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All-optical switch and transistor based on coherent light-controlled single two-level atom coupling with two nanowires*

Xin-Qin Zhang(张新琴)[1], Xiu-Wen Xia(夏秀文)[1,2,†], Jing-Ping Xu(许静平)[2], Mu-Tian Cheng(程木田)[3], and Ya-Ping Yang(羊亚平)[2]

[1] *Institute of Atomic and Molecular Physics and Functional Materials, School of Mathematics and Physics, Jinggangshan University, Ji'an* 343009, *China*
[2] *MOE Key Laboratory of Advanced Micro-structure Materials, School of Physics Science and Engineering, Tongji University, Shanghai* 200092, *China*
[3] *School of Electrical Engineering & Information, Anhui University of Technology, Maanshan* 243002, *China*

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Atom–nanowire coupling system is a promising platform for optical quantum information processing. Unlike the previous designing of optical switch and transistor requiring a dedicated multi-level emitter and high fineness microcavity, a new proposal is put forward which contains a single two-level atom asymmetrically coupled with two nanowires. Single-emitter manipulation of photonic signals for bilateral coherent incident is clear now, since we specify atomic saturation nonlinearity into three contributions which brings us a new approach to realizing light-controlled-light at weak light and single-atom levels. An efficient optically controllable switch based on self-matching-induced-block and a concise optical transistor are proposed. Our findings show potential applications in full-optical devices.

Keywords: optical transistor, optical switch, nano-waveguide, light-controlled-light

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1. Introduction

Optical switches and transistors, which are fundamental to optical circuits, are expected to improve the performance of the fiber-optic communication and optical digital computers, and to create new types of optical amplifiers to compensate for signal attenuation along transmission lines.[1–3] So far, much effort has been made to study and develop all-optical switches and transistors in the schemes of optical lattices and photonic crystals,[4,5] micro-resonators,[6–8] nano-waveguides,[9–12] opto-mechanisms,[13,14] and so on. Among these designs, the single-atom devices have natural advantages in good performance of weaker operating light, but single-emitter manipulation of photonic signals has remained elusive yet,[12,15,16] where a dedicated multilevel atom is always selected which results in a much complicated construction finally.[17,18] However, if one can manipulate the photon amplification in a single two-level system, it will simplify the setup greatly and also has the potential to be integrated conveniently.

In this work, we introduce a method of light-controlled-light by a single two-level emitter since light-controlled-light is one of the core technologies of an all-optical network.[19] The potential for optical devices in direct manipulating light remains unfulfilled due to lack of bulk materials with fast strong optical nonlinearities,[20,21] causing most of schemes of light-controlled-light at present to need a strong light serving as the controlling light for prefabricating the optical medium into some specific initiation.[22–26] In order to keep the medium in such an initial state all the time, the working light or signal should be much weaker than the controlling light, such as electromagnetically induced transparency (EIT) in which strong light turns the medium state into dark state and makes a weak resonant signal change from opaque to transparent.[27] However, strong-light controlling may lead to some deficiencies, such as optical instability, massive loss of energy, *etc*. Therefore, lowering the intensity of controlling light is critical in practice and recently an approach of controlling light with coherent weak light has been introduced.[20,28–30]

Recently, researches on nanowire-based systems show that they are more competitive solutions than cavity-based systems since nanowire exhibits good confinement and guiding even when its radius is reduced to well below the optical wavelength.[11,12,31–35] In our previous researches, we have introduced an atom–nanowires strong coupling system of rich physics.[36,37] In this work, by introducing two coherent beams to cast onto a single two-level atom simultaneously, we show an approach to controlling light with light (light-controlled light) at weak light level and propose applications in all-optical switch and transistor at single-atom level.

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†Corresponding author. E-mail: jgsuxxw@126.com

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2. Model and theory

The scheme of atom–nanowires coupling system is presented in Fig. 1(a). A single two-level atom with transition frequency ω_{at} coupled with two individual terminated metallic nanowires with 100% reflectivity at the right ends is excited by two coherent input-light fields b_{in} and c_{in} from ports 1 and 2 simultaneously.[37,38] The semi-infinite nanowire terminated by in-built mirror (such as a spherical endcap whose radius equals the radius of the nanowire or a distributed-Bragg-reflector[11,39]) serves as single-sided waveguide cavity, and excitons propagating on the wires will be completely reflected by the mirror. Two nanowires are placed properly (such as vertically) to exclude their direct coupling and they only interact through the imbedded atom. Atomic nonlinearity shows richer physics at the exposure of two driving beams than the case of single light incident.

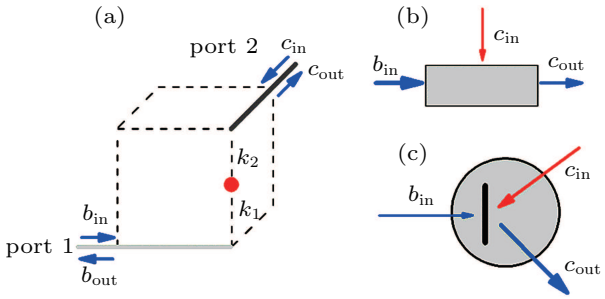


Fig. 1. Sketch of (a) atom–nanowires coupling system and (b) its potential application as optically controllable switch and (c) optical transistor. Two gray terminated lines in panel (a) represent two terminated nanowires and the small red circle is a two-level emitter asymmetrically coupled to two nanowires. Gray rectangle in panel (b) and gray circle in panel (c) represent atom–nanowires setup, respectively.

Assuming that two coherent light fields with the same frequency ω_L are simultaneously incident on two ports: $b_{in} = |b_{in}|$ on port 1 and $c_{in} = \alpha|b_{in}|e^{i\phi}$ on port 2, where α is a positive number and ϕ is the initial phase difference. Here, both b_{in} and c_{in} belong to the propagation mode of nanowires. Following a standard procedure, the dynamic behavior of the open quantum system can be treated in the mean-field framework. After a series of manipulations of derivation and transformation, nonlinear reflectivity r_m on port m ($m = 1, 2$) and transmittivity t_{mn} from port m to port n ($m, n = 1, 2$) can be solved analytically (the details are shown in Appendix A) from

$$r_m = 1 - \frac{k_m}{\Gamma/2 + i\Delta} \cdot \frac{1}{1+x}, \quad (m = 1,2), \tag{1}$$

$$t_{mn} = -\frac{\sqrt{k_m k_n}}{\Gamma/2 + i\Delta} \cdot \frac{1}{1+x}, \quad (m,n = 1,2). \tag{2}$$

Here, $\Delta = \omega_{at} - \omega_L$ is the atom–light detuning, x is the total atomic saturation nonlinear factor, $\Gamma = k_1 + k_2 + \gamma_{at}$ is the total decay rate which contains three components, *i.e.*, k_1 (the rate decaying into lower waveguide modes), k_2 (the rate decaying into the upper waveguide modes), and γ_{at} (the rate decaying into the free vacuum modes). The effective Purcell factor is $P = (k_1 + k_2)/\gamma_{at}$.[10]

Until now, single atom saturation nonlinearity has been well studied either in the case of single-beam incidence, or in the case of two-beam incidence of which one is the strong driving field producing a nonlinear optical environment and the other is the weak linear probe field. In this work, single atom saturation nonlinearity is truly produced by these two beams, and the total nonlinear factor x is from three different origins and expressed as

$$x = x_1 + x_2 + x_{coh}. \tag{3}$$

Here, $x_1 = I_{bin}/P_1$ and $x_2 = I_{cin}/P_2$ are nonlinear factors induced respectively only by b_{in} and c_{in}, and $x_{coh} = 2(x_1 x_2)^{1/2}\cos\phi$ originates from optical interference. $I_{bin} = |b_{in}|^2$ and $I_{cin} = |c_{in}|^2$ are used to represent the two input light intensities, and P_m ($m = 1, 2$) is denoted as the critical intensity for the incidence from port m and fulfills the following equation

$$P_m = (\Delta^2 + \Gamma^2/4)/2k_m. \tag{4}$$

The critical intensities P_1 and P_2 are not equal to each other when the setup breaks the spatial symmetry. Both the reflectivity and transmittivity are nonlinear with respect to the intensity and phase of two driving light beams, which is well consistent with the physics of coherent light-controlling-light.[20,28–30]

Output field from each port is the superposition of r-component (reflected component $r_1 b_{in}$ or $r_2 c_{in}$) and t-component (transmitted component $t_{21} c_{in}$ or $t_{12} b_{in}$) and expressed below

$$b_{out} = r_1 b_{in} + t_{21} c_{in}, \tag{5}$$

$$c_{out} = r_2 c_{in} + t_{12} b_{in}. \tag{6}$$

Thus, the final output light intensity is related not only to single atom saturation nonlinearity, but also to optical interference between r- and t-components. Output beams may be suppressed by destructive interference or enhanced by constructive interference.

This study is superior to previous work where only atomic saturation nonlinearity for single light incidence or optical interference in linear regime is taken into account. In this work, both atomic nonlinearity for bilateral incidence and that for optical interference are considered, which makes us an approach to manipulating light scattering by using both of them. We have proposed a single-atom nonlinear coherent perfect absorber in our previous work.[38] A more in-depth analysis shows that light-controlled-light at a weak light level is also available after carefully determining which is the essential to optical switch and transistor.

3. Discussion

3.1. Light-controlled-light

In previous incoherent light-controlled schemes,[21–27] bulk materials or optical resonators were excited by strong light to change their dielectric coefficients to control the transmission of weak signals, or multi-level atoms are strongly excited by the gate photons to initialize atoms in some special superposition to generate light controlling. These constructions are so complicated that a dedicated atomic energy structure is needed, and their nonlinearities are only generated by controlling light beams. Even in the recent coherent light-controlled systems,[20,28–30] optical nonlinear performances only come from optical interference, while the atomic saturation nonlinearities induced by light are omitted.

In this work, we introduce light controlling into a simple two-level system, which will simplify the light-controlled setup greatly. Unlike previous work, this work takes into consideration both atomic nonlinearity and optical interference. As shown in our model, light scattering is dependent on total atomic nonlinear parameter x and optical interference. It suggests that a light can be manipulated not only by the intensity of another light, but also by its relative phase, which provides an approach to controlling strong light with weak light after careful design.

For simplicity, we restrict our discussion in the resonant case by setting $\Delta = 0$ and fixing $k_1 + k_2 = 8$ to present the strong coupling throughout this work, and examine the scattering property of port 2 without loss of generality. In this case, r-component and t-component interfere destructively or constructively when $b_{\rm in}$ and $c_{\rm in}$ are in-phase or anti-phase, respectively. Coupling strength is normalized by setting $\gamma_{\rm at} \equiv 1$ and all of the light intensities are normalized by the nonlinear coherent perfect absorption intensity $I_{\rm ncpa} = k_1(1 - 1/P^2)/8$.

We first show the reflected property controlled by a weak coherent in-phase light. The difference between reflected light beams with and without a controlling light $b_{\rm in}$ is shown in Fig. 2(a), where reflected output intensity $I_{\rm cout} = |c_{\rm out}|^2$ increases with the increase of input intensity $I_{\rm cin}$ constantly when controlling light does not exist ($I_{\rm bin} = 0$), while it drops to zero followed by a sustaining increase to match the case of $I_{\rm bin} = 0$ when $b_{\rm in}$ exists ($I_{\rm bin} = 1$). The reflected light shows an evident difference when controlling light is turned on. To explain such a difference, atomic saturation nonlinear factors (x, x_1, x_2, and $x_{\rm coh}$) are also plotted in Fig. 2(b). Atomic nonlinearity only comes from $I_{\rm cin}$ when $I_{\rm bin}$ does not exist ($x = x_2$), while it is strengthened when $I_{\rm bin}$ exists ($x = x_1 + x_2 + x_{\rm coh}$) since $x_{\rm coh} > 0$.

The physics of controllable reflection originates from the enhancement of atomic nonlinearity and destructive interference. A larger nonlinear factor x results in a smaller t-component and a larger anti-phase r-component when $\phi = 0$. They interfere destructively, which makes $I_{\rm cout}$ a remarkable decline at first. Specially, at the point of $I_{\rm bin} = I_{\rm cin} = 1$, the completely destructive interference swallows any output, which is called the nonlinear perfect photon absorption.[38,40] In the following discussion, we will show that the transmission is also controlled by weak control light as expected.

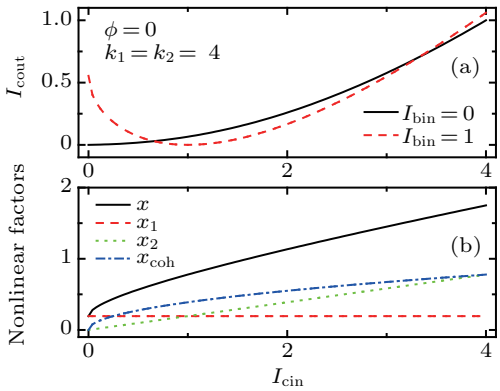


Fig. 2. Optically controllable reflection by in-phase controlling light in symmetrical coupling system. (a) $I_{\rm cout}$ *versus* $I_{\rm cin}$ with and without in-phase controlling light $b_{\rm in} = 1$. (b) Nonlinear factor *versus* $I_{\rm cin}$ in the presence of in-phase controlling light. Here, normalized parameters are set to be $\gamma_{\rm at} \equiv 1$, $k_1 = k_2 = 4$, $\Delta = 0$, and $\phi = 0$.

3.2. Optically controllable switch

As mentioned above, transmission is also controlled at a weak-intensity level, where $b_{\rm in}$ is specified as in-coming light or signal, $c_{\rm in}$ the bias or controlling filed, and $c_{\rm out}$ the outcoming light.

The transmitted curves of $I_{\rm cout}$ *versus* $I_{\rm bin}$ for controlling light $I_{\rm cin} = 0$, 1/4, 1/2, 1, and 2 in the in-phase case $\phi = 0$ are presented in Fig. 3(a), which shows an optically controllable switch-like behavior. As shown in the figure, $I_{\rm cout}$ increases steadily with $I_{\rm bin}$ increasing, which makes light easily propagate from port 1 to port 2 due to the dipole-induced transmission when $I_{\rm cin}$ does not exist ($I_{\rm cin} = 0$). However, the destructive interference leads $I_{\rm cout}$ to sharply decrease followed by a slight increase when $I_{\rm cin}$ exists ($I_{\rm cin} = 1/4$, 1/2, 1, and 2). Especially for the case of $I_{\rm cin} = 1$, light transportation is almost blocked when $|b_{\rm in}|^2 > 0.62$, which can be explained as self-matching-induced-block in the following discussion.

First we point out that such an optical block can be used to fabricate an optically controlled switch whose scheme is shown in Fig. 1(b). The switch is optically controllable by turning the in-phase coherent controlling light $I_{\rm cin} = 1$ on or not. When controlling light is turned off ($I_{\rm cin} = 0$), light can propagate from port 1 to port 2 easily, while light transmission is blocked when controlling light is turned on ($I_{\rm cin} = 1$). Contrast ratio $C = 10 \times \log_{10}(I_{\rm cout-cin=0}/I_{\rm cout-cin=1})$ is defined to characterize the property of optical switch, where $I_{\rm cout-cin=0}$ and $I_{\rm cout-cin=1}$ represent outputting intensities $I_{\rm cout}$ for $I_{\rm cin} = 0$ and $I_{\rm cin} = 1$, respectively. As shown in Fig. 3(b), contrast ratio C is easy to exceed 30 dB in the range of $0.62 < |b_{\rm in}|^2 < 4$. The infinite C for $I_{\rm bin} = 1$ is the consequence of nonlinear perfect photon absorption.[38,40]

Next, we figure out that the physics behind the switch is self-matching-induced-block, that is, the quasi-completely destructive interference of the self-matched r-component and t-component makes almost nothing output. When controlling light is switched on ($I_{\rm cin}=1$), $|r_2|^2$ increases while $|t_{12}|^2$ decreases constantly with the increasing of $|b_{\rm in}|^2$ due to atomic saturation nonlinearity, and it leads the amplitudes of r component and t component (*i.e.*, $r_2c_{\rm in}$ and $t_{12}b_{\rm in}$) to match each other adaptively in a wide range (as shown in Figs. 3(c) and 3(d)). Such the self-matched two components are the consequence of the single atom saturation nonlinearity induced by the two light beams. As r- and t-components are antiphase, their quasi-completely destructive interference presents almost no $I_{\rm cout}$ finally.

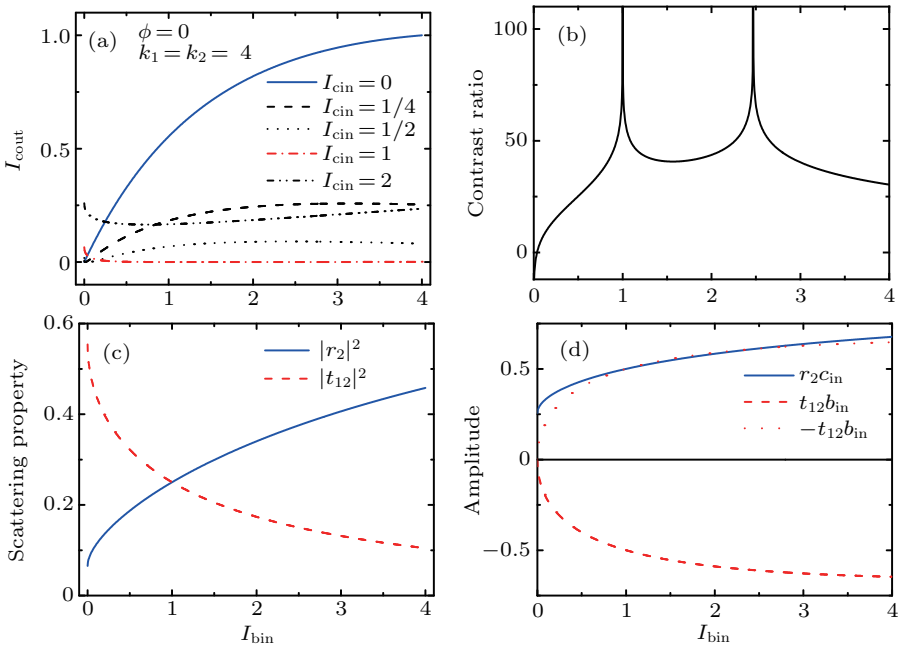


Fig. 3. Optically controllable switch and self-matching-induced-block by in-phase controlling light in symmetrical coupling system. Panel (a) shows curves of $I_{\rm cout}$ *versus* $I_{\rm bin}$ in the presence of in-phase controlling field $c_{\rm in}$. Panel (b) shows optical block property of switch and its scheme is plotted in Fig. 1(b). Panel(c) shows $I_{\rm bin}$-dependent scattering property for $|r_2|^2$ and $|t_{12}^2$. Panel (d) indicates $I_{\rm bin}$-dependent self-matching amplitudes of $r_2c_{\rm in}$ and $t_{12}b_{\rm in}$ in the presence of in-phase controlling light $I_{\rm cin}=1$.

3.3. Optical transistor

Until now, all the setups of light amplification are performed in a multi-level system. So there comes a question, *i.e.*, does an optical transistor exist in a two-level system? To our interest, optically controllable transistor-like behavior is uncovered when two coherent anti-phase beams enter into the asymmetrical coupling setup and the broken spatial symmetry takes effect.

The curves of $I_{\rm cout}$ *versus* $I_{\rm bin}$ are calculated at a series of bias light beams ($I_{\rm cin}=0$, 1/2, 1, 3/2, and 2) for the antiphase case $\phi=\pi$ in the asymmetrical coupling setups ($k_1=6$, $k_2=2$, and $k_1=7$, $k_2=1$). In the presence of nonzero bias light ($I_{\rm cin}=1/2$, 1, 3/2, and 2), $I_{\rm cout}$ presents a nonzero background when $I_{\rm bin}=0$. After removing the background intensity, we plot the curves of transmitted intensities *versus* incident intensity in Figs. 4(a) and 4(c), which clearly show that a slight amplification occurs in a proper regime. As shown in the figure, when bias light does not exist ($I_{\rm cin}=0$), transmitted intensity is less than incident intensity since part energy is reflected and absorbed. However, when $I_{\rm cin}$ is switched on ($I_{\rm cin}=1/2$, 1, 3/2, and 2), part of bias light $c_{\rm in}$ is reflected into $c_{\rm out}$ to supply the transmitted light, and their constructive interference makes amplification ratio $I_{\rm cout}/I_{\rm bin}>1$ finally.

The asymmetric atom–nanowire setup can be used to realize a single-atom optical transistor and the scheme is shown in Fig. 1(c). Although the light amplification ratio is not high, we really show optical amplification can occur in the single two-level system. Optical transistor regime and the amplification ratio in the present asymmetric setups are shown in Figs. 4(b) and 4(d). The larger the value of k_1/k_2, the wider the the transistor regime is. Only in the transistor regime does the amplification ratio exceed 100%.

In the core of present light amplification a weak signal $b_{\rm in}$ is used to disturb the scattering of a strong bias light $c_{\rm in}$ for supplying the output light, and brocken spatial symmetry takes effect. In the asymmetrical coupling setup of $k_1>k_2$, we achieve critical power $P_1<P_2$ which indicates that a weaker $b_{\rm in}$ can produce a much considerable atomic saturation nonlinearity to perturb the scattering of $c_{\rm in}$. The harder the spatial symmetry is broken (corresponding to the larger of k_1/k_2), the wider the transistor regime is. As $\phi=\pi$, the r- and t-components are in-phase, and their constructive interference makes light amplified without gain medium.

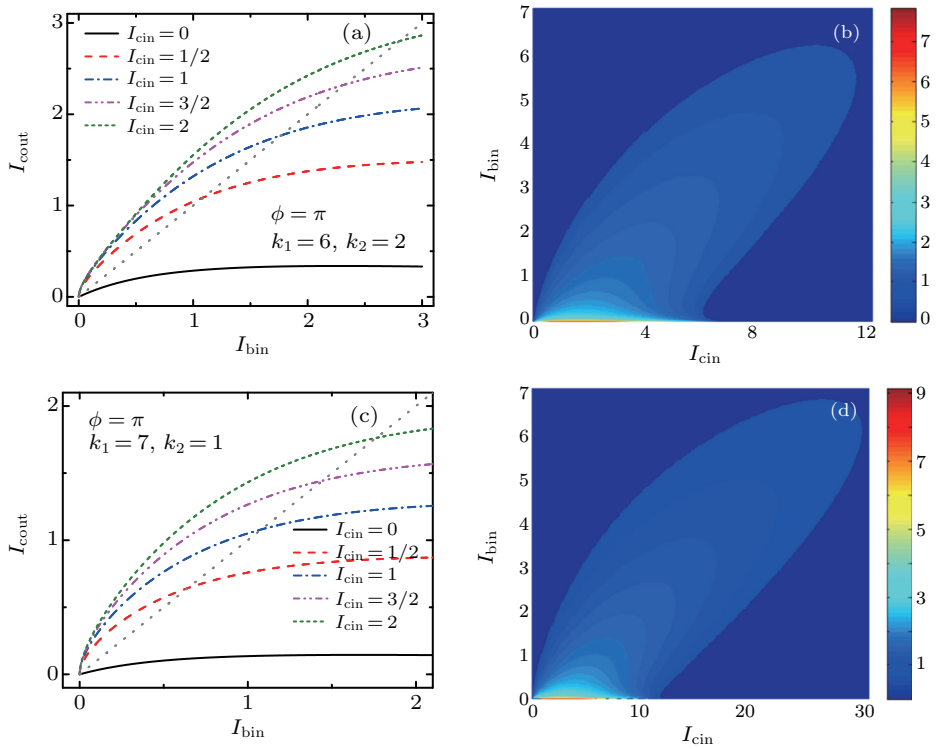


Fig. 4. Transport property of optical transistor by anti-phase controlling light in asymmetrical coupling system. Panels (a) and (c) show that I_{cout} *versus* I_{bin} is dependent on the presence of antiphase bias field I_{cin}. Light amplification regime is restricted by the gray dotted line of $I_{cout}=I_{bin}$. Panels (b) and (d) display optical transistor regime and its amplification ratio. Scheme of optical transistor is shown in Fig. 1(c).

3.4. Fabrication feasibility

It is feasible to fabricate such an atom-waveguide coupling system with the present technology by carefully designing it. Atom interacts with metal nanowire through surface plasmons propagating thereon, where interaction strength is enhanced greatly. Recently, a strong coupling system containing a single emitter and a nanowire has been proposed.[12,41,42] Atom–light coupling strength relates to the shape and material of nanowire and the distance between them. For example, consider a scheme where a fixed 20-nm-radius silver nanowire ($\varepsilon_{Ag}=-50+0.6i$) embedded in the host material with index $n=1.414$, couples with an emitter 10 nm far from the nanowire with emission wavelength of 1000 nm, and P is about 37.[39] Adopting such a scheme, it is not difficult to adjust P to 8 by changing the atomic position since we take $k_1+k_2=8$ in our discussion.

However, the setup of a single atom interacting with two individual nanowires has not been reported experimentally so far. The main challenge of the fabrication is how to exclude their direct interaction between two nanowires while they both strongly coupled with the imbedded atom. Two nanowires should be close enough to the atom to generate strong atom–nanowire coupling, while they should be far enough away to exclude their direct coupling. Therefore, two nanowires should be placed properly (such as vertically) to exclude their direct coupling and only interact with the imbedded atom. The other challenge is how to manipulate a single atom between two nanowires. Although few-atom transference and manipulation has been realized recently by the technology of magneto–optical trapping, it is still very difficult to trap and fix a single atom between two nanowires. Therefore, great efforts are still needed to construct such an atom–nanowires coupling system.

4. Conclusions

In this work, we present a strong coupling system composed of a single two-level atom and two individual terminated nanowires undergoing two coherent input beams. The model is worked out in the mean-field framework. Three contributions of single atom saturation nonlinearity and two components of output fields are specified. Optical response is fully determined by atomic saturation nonlinearity and optical interference between r- and t-components.

The setup provides us with a method of generating the coherent light-controlled-light, even at weak light and single-atom level. For in-phase coherent incidence, we introduce an optically controllable switch based on self-matching-induced-block. The amplitude of r- and t-components are self-matched in a wide range, and their quasi-completely destructive interference generates almost no output light finally. For anti-phase

incidence, a two-level atom optical transistor is proposed by introducing the break of spatial symmetry. The core of present transistor is using a weak signal to disturb a strong bias light, which supplies the output light to make light amplified without gain medium.

Such a single-atom switch and transistor may be the simplest setups until now and may be integratable with silicon. Furthermore, they have great potential convenience to assemble optical circuits by waveguide-waveguide coupling. Our findings show their promising applications in full-optical devices.

Appendix A: Derivation of Eqs. (1)–(6)

In the present model, the efficient Hamiltonian for the coupled system driven by two coherent laser beams $b_{\rm in}$ and $c_{\rm in}$ is[36,38,39,43]

$$H=\hbar\Delta S_z+\left(\hbar\sqrt{k_1}S_+b_{\rm in}+\hbar\sqrt{k_2}S_+c_{\rm in}+{\rm H.c.}\right), \tag{A1}$$

where H.c. represents the complex conjugate. Atomic operators are defined as $S_z=(|e\rangle\langle e|-|g\rangle\langle g|)/2$ and $S_+=|e\rangle\langle g|$ where $|g\rangle$ and $|e\rangle$ represent the ground and excited states, respectively. The two driving fields $b_{\rm in}$ and $c_{\rm in}$ must belong to the transmission modes of the nanowires to ensure light propagating on them.

Following the standard processing, the equations of motion for the coupled system are given by Langevin equation, and those expectation values of $s=\langle S_-\rangle$ and $s_z=\langle S_Z\rangle$ are obtained by adding a damping term of atomic spontaneous emission and by dropping the quantum fluctuation terms, and expressed as

$$\dot{s}=-{\rm i}\Delta s-\frac{\Gamma}{2}s-{\rm i}\,(-2s_z)\left(\sqrt{k_1}b_{\rm in}+\sqrt{k_2}{\rm c}_{\rm in}\right), \tag{A2}$$

$$\dot{s}_z=\left({\rm i}\sqrt{k_1}b_{\rm in}^*s+{\rm i}\sqrt{k_2}c_{\rm in}^*s+{\rm c.c.}\right)-\Gamma\,(s_z+1/2)\,. \tag{A3}$$

Here, c.c. refers to two complex conjugate terms in the round bracket, and the superscript star is the conjugate value of single complex quantity. Output fields characterized by quantum input–output relations are related to the atomic transition and input fields, and given as

$$b_{\rm out}=b_{\rm in}-{\rm i}\sqrt{k_1}{\rm s}, \tag{A4}$$

$$c_{\rm out}=c_{\rm in}-{\rm i}\sqrt{k_2}s. \tag{A5}$$

Assuming that $b_{\rm in}=|b_{\rm in}|$ and $c_{\rm in}=\alpha|b_{\rm in}|\,{\rm e}^{{\rm i}\phi}$ (α is a positive number and ϕ is the relative phase), the steady solutions can be obtained by setting the left time derivatives to be zeros. The steady solution of dipole moment s is

$$s=-\frac{{\rm i}(-2S_z)\sqrt{k_1}b_{\rm in}\left(1+\alpha\sqrt{k_2/k_1}\,{\rm e}^{{\rm i}\phi}\right)}{\Gamma/2+{\rm i}\Delta}. \tag{A6}$$

Inserting Eq. (A6) into Eq. (A3), the steady atomic population s_z is

$$s_z=-\frac{1}{2}\frac{1}{1+x}, \tag{A7}$$

where x is the total atomic saturation nonlinear parameter. In the present bilateral coherent incidence, atomic nonlinearity is the consequence of two incident light beams and their interference, they fulfilling

$$x=x_1+x_2+x_{\rm coh}, \tag{A8}$$

where $x_1=|b_{\rm in}|^2/P_1$ and $x_2=|c_{\rm in}|^2/P_2$ are the nonlinear factors respectively induced by $b_{\rm in}$ and $c_{\rm in}$, and $x_{\rm coh}=2(x_1x_2)^{1/2}\cos\phi$ is the effect of coherent interference. Here, $|b_{\rm in}|^2$ and $|c_{\rm in}|^2$ represent the two input intensities. P_m ($m=1$, 2) is the critical intensity for the incident from port m, given as

$$P_m=\left(\Delta^2+\Gamma^2/4\right)/2k_m,\quad (m=1,2). \tag{A9}$$

In this work, the three contributions of atomic saturation nonlinearity from each light and from their interference are all explicated. The difference between P_1 and P_2 shows that the degrees of atomic saturation nonlinearities are different even for the same incidence from different ports in the asymmetric coupling system. The total atomic nonlinearity is controllable by varying the frequencies, intensities and relative phase of two incident laser beams, as well as the atom–nanowire coupling strength.

Using the quantum input–output relations of Eqs. (A4) and (A5), the output field from each port can be obtained to be

$$b_{\rm out}=b_{\rm in}\left(1-\frac{k_1+\alpha\sqrt{k_1k_2}\,{\rm e}^{{\rm i}\phi}}{\Gamma/2+{\rm i}\Delta}\cdot\frac{1}{1+x}\right), \tag{A10}$$

$$c_{\rm out}=b_{\rm in}\left(\alpha\,{\rm e}^{{\rm i}\phi}-\sqrt{\frac{k_2}{k_1}}\frac{k_1+\alpha\sqrt{k_1k_2}\,{\rm e}^{{\rm i}\phi}}{\Gamma/2+{\rm i}\Delta}\cdot\frac{1}{1+x}\right). \tag{A11}$$

Basically, each output light can be written as the superposition of reflected and transmitted fields as seen in Eqs. (5) and (6). By rewriting Eqs. (A10) and (A11), we can obtain the reflectivity and transmittivity as given below

$$r_m=1-\frac{k_m}{\Gamma/2+{\rm i}\Delta}\cdot\frac{1}{1+x},\quad (m=1,2), \tag{A12}$$

$$t_{mn}=-\frac{\sqrt{k_mk_n}}{\Gamma/2+{\rm i}\Delta}\cdot\frac{1}{1+x},\quad (m,n=1,2). \tag{A14}$$

Here, r_m ($m=1$, 2) is the reflectivity from port m, and t_{mn} (m, $n=1$, 2) is the transmittivity from port m to port n. Thus, we work out the coupled system in the framework of mean-field theory and obtain Eqs. (1)–(6).

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