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Nonlinear coherent perfect photon absorber in asymmetrical atom–nanowires coupling system*

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Coherent perfect absorption provides a method of light-controlling-light and has practical applications in optical communications. Recently, a cavity-based nonlinear perfect photon absorption extends the coherent perfect absorber (CPA) beyond the linear regime. As nanowire-based system is a more competitive candidate for full-optical device, we introduce a nonlinear CPA in the single two-level atom–nanowires coupling system in this work. Nonlinear input–output relations are derived analytically, and three contributions of atomic saturation nonlinearity are explicit. The consociation of optical nonlinearity and destructive interference makes it feasible to fabricate a nonlinear monoatomic CPA. Our results also indicate that a nonlinear system may work linearly even when the incoming lights are not weak any more. Our findings show promising applications in full-optical devices.

Keywords: single-atom system, atom–nanowires coupling, nonlinear coherent perfect absorber

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The coherent perfect absorber (CPA) is the time reversed counterpart of the laser and may have practical applications in optical communications and photonic devices such as transducers, modulators, and optical switches and transistors.[1–4] Until now, almost all the previous studies have focused on the linear CPA in the cavity-based system where the linear absorbers of the first-order polariton states are considered.[5,6] Recently, optical nonlinearities beyond weak-excitation approximation have been introduced to produce nonreciprocal light propagation in optomechanical array,[7] single-mode cavity,[8,9] and coupled two microcavities.[10] Perfect photon absorption in cavity-based system has also been expanded from the linear regime into the nonlinear regime.[11] The physics under linear CPA is the destructive interference between the transmitted field and the input field, leading the absorbed photon energy only to the spontaneous decay of the atomic excitation.

However, these cavity-based CPA are too large to be integrated or need a strong working power which restricts their practical applications.[12–16] In order to minimize its physical size and lower its operating power, we introduced a monoatomic CPA in atom–nanowires coupling system in the linear regime.[17] We have shown rich physics in the system, such as dipole-induced transmission at single-photon level,[18] Rabi-like splitting, and a negative differential transporter.[17] Nanowire-based systems catch a lot of highlights since nanowires exhibit good confinement and guiding even when their radii are reduced far below the optical wavelength.[19–22] Compared to the cavity-based systems, nanowire-based systems are more competitive candidates for full-optical devices.[23–25]

Although we have introduced a linear CPA in atom–nanowires coupling system, a lot of further work needs to be done to improve its performance in this work. First, nanowire-based single-atom linear CPA requires that the incident light is weak enough that the single emitter will not saturate. However, optical nonlinearity is almost inevitable for monoatomic system in practice. Therefore, we need to extend the linear CPA to nonlinear excitement regime in this work. Second, as we know, a hypersensitized photon detector is necessary in detecting the weak linear response since the driving filed is very weak in the single-atom system. Therefore, it raises an interesting question: is the weak driving filed always necessary in the linear operation? How can a nonlinear system work linearly in the classical nonlinear regime?

In order to conquer the above ridges, we introduce two coherent driving laser beams simultaneously input on the single atom in this work. Two coherent lights will be scattered by the single atom, leading to optical nonlinearity and mutual interference simultaneously. We will show that it provides us an approach to realizing the nonlinear CPA and to performing the linear operation in the monoatomic system beyond weak

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driving restriction.

The model containing a single two-level system with transition frequency ω_{at} coupled with two individual terminated metallic nanowires with 100% reflectivity at the right ends has been presented in our previous work[17] and is shown in Fig. 1. Two nanowires are separated wide enough to exclude their direct coupling, and they only interact through the imbedded atom. Unlike the previous work of single-light driving, we consider its scattering properties by two coherent input fields b_{in} and c_{in} from ports 1 and 2 simultaneously. Single atomic saturation nonlinearity will show richer physics at the exposure of two laser beams compared to the case of single light incident.

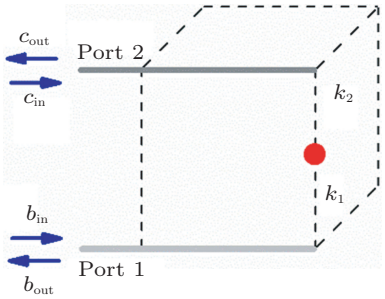


Fig. 1. (color online) Sketch of bilateral coherent incident for atom–nanowires coupling system. Two gray terminated lines represent two individual one-dimensional nanowires and the small red circle is a two-level emitter coupled asymmetrically to the two nanowires.

Two driving fields with in-tuned frequency ω_L are tuned from the atomic transition by $\Delta = \omega_{at} - \omega_L$. Due to the Purcell effect, the total atomic decay rate $\Gamma = k_1 + k_2 + \gamma_{at}$ contains three components, i.e., k_1 which is the decay into the lower waveguide modes, k_2 which is the decay into the upper waveguide modes, and γ_{at} which is the decay into the free vacuum modes.[26] Light–matter coupling strength can be manipulated from weak to strong coupling regimes, as k_1 and k_2 are dependent on the radius of wires and on the atomic distance from the wires.[23–25] The Hamiltonian for the coupled system is[14,18,24]

$$H = \hbar\Delta S_z + \left(\hbar\sqrt{k_1}S_- b_{in}^{\dagger} + \hbar\sqrt{k_2}S_- c_{in}^{\dagger} + \text{H.c.}\right), \quad (1)$$

where H.c. stands for the complex conjugate. Atomic operators are $S_z = (|e\rangle\langle e| - |g\rangle\langle g|)/2$ and $S_- = |g\rangle\langle e|$, where $|g\rangle$ and $|e\rangle$ represent the ground and excited states, respectively. The equations of motion for the coupled system are given by the Langevin equation. Following the standard processing, the equations of motion of the coupled system for the expectation values of $s = \langle S_-\rangle$ and $s_z = \langle S_Z\rangle$ are obtained by dropping the quantum fluctuation terms, reading

$$\dot{s} = -\mathrm{i}\Delta s - \frac{\Gamma}{2}s - \mathrm{i}\,(-2s_z)\left(\sqrt{k_1}b_{in} + \sqrt{k_2}c_{in}\right), \quad (2)$$

$$\dot{s_z} = \left(\mathrm{i}\sqrt{k_1}b_{in}^{*}s + \mathrm{i}\sqrt{k_2}c_{in}^{*}s + \text{c.c.}\right) - \Gamma\,(s_z + 1/2). \quad (3)$$

Here, c.c. stands for the complex conjugate. The output fields characterized by quantum input–output relations are related to the atomic transition and input fields, reading

$$b_{out} = b_{in} - \mathrm{i}\sqrt{k_1}s, \quad (4)$$

$$c_{out} = c_{in} - \mathrm{i}\sqrt{k_2}s. \quad (5)$$

Two coherent input lights are considered by assuming $b_{in} = |b_{in}|$ and $c_{in} = \alpha|b_{in}|\,\mathrm{e}^{\mathrm{i}\phi}$, where α is a positive number and ϕ is the relative phase. The output light from each port is the superposition of reflected and transmitted fields, reading

$$b_{out} = r_1 b_{in} + t_{21}c_{in}, \quad (6)$$

$$c_{out} = r_2 c_{in} + t_{12}b_{in}, \quad (7)$$

where 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, reading

$$r_m = 1 - \frac{k_m}{\Gamma/2 + \mathrm{i}\Delta}\frac{1}{1+x}, \quad (m = 1,2), \quad (8)$$

$$t_{mn} = -\frac{\sqrt{k_m k_n}}{\Gamma/2 + \mathrm{i}\Delta}\frac{1}{1+x}, \quad (m,n = 1,2). \quad (9)$$

Optical nonlinearity is characterized by the total optical nonlinear parameter x which is caused by the monoatomic absorption saturation. In the case of bilateral coherent incident, optical nonlinearity is the consequence of two incident lights and their interference, which indicates that x includes three contributions, reading

$$x = x_1 + x_2 + x_{coh}, \quad (10)$$

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

$$P_m = (\Delta^2 + \Gamma^2/4)/2k_m, \quad (m = 1,2). \quad (11)$$

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

Light-controlling-light is essential to optical devices and intrinsic atomic spontaneous decay plays a role in dissipative systems.[27,28] Coherent perfect absorption provides us a method of light-controlling-light using coherent laser beams. By using coherent light control in metamaterials,[29,30] photon perfect absorption and optical transistor have been proposed.[31] Such kind of elaborate metamaterial CPA that requires careful design is also a kind of linear CPA since only the effect of destructive interference was considered. Recently,

a cavity-based nonlinear CPA shows that the perfect photon absorption is a phenomenon that can be observed in both linear and nonlinear regimes.[11] Here, we show how to construct a nonlinear CPA in the current atom–waveguide coupling system at the single-atom level.

According to Eqs. (6) and (7), the nonlinear CPA is defined by the disappearance of outputs $|b_{\rm out}|$ and $|c_{\rm out}|$ undergoing non-zero inputs. After some algebra, we get the restrictions for nonlinear CPA, i.e., a frequency restriction ($\Delta = 0$), an amplitude condition ($\alpha = (k_2/k_1)^{1/2}$), a phase restriction ($\phi = 0$), and a compound restriction combining the requirements of configuration and input intensity, reading

$$|b_{\rm in0}|^2 = \frac{k_1}{8}\left(1 - \frac{1}{P^2}\right), \tag{12}$$

where $P = \Gamma/\gamma_{\rm at} - 1$ is the Purcell factor due to Purcell effect.

Compared to the results of nanowire-based linear CPA,[17] the frequency restriction $\Delta = 0$, amplitude condition $\alpha = (k_2/k_1)^{1/2}$, and phase restriction $\phi = 0$ are the same, while the configuration restriction $k_1 + k_2 = \gamma_{\rm at}$ is replaced by the compound restriction of configuration and input intensity now. In the case of linear CPA, the configuration restriction is sufficient since the optical nonlinearity is omitted when the incident intensities are weak enough, i.e., $x \to 0$. However, in the case of nonlinear CPA, the optical nonlinearity originates from single atomic saturation absorption naturally with $x = 0.7778$, which requires the compound restriction combining the requirements of configuration and input intensity.

In order to show the nonlinear CPA clearly, we plot Figs. 2(a)–2(d) to present the four restrictions within the asymmetric environment. It is convenient to normalize all the other parameters, i.e., k_1, k_2, and Δ, by taking $\gamma_{\rm at} = 1$. We set $k_1 = 3$ and $k_2 = 5$ to present asymmetric coupling, and then $|b_{\rm in}|^2$ should be $|b_{\rm in0}|^2 = 0.3691$ to generate nonlinear CPA. As is shown, the nonlinear CPA only appears when the four restrictions match exactly.

The physics under the present nonlinear perfect absorption is optical nonlinearity and destructive interference. From Eqs. (8) and (9), we know that the reflectivity r_m ($m = 1, 2$) is positive while the transmittivity t_{mn} ($m, n = 1, 2$) is negative when $\Delta = 0$. Therefore, only when $\phi = 0$ can the two components of the output light interfere destructively. The amplitude condition and the compound restriction jointly lead the amplitudes of the two components to be exactly equal in the nonlinear regime, and their completely destructive interference makes the output nothing finally.

Since three contributions of atomic saturation nonlinearity (i.e., x_1, x_2, and $x_{\rm coh}$) are analytically explicit in this work, it provides us a method to perform linearly in the classical nonlinear system beyond weak driving restriction. As we know, optical nonlinearity closely relies on the intensity of unilateral incoming laser beam in the monoatomic system. For $x \to 0$, the system works linearly. With the increase of x, optical nonlinearity appears and dominates the scattering property gradually. Therefore, the classical linear regime requires that the incident field is weak enough that it will not saturate the atom. The weak driving restriction shows that performing linearly in the case of single-driving is out of the question when the incident light is not weak any more. However, we can produce a linear response from a classical nonlinear system beyond the weak-driving restriction when we input two coherent driving beams. By solving $x = 0$, we can first get $x_1 = x_2$ and $\phi = \pi$, and their amplitudes should fulfill a new amplitude condition, i.e., $\alpha = (k_1/k_2)^{1/2}$. In this case, both the reflectivity r_m ($m = 1, 2$) and transmittivity t_{mn} ($m, n = 1, 2$) have something with incident lights no longer. The atomic absorption is suppressed from perfect absorption to prefect reflection. Especially for the symmetrical coupling system, linear response from nonlinear regime requires $b_{\rm in} = -c_{\rm in}$. It will be convenient to detect the linear performance since the ultrasensitive photon detector is not necessary now.

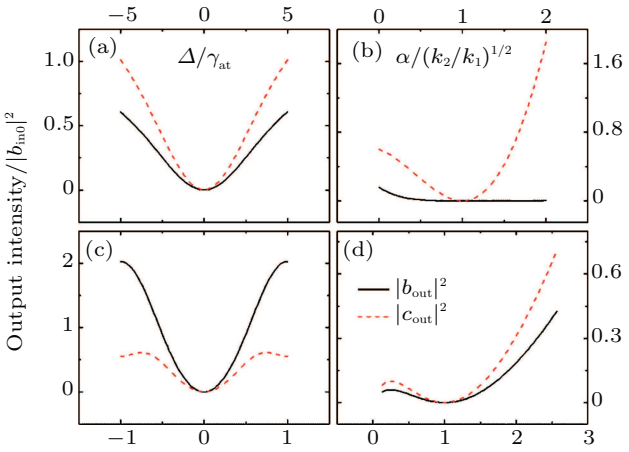


Fig. 2. (color online) Nonlinear CPA restrictions. Here, we set $\gamma_{\rm at} = 1$, $k_1 = 3$, $k_2 = 5$, and $|b_{\rm in0}|^2 = 0.3691$ as common parameters. $|b_{\rm in}|^2$ equals $|b_{\rm in0}|^2$ in (a), (b), and (c). All the input and output lights are renormalized by $|b_{\rm in0}|^2$. (a) Frequency restriction with $\alpha = (k_2/k_1)^{1/2}$, $\phi = 0$, and $|b_{\rm in}|^2 = |b_{\rm in0}|^2$. (b) Amplitude restriction with $\Delta = 0$, $\phi = 0$, and $|b_{\rm in}|^2 = |b_{\rm in0}|^2$. (c) Phase restriction with $\Delta = 0$, $\alpha = (k_2/k_1)^{1/2}$, and $|b_{\rm in}|^2 = |b_{\rm in0}|^2$. (d) Compound restriction with $\Delta = 0$, $\alpha = (k_2/k_1)^{1/2}$, and $\phi = 0$.

As a summary, we analytically solve the quantum optical system which is made up of two individual optical nanowires and a two-level emitter driven by two coherent lasers, and find a controllable nonlinearity by their frequencies, intensities, and relative phase, as well as the asymmetrical atom–nanowires coupling. As the result, we present a nonlinear photon perfect absorber in the asymmetrical coupling system and show how to operate the system linearly in the nonlinear regime. Compared to the previous cavity-based and metamaterial CPAs, our scheme of nonlinear CPA is rather simple and efficient. Our findings show promising applications in full-optical device.

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