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Localization of light in induced triangular photonic lattices with defects

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ABSTRACT

In this paper, the electromagnetically induced lattice with defect is proposed with the destructive quantum interference. The ensemble of the four-level *N* type cold atoms is considered to follow the spatial modulation where the strong control field is employed with the spatial light modulator (SLM). Due to the flexible controllability, the variable positions of the defect, as well as the localization of the signal field can be realized and effectively manipulated. Additionally, the propagation properties of signal light in multi-defects are also discussed in this work.

1. Introduction

The concept of localization was first proposed by Anderson [1] and is one of the unusual propagation properties in optical system [2–4]. Anderson localization was first found in random media [1], and it was then investigated in many system including periodic or quasi-periodic media [5–7]. Study of light propagation in periodic media such as photonic crystals and optically induced photonic lattices is of great interest to both fundamental physics and applications [8–11]. To guide light in periodic media, one of the convenient ways is to introduce a defect into the medium [12], which disrupts the periodicity of the lattices and provides an additional physical mechanism for light confinement. Due to the defect guidance, the localization of light can be realized and manipulated [13,14].

In the recent years, the localization of light in periodic lattices with defects is very active and of interesting in theoretical and experimental studies [15,16]. Most defects that employed as the guidance are produced by artificial preparation [16], and there are also some other ways, such as quantum interference [17]. With quantum interference, one can generate a susceptibility (or refractive) distribution with any shape as needed in a coherently prepared atomic medium.

In this paper, the triangular photonic lattices is induced in the four-level *N* type cold atoms with the method of quantum interference. During the destructive interference, the strong control field after a spatial light modulator with high damage threshold (the alternative SLM, Hamamatsu X10468-02) is employed to modulate a periodic susceptibility. As we know, the properties of the induced media depend on the coherent parameters to a large extent, such as the constant of the induced lattices, the geometry and position of the defect, etc. As a result, the controllable spatial structure of the induced lattices in this work provides a flexible and tunable method to manipulate the dynamics of the signal field. The paper is organized as follows. In the next section, we present the description of the theoretical model and equations. In sec. 3, the global propagation and localization in the induced triangular photonic lattices with defect (or defects) are investigated. In the final section, a summary and discussion of the main results are given.

2. Mode and equations

We take ^{87}Rb as an example, the energy structure is shown in Fig. 1(a). The *N*-type four-level atomic system includes two upper levels $|3\rangle$, $|4\rangle$ and two lower levels $|1\rangle$, $|2\rangle$. The atomic transition of $|3\rangle \leftrightarrow |1\rangle$, $|3\rangle \leftrightarrow |2\rangle$, $|4\rangle \leftrightarrow |2\rangle$ are coupled by signal field, pump field and control field respectively. Here Ω_s, Ω_p, Ω_c are the Rabi frequencies of the signal field, pump field and control field respectively. The schematic of the induced lattices is shown in Fig. 1(b). The control beam is modulated by SLM, the pump beam is incident on the medium in the same direction with the control beam

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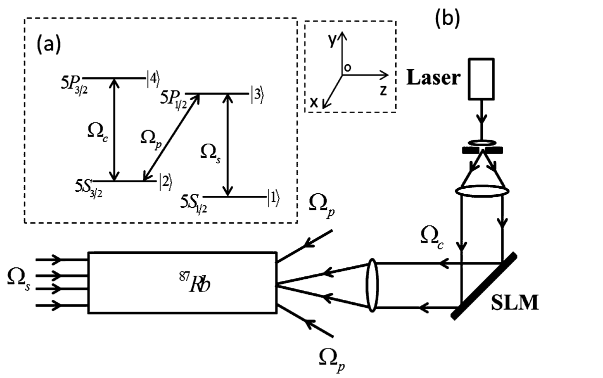

Fig. 1. (a) The configuration for a four-level atomic system. (b) Schematic diagram of the induced lattices. The control beam is modulated by SLM, the pump beam is incident on the medium in the same direction with the control beam and the signal light propagates in the opposite direction.

and the signal light propagates in the opposite direction. Under electric-dipole and rotating-wave approximations, the Hamiltonian of the system reads

$$H=\hbar\sum_{j=1}^{4}\omega_j|j\rangle\langle j|-\hbar(\tilde{\Omega}_s|3\rangle\langle 1|+\tilde{\Omega}_p|3\rangle\langle 2|+\tilde{\Omega}_c|4\rangle\langle 2|+h.c.). \quad (1)$$

We give the density matrix equations of motion as follows:

$$\begin{aligned}\dot{\rho}_{21}&=-(i(\omega_2-\omega_1)+\gamma_{12})\rho_{21}+\frac{i}{2}\tilde{\Omega}_p{}^{*}\rho_{31}-\frac{i}{2}\tilde{\Omega}_s\rho_{32}^{*}\\&\quad+\frac{i}{2}\tilde{\Omega}_c{}^{*}\rho_{41},\\ \dot{\rho}_{31}&=-(i(\omega_3-\omega_1)+\gamma_{13})\rho_{31}+\frac{i}{2}\tilde{\Omega}_p\rho_{21}+\frac{i}{2}\tilde{\Omega}_s(\rho_{11}-\rho_{33}),\\ \dot{\rho}_{41}&=-(i(\omega_4-\omega_1)+\gamma_{14})\rho_{41}+\frac{i}{2}\tilde{\Omega}_c\rho_{21}-\frac{i}{2}\tilde{\Omega}_s\rho_{43}, \qquad (2)\end{aligned}$$

where $\tilde{\Omega}_p=\Omega_p e^{-i\varphi_p}e^{-i\omega_p t}$, $\tilde{\Omega}_c=\Omega_c e^{-i\varphi_c}e^{-i\omega_c t}$, $\tilde{\Omega}_s=\Omega_s e^{-i\varphi_s}e^{-i\omega_s t}$ and φ_s, φ_p, φ_c are the phase of the dipole matrix element. We assume that the atoms always stay in the ground state and the frequency of the signal field ω_s is close to the transition frequency of $|1\rangle\to|3\rangle$. Under these assumptions and the action of quantum interference, the stable solution is obtained,

$$\rho_{31}=\frac{\mu_{13}\varepsilon_s}{\hbar}\frac{|\Omega_c|^2-4\Delta\tilde{\omega}_p\Delta\tilde{\omega}_c}{4\Delta\tilde{\omega}_s\Delta\tilde{\omega}_p\Delta\tilde{\omega}_c-|\Omega_p|^2\Delta\tilde{\omega}_c-|\Omega_c|^2\Delta\tilde{\omega}_s}, \quad (3)$$

which ε_s is the amplitude of signal field. So the susceptibility of the signal field χ is

$$\chi=\frac{K(|\Omega_c|^2-4\Delta\tilde{\omega}_p\Delta\tilde{\omega}_c)}{4\Delta\tilde{\omega}_s\Delta\tilde{\omega}_p\Delta\tilde{\omega}_c-|\Omega_p|^2\Delta\tilde{\omega}_c-|\Omega_c|^2\Delta\tilde{\omega}_s}. \quad (4)$$

The constant $K=N_a|\mu_{13}|^2/\hbar\varepsilon_0$ with the atomic density N_a and the electric dipole moment μ_{13} of transition $|1\rangle\to|3\rangle$. The complex detunings $\Delta\tilde{\omega}_s=\Delta\omega_s+i\gamma_{13}$, $\Delta\tilde{\omega}_p=\Delta\omega_p+i\gamma_{12}$ and $\Delta\tilde{\omega}_c=\Delta\omega_c+i\gamma_{14}$, in which $\Delta\omega_s=\omega_s-(\omega_3-\omega_1)$, $\Delta\omega_p=(\omega_s-\omega_p)-(\omega_2-\omega_1)$, $\Delta\omega_c=(\omega_s-\omega_p+\omega_c)-(\omega_4-\omega_1)$ and γ_{13}, γ_{12}, γ_{14} are the coherence decay rates of the transitions $|1\rangle\to|3\rangle$, $|1\rangle\to|2\rangle$, $|1\rangle\to|4\rangle$. Under the slowly varying envelope approximation, the wave equation of a paraxial propagating signal field in the induced medium is

$$2ik\phi_z+(\partial_{xx}+\partial_{yy})\phi+k^2\chi\phi=0, \quad (5)$$

where ϕ is the envelope of the signal field, $\Omega_s(x,y,z)=\phi(x,y,z)\exp(-i\omega_s t+ikz)$ with $k=\omega_s/c$, and χ is the linear susceptibility, which has been given by Eq. (4).

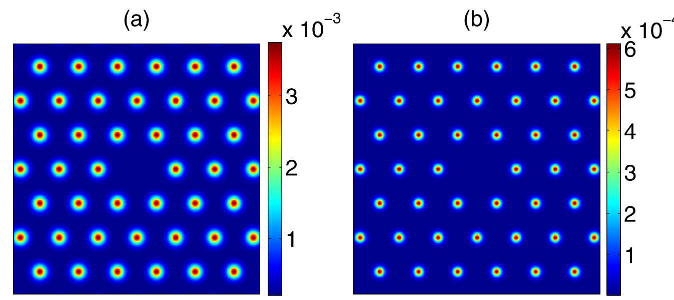

Fig. 2. The susceptibility of the induced lattice. (a) The real part and (b) the imaginary part. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Numerical simulation and results

The control field in this paper can be generated by the spatial light modulator with high damage threshold, which can modulated the spatial intensity distribution as needed. Considering the condition of the destructive interference, the control field should be much stronger. Consequently, the SLM with high damage threshold is required (the alternative SLM is Hamamatsu X10468-02). According to arrangement, the structure of the control field can be modulated to the form of $\Omega_c=\Omega_{c0}V(x,y)$, where the Ω_{c0} is the constant relative to Rabi frequency, indicates the intensity of the control field, and $V(x,y)$ is the modulation item with the form of

$$V(x,y)=V_0(x,y)\times(1-\sum_m(\exp(((x-md)^2+y^2)^4/128))), \quad (6)$$

in which

$$\begin{aligned}V_0(x,y)&=\frac{2}{3}\times(\frac{3}{2}+\cos(k_0(x+\frac{\sqrt{3}}{3}y))+\cos(k_0(x-\frac{\sqrt{3}}{3}y))\\&\quad+\cos(k_0(\frac{2\sqrt{3}}{3}y))). \qquad (7)\end{aligned}$$

The spatial frequency $k_0=2\pi/d$, $d=\pi$ is the period in the x direction with the unit of 5 μm. As $V(x,y)$ is the function of the spatial coordinates, the assemble of the atoms can be induced to the periodic medium with structure of the triangular photonics lattices. The first term of $V(x,y)$ ($V_0(x,y)$) shows the periodic structure, while the second term presents the defect, which position depends on the value of the integer m. We set the pump field strong enough so that it will not be depleted and the control field should be a little weak but still stronger than the signal field, the parameters are $K=4\times10^5$ s^{-1}, $\Omega_{c0}=5\times10^8$ s^{-1}, $\Omega_p=4/3\Omega_{c0}$, $\Delta\omega_c=-7\times10^9$ s^{-1}, $\Delta\omega_s=3\times10^8$ s^{-1}, $\Delta\omega_p=0.5\times10^8$ s^{-1}, $\gamma_{12}=1.5\times10^3$ s^{-1} and $\gamma_{13}=\gamma_{14}=1.5\times10^7$ s^{-1}. The wavelength is $\lambda=800$ nm.

Considering $m=0$, the induced photonic lattice with one defect in the center of the media. The induced lattice with spatial susceptibility is shown in Fig. 2. For $n=\sqrt{1+Re(\chi)}$, the real part (a) indicates the refractive index of the media, and the imaginary part (b) shows the absorption. Though the real and imaginary part of the susceptibility have the similar structure, the value of imaginary is much smaller than the real part, which demonstrates low absorption and high transparency of the coherent media, for different coherent parameters, the susceptibility distribution realtimely varies. So the investigation of signal field in such media is meaningful. Suppose the signal field (initial effective beam radius $w_0=2d$) incidents on the induced photonic lattice in the center, the normalized amplitude distribution on the output $z=60$ mm is plotted in Fig. 3 for different detuning $\Delta\omega_c$. From Fig. 3(a), as $\Delta\omega_c=-7.0\times10^9$ s^{-1}, the signal expands seriously and the radius of spot on the output is relatively large, while as the absolute