [|e_1, g_2, n, m+1\rangle + |g_1, e_2, n+1, m\rangle]. \quad (9)$$

It is evident that the device exhibits atomic trapping, i.e. $\langle \hat{\sigma}_z^{(1)}(t) \rangle = \langle \hat{\sigma}_z^{(2)}(t) \rangle = 0$. Furthermore, the device is able to generate nonclassical effects, in particular, in the quantities, which depend on the off-diagonal elements of the density matrix such as
15 squeezing.

The switching mechanism in the linear atomic quantum coupler of the present invention is discussed herein. Assume, $\beta = 0$ is substitute in relations (2)–(6) and the mean-photon numbers are computed as:

$$20 \quad \begin{aligned} \langle \hat{a}_1^\dagger(T) \hat{a}_1(T) \rangle &= |\alpha|^2 + \sum_{n=0}^{\infty} |C_{n,0}|^2 [|X_3(T, n, 0)|^2 + |X_4(T, n, 0)|^2], \\ \langle \hat{a}_2^\dagger(T) \hat{a}_2(T) \rangle &= \sum_{n=0}^{\infty} |C_{n,0}|^2 [|X_2(T, n, 0)|^2 + |X_4(T, n, 0)|^2]. \end{aligned} \quad (10)$$

From these equations it is obvious that the intensity of the mode in the first waveguide cannot be switched to the other one. This is in clear contrast with the linear directional coupler. This behavior is related to the nature of the atom-field interaction mechanism, which is close to the classic Lee model of quantum field theory. Moreover, this behavior is still valid even if the interaction between the modes and the atoms in the same waveguide is neglected, i.e. $\lambda_1 = \lambda_2 = 0$. In this case, expression (10) exhibits the well-known RCP of the standard JCM.

The linear atomic quantum coupler of the present invention is able to switch the nonclassical effects from one waveguide to another based on the values of the interaction parameters. This is remarkable from (12), where the mean-photon number in the second waveguide $\langle \hat{a}_2^\dagger(T) \hat{a}_2(T) \rangle$ can exhibit RCP even though the second mode is initially in vacuum state.

On the other hand, assuming that the mode in the first waveguide is initially prepared in the even coherent state, which exhibits squeezing, while the second mode is still in vacuum state, the density matrix of the second mode takes the form of:

$$\hat{\rho}_2 = \sum_{n=0}^{\infty} |C_{2n,0}|^2 \left\{ [|X_1(T, 2n, 0)|^2 + |X_3(T, 2n, 0)|^2] |0\rangle\langle 0| + [|X_2(T, 2n, 0)|^2 + |X_4(T, 2n, 0)|^2] |1\rangle\langle 1| \right\}, \quad (11)$$

where $|C_{2n}|^2$ is the photon-number distribution of the even coherent state. From (11), squeezing cannot be switched to the second mode. Nevertheless, if the second mode is prepared in the coherent state, it can exhibit squeezing. In this case, the source of the nonclassical effects could be the switching mechanism between the waveguides or the nature of the atom-field interaction.

Reference is now made to FIGs. 3 and 4 collectively. FIG. 3 illustrates the evolution of the $\langle \hat{\sigma}_z^{(1)}(t) \rangle$ against the interaction time $T = \lambda_1 t$ with $(\alpha, \beta) = (5, 5)$ for $(\lambda_2, \lambda_3) = (1, 0)$ (a), $(1, 0.6)$

(b), (2, 3) (c) and (1, 1) (d). FIG. 4 illustrates the evolution of the single-mode second order correlation function as indicated against the interaction time $T = \lambda_1 t$ with $(\lambda_2, \lambda_3) = (1, 0)$ (a), (1, 0.6) (b), (2, 3) (c)-(d).

5 Atomic inversion of the standard JCM is well known in quantum optics by exhibiting RCP. The RCP has a nonclassical origin and reflects the nature of the statistics of the radiation field. The evolution of the atomic inversion has been realized via, e.g., the one-atom mazer and using technique similar to that of the NMR refocusing. According to the embodiments of the present invention, the behavior of the linear atomic quantum coupler is further
10 investigated by studying the evolution of the atomic inversions and the second-order correlation functions.

As the device includes two atoms, there will be two types of the atomic inversion, namely,

single atomic inversion and total atomic inversion $\langle \hat{\sigma}_z(t) \rangle = \frac{1}{2} [\langle \hat{\sigma}_z^{(1)}(t) \rangle + \langle \hat{\sigma}_z^{(2)}(t) \rangle]$. From (2)

15 the following expressions can be obtained:

$$\begin{aligned} \langle \hat{\sigma}_z^{(1)}(t) \rangle &= \sum_{n,m=0}^{\infty} |C_{n,m}|^2 [|X_1(t, n, m)|^2 + |X_2(t, n, m)|^2 - |X_3(t, n, m)|^2 - |X_4(t, n, m)|^2], \\ \langle \hat{\sigma}_z^{(2)}(t) \rangle &= \sum_{n,m=0}^{\infty} |C_{n,m}|^2 [|X_1(t, n, m)|^2 - |X_2(t, n, m)|^2 + |X_3(t, n, m)|^2 - |X_4(t, n, m)|^2], \\ \langle \hat{\sigma}_z(t) \rangle &= \sum_{n,m=0}^{\infty} |C_{n,m}|^2 [|X_1(t, n, m)|^2 - |X_4(t, n, m)|^2]. \end{aligned} \quad (12)$$

The conventional directional coupler cannot exhibit RCP in the evolution of the mean-photon numbers. Nevertheless, the standard JCM can exhibit RCP provided that the photon-number
20 distribution of the initial field has a smooth envelope. Similar conclusion has been reported to the two-atom single-mode JCM.

According to the embodiments of the linear atomic quantum coupler of the present invention, it is found that when $\alpha = \beta$ and $\lambda_j \neq 0$ the different types of the atomic inversions (12) provide quite similar behaviors. The contributions of the coherence coefficients X_2, X_3 are comparable. Moreover, it can be easily proven when $\lambda_3 = 0$ and $\lambda_1 = \lambda_2$ the atomic
 5 inversions reduce to that of the standard JCM (see FIG. 3(a)). For the standard JCM the revival patterns occur in the atomic inversion over certain period of the interaction time, afterward they interfere providing chaotic behavior. Additionally, the revival time is connected with the amplitude α through the relation $T_r = 2\pi\sqrt{n} \simeq 2\pi|\alpha|$.

10 For $\lambda_1 \neq \lambda_2$, different forms of the revival patterns are provided. The description given herein is restricted to the atomic inversion of the first atom (see FIGs. 3(b)-(d) for the given values of the interaction parameters). Three cases are considered based on the relationship between the strength of the switching mechanisms in and between the waveguides, namely, $\lambda_3 < \lambda_j, \lambda_3 = \lambda_j, \lambda_3 > \lambda_j$. Comparisons between FIGs. 3(b)-(d) and FIG. 3(a) are
 15 instructive. From FIG. 3(b) it can be observed that the atomic inversion, after the zero and first revival patterns, exhibits long series of the subsidiary-revival patterns (see the inset in FIG. 3(b)). This behavior is completely different from that of the JCM. This indicates that the nonclassical effects generated by the linear atomic quantum coupler of the present invention can sustain for an interaction time longer than that of the JCM.

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The subsidiary-revival patterns have been observed for the JCM against the squeezed coherent state. This has been explained in relation to the photon-number distribution of the initial states. More illustratively, the photon-number distributions of the squeezed states exhibit many peaks structure, each of which gives its own revival patterns in the evolution of
 25 the atomic inversion. These patterns interfere with each other to produce these subsidiary-revival patterns. Nevertheless, for the device under consideration the occurrence of these

patterns is related to the switching mechanism between the waveguides (compare FIGs. 3(a) and (b)). This mechanism reflects itself in very complicated Rabi oscillations $\Omega_{\pm}$ as well as in the double summations in the atomic inversions formulae (12). FIG. 3(c) presents the case when the coupling constants are different. It is obvious that the RCP is still remarkable and the subsidiary revivals are smoothly washed out compared to those in FIG. 3(b).

Generally, it is found that when $\lambda_3 \geq \lambda_1 = \lambda_2$, the atomic inversion exhibits long RCP (see FIG. 3(d)). This indicates that the switching mechanism between the waveguides plays an important role in the behavior of the the linear atomic quantum coupler of the present invention.

The second-order correlation functions for the single-mode case is defined as:

$$g_j^{(2)}(t) = \frac{\langle \hat{a}_j^{\dagger 2}(t) \hat{a}_j^2(t) \rangle}{\langle \hat{a}_j^{\dagger}(t) \hat{a}_j(t) \rangle^2} - 1, \quad j = 1, 2, \quad (13)$$

where $g_j^{(2)}(t) = 0$ for Poissonian statistics (standard case), $g_j^{(2)}(t) < 0$ for sub-Poissonian statistics (nonclassical effects) and $g_j^{(2)}(t) > 0$ for super-Poissonian statistics (classical effects).

The second-order correlation function can be measured by a set of two detectors, e.g. the standard Hanbury Brown-Twiss coincidence arrangement. For the device under consideration, this quantity is plotted in FIG. 4 for the given values of the interaction parameters. From FIG. 4 it is obvious that the linear atomic quantum coupler of the present invention is able to generate long-lived sub-Poissonian effects, i.e. $g_j^{(2)}(t) < 0$.

Furthermore, the basic features of the dynamics are still similar to those of the atomic inversion. FIG. 4(a) presents the well-known shape of the second-order function of the

standard JCM. When the switching mechanism between the waveguides is involved, the long RCP is dominant in the evolution of the $g_j^{(2)}(t)$. Nevertheless, the shape of this phenomenon is quite different from that in the corresponding atomic inversion (compare FIG. 3(b) to FIG. 4(b)).

5

For instance, the revival times in the two quantities are different. Also, the number of the subsidiary revivals in the atomic inversion is greater than that in the corresponding $g_1^{(2)}(t)$.

In contrast to the atomic inversions, $g_1^{(2)}(t)$ and $g_2^{(2)}(t)$ can provide different behavior for the same values of the interaction parameters. This fact can be realized by comparing FIG. 4(c)

10 to (d).

In contrast to the conventional coupler, the linear atomic quantum coupler of the present invention can generate nonclassical effects. Nevertheless, the switching mechanism in the former is more effective than that in the latter. Furthermore, the behavior of the linear atomic quantum coupler of the present invention is sensitive to the types of the initial atomic states.

15

The device of the linear atomic quantum coupler of the present invention is able to produce the results of the two-mode JCM under certain conditions. Additionally, the evolution of the atomic inversions and second-order correlation functions exhibits RCP, long RCP and long subsidiary-revival patterns based on the values of the coupling constants. Second-order correlation function can exhibit long-lived nonclassical effects.

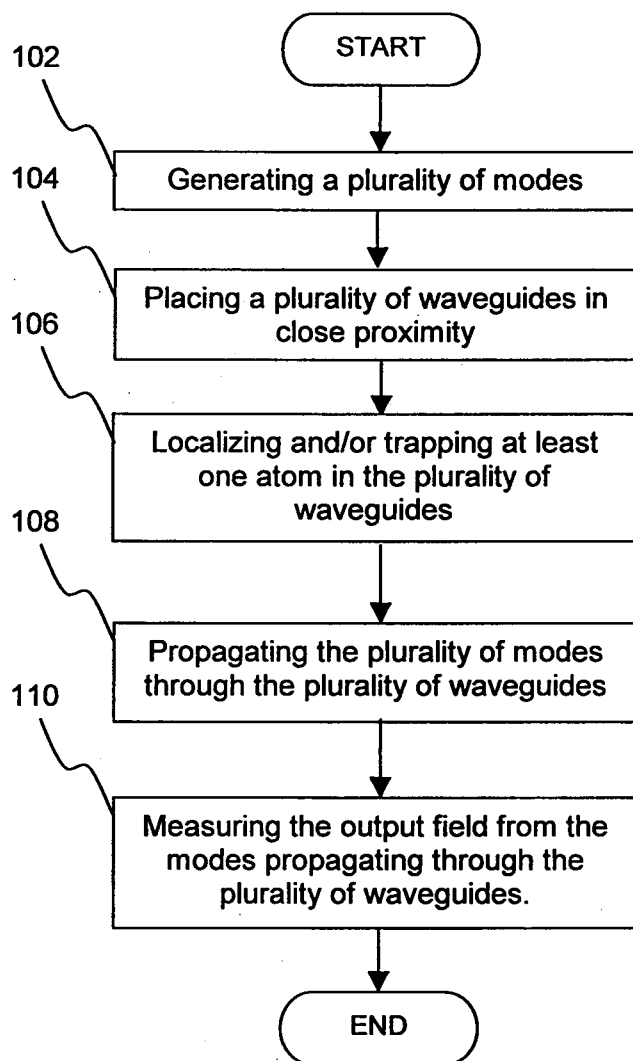
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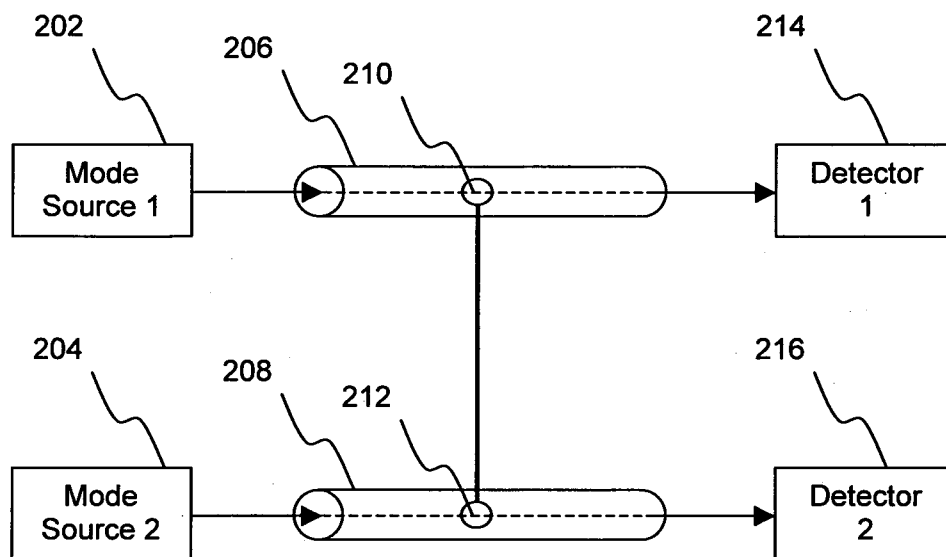
CLAIMS

1. A device (200) for a linear atomic quantum coupler, the device (200) comprises
a plurality of mode sources; and a plurality of waveguides;
5 characterized in that the plurality of waveguides are placed in close proximity
to allow exchanging of energy via evanescent waves; and the plurality of
waveguides comprises at least one localized and/or trapped atom; wherein
the plurality of mode sources comprises means for generating a
plurality of modes; and the plurality of waveguides comprises means
10 for propagating the plurality of modes through the plurality of
waveguides.
2. The device (200) according to claim 1, wherein the device further comprises a
plurality of detectors (214, 216) comprising means for measuring output field from the
15 plurality of modes propagating through the plurality of waveguides.
3. The device (200) according to claim 1, wherein the plurality of mode sources further
comprises at least two mode sources (202, 204).
- 20 4. The device (200) according to claims 1, wherein the plurality of waveguides further
comprises at least two waveguides (206, 208).
5. The device (200) according to claim 1, wherein rate of the exchanging of energy is
controlled by a flux intensity of the plurality of mode sources.
- 25 6. The device (200) according to claim 1, wherein the linear atomic quantum coupler
generates nonclassical effect in the output field.

7. The device (200) according to claim 1, wherein the linear atomic quantum coupler reduces noise in the output field.
8. A method (100) for constructing a linear atomic quantum coupler, the method (100) comprises
- 5 generating a plurality of modes (102);
- placing a plurality of waveguides in close proximity (104) to allow exchanging of energy via evanescent waves;
- localizing and/or trapping at least one atom in the plurality of waveguides
- 10 (106); and
- propagating the plurality of modes through the plurality of waveguides (108).
9. The method (100) according to claim 8, wherein the method further comprises measuring output field from the plurality of modes propagating through the plurality of
- 15 waveguides (110).
10. The method (100) according to claim 8, wherein generating the plurality of modes (102) further comprises generating at least two modes.
- 20 11. The method (100) according to claim 8, wherein propagating the plurality of modes through the plurality of waveguides (108) further comprises propagating at least two modes through at least two waveguides.
12. The method (100) according to claim 8, wherein rate of the exchanging of energy is
- 25 controlled by a flux intensity of the plurality of modes.
13. The method (100) according to claim 8, wherein the linear atomic quantum coupler generates nonclassical effect in the output field.

14. The method (100) according to claim 8, wherein the linear atomic quantum coupler reduces noise in the output field.

100**FIG. 1**

200**FIG. 2**

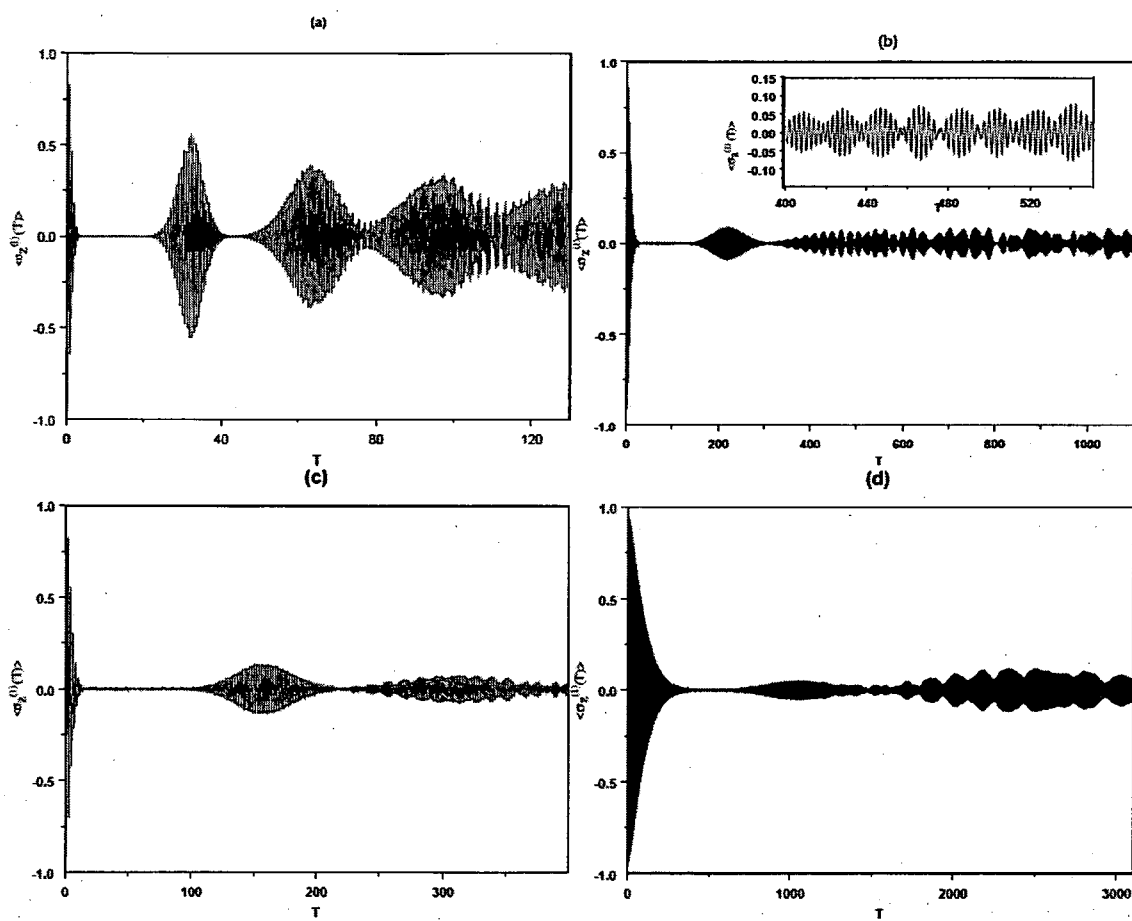


FIG. 3

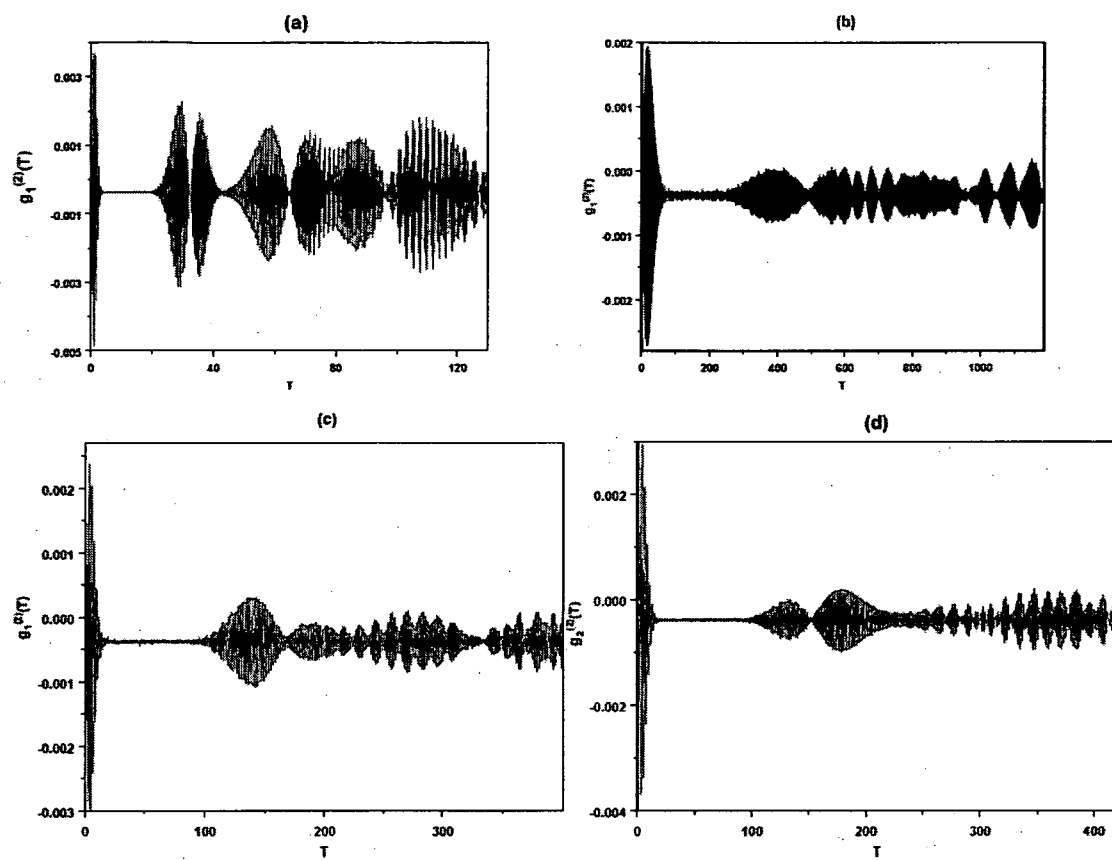


FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.

PCT/MY2010/000158

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

G02B 6/26 (2006.01)

G02F 1/17 (2006.01)

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)

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

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

DWPI, EPODOC, INSPEC, Google Scholar Keywords: atom; waveguid, fibre, fiber; couple, entang, evanesc; trap, locali; optic, opto, light; adjacent, side by side, near by, parallel, proxim, vicinit

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	F.A.A. EL-ORANY et al., "A linear atomic quantum coupler", Journal of Physics B: Atomic Molecular and Optical Physics, 23 March 2010, vol. 43, article 085502 (9pp) Pages 1-3, 8	1-14
X	J.D. FRANSON et al., "Zeno logic gates using microcavities", Journal of the Optical Society of America B, February 2007, vol. 24, pp. 209-213 Section 3, Figures 1, 4	1-14
X	US 2004/0156407 A1 (BEAUSOLEIL et al.) 12 August 2004 Pages 2, 6-9, Figures 6B, 7-11	1-14
A	G. SAGUE et al., "Cold-Atom Physics Using Ultrathin Optical Fibers: Light-Induced Dipole Forces and Surface Interactions", Physical Review Letters, 2007, vol. 99, article 163602 (4pp) Page 1	



Further documents are listed in the continuation of Box C



See patent family annex

* "A"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

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20 December 2010Date of mailing of the international search report
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/MY2010/000158

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member		
US	2004156407	EP	1609037	KR 20050100677 US 7560726
		WO	2004072806	

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX