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PHYSICS LETTERS A
Physics Letters A 363 (2007) 497–501
www.elsevier.com/locate/pla

Electromagnetically induced negative refractive index in a V-type four-level atomic system

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Received 17 July 2006; received in revised form 26 October 2006; accepted 26 October 2006

Available online 16 November 2006

Communicated by R. Wu

Abstract

We propose a scheme for realizing negative refractive index in a V-type four-level atomic system. It is shown that the negative refractive index can be achieved in a wide frequency band based on the effect of quantum coherence. It is also found that the frequency band of negative refractive index and the absorption property of left-handed material are manipulated by the pump and control fields. Furthermore, left-handed material with reduced absorption is possible by choosing appropriate parameters.

PACS: 42.50.Gy; 42.25.Bs; 78.20.Ci

Keywords: Quantum coherence; Negative refractive index; Atomic system

Recently, an interesting research about left-handed material (LHM) [1] has attracted considerable attention because of its surprising and counterintuitive electromagnetic and optical properties. This material has a negative refractive index when the permittivity and permeability are negative simultaneously [1]. Although naturally occurring materials with both negative permittivity and permeability simultaneously are not available, the left-handed materials have been artificially realized [2–4]. In LHM, the wave vector is opposite to the direction of energy propagation. Some unusual phenomena, such as the reversals of both Doppler shift and Cerenkov effect [1], amplification of evanescent waves [5], subwavelength focusing [5,6], negative Goos–Hänchen shift [7], and so on, are expected in LHM. One of the potential applications of LHM is the perfect lens because a slab of such materials may have the power to focus all Fourier components of a two-dimensional image, including the evanescent waves [8,9]. However, the absorption in LHM makes the perfect lens cannot focus large wave-vector components and will decrease its resolution [10]. Therefore, it is necessary to search low-loss LHM.

Up to now, there are several approaches to the realization of LHM, including artificial composite metamaterials [11–14], photonic crystal structures [15–17], transmission line simulation [18], and chiral material [19–21] as well as photonic resonant materials (coherent atomic vapor) [22–26]. The former four methods, based on the classical electromagnetic theory, require delicate manufacturing of spatially periodic structure. The last method is a quantum optical approach where the physical mechanism is the quantum interference and coherence that arises from the transition process in a multilevel atomic system. It was first simultaneously proposed by Oktel et al. and Shen et al. in a three-level medium [22], which requires rigorous level condition. For the purposes of enhancing the freedom of choice of levels and making the scheme much more applicable to realistic system, recently, Thommen et al. presented a proposal

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0375-9601/$ – see front matter
doi:10.1016/j.physleta.2006.10.101

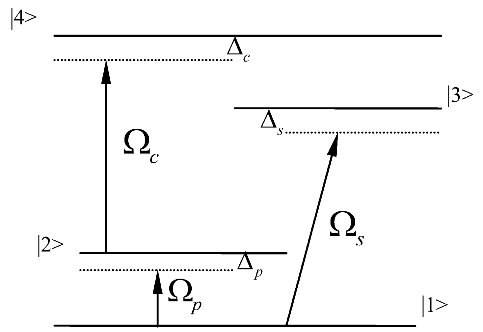

Fig. 1. The scheme of a four-level V-type atom interacting with the probe, pump and control fields as described in the text.

based on a coherent cross-coupling between electric and magnetic dipole transitions in a four-level scheme, which is carried out in atomic hydrogen and neon [25]. However, the frequency band with negative refraction is narrow (0.2 MHz).

In this Letter, we put forward a V-type four-level atomic scheme. In our scheme, we consider a dense atomic gas in which the contribution of Lorentz–Lorenz local field should be considered. In the dense gas, we combine the modification of the permeability by an induced magnetic moment with the modification of the permittivity due to an electric transition [22]. It is shown that the negative permittivity and the negative permeability can simultaneously be achieved in a wider frequency band than that of [25]. Moreover, the probe absorption is significantly reduced by electromagnetically induced transparency (EIT) [27]. We find that the frequency band of negative refractive index and the absorption property of LHM can be controlled by the pump and control fields. Furthermore, LHM with reduced absorption is possible by choosing appropriate parameters.

We consider a V-type four-level atomic system as shown in Fig. 1. The two upper levels, $|3\rangle$ and $|4\rangle$, have the same parity and $\mu_{34} = \langle 3|\hat{\vec{\mu}}|4\rangle \neq 0$, where $\hat{\vec{\mu}}$ is the magnetic dipole operator. The two lower levels $|1\rangle$ and $|2\rangle$ have opposite parity with $d_{21} = \langle 2|\hat{\vec{d}}|1\rangle \neq 0$, where $\hat{\vec{d}}$ is the electric dipole operator. Levels $|1\rangle$ and $|2\rangle$ are coupled by a weak probe field Ω_p with frequency ω_p, while levels $|1\rangle$ and $|3\rangle$ are coupled by a strong pump field Ω_s with frequency ω_s. Levels $|2\rangle$ and $|4\rangle$ are coupled by a control field Ω_c with frequency ω_c. According to the parity selection rules, either one of transitions must involve two photons. In the following, we shall always assume the transition $|2\rangle \to |4\rangle$ is a two photon process.

In the interaction representation, the semiclassical Hamiltonian in a rotating frame is

$$H = \hbar \begin{bmatrix} 0 & -\Omega_p & -\Omega_s & 0 \\ -\Omega_p & \Delta_p & 0 & -\Omega_c \\ -\Omega_s & 0 & \Delta_s & 0 \\ 0 & -\Omega_c & 0 & (\Delta_p + \Delta_c) \end{bmatrix}. \tag{1}$$

Here, $\Delta_p = \omega_{21} - \omega_p$, $\Delta_s = \omega_{31} - \omega_s$ and $\Delta_c = \omega_{24} - \omega_c$ denote the detuning of the probe, pump and the control field, respectively; $\omega_{ij} = \omega_i - \omega_j$ is the transition frequency of level $|i\rangle$ and $|j\rangle$ $(i, j = 1, 2, 3, 4)$; Ω_i $(i = p, s, c)$ denotes the Rabi frequency for the corresponding transition.

Using the density-matrix approach, the time-evolution of the system is described as

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] + \Lambda\rho, \tag{2}$$

where $\Lambda\rho$ represents the irreversible decay part in the system which is a phenomenological added decay term that corresponds to the incoherent processes. The density matrix equations are given as

$$\dot{\rho}_{11} = i\Omega_p(\rho_{21} - \rho_{12}) + i\Omega_s(\rho_{31} - \rho_{13}) + \gamma_{21}\rho_{22} + \gamma_{31}\rho_{33}, \tag{3.1}$$

$$\dot{\rho}_{22} = i\Omega_p(\rho_{12} - \rho_{21}) + i\Omega_c(\rho_{42} - \rho_{24}) + \gamma_{42}\rho_{44} + \gamma_{32}\rho_{33} - \gamma_{21}\rho_{22}, \tag{3.2}$$

$$\dot{\rho}_{33} = i\Omega_s(\rho_{13} - \rho_{31}) + \gamma_{43}\rho_{44} - (\gamma_{31} + \gamma_{32})\rho_{33}, \tag{3.3}$$

$$\dot{\rho}_{12} = -(\Lambda_{21} - i\Delta_p)\rho_{12} + i\Omega_p(\rho_{22} - \rho_{11}) + i\Omega_s\rho_{32} - i\Omega_c\rho_{14}, \tag{3.4}$$

$$\dot{\rho}_{13} = -(\Lambda_{13} - i\Delta_s)\rho_{13} + i\Omega_s(\rho_{33} - \rho_{11}) + i\Omega_p\rho_{23}, \tag{3.5}$$

$$\dot{\rho}_{14} = -\left[\Lambda_{14} - i(\Delta_p + \Delta_c)\right]\rho_{14} + i\Omega_p\rho_{24} + i\Omega_s\rho_{34} - i\Omega_c\rho_{12}, \tag{3.6}$$

$$\dot{\rho}_{23} = -\left[\Lambda_{23} - i(\Delta_s - \Delta_p)\right]\rho_{23} - i\Omega_s\rho_{21} + i\Omega_c\rho_{43} + i\Omega_p\rho_{13}, \tag{3.7}$$

$$\dot{\rho}_{24} = -(\Lambda_{24} - i\Delta_c)\rho_{24} + i\Omega_p\rho_{14} + i\Omega_c(\rho_{44} - \rho_{22}), \tag{3.8}$$

$$\dot{\rho}_{43} = -\left[\Lambda_{43} - i(\Delta_p + \Delta_c - \Delta_s)\right]\rho_{43} - i\Omega_s\rho_{41} + i\Omega_c\rho_{23}, \tag{3.9}$$

along with the equations of their complex conjugates. Here the coherence damping coefficient Λ_{ij} due to spontaneous emission is given by $\Lambda_{ij} = (\gamma_i + \gamma_j)/2$, where $\gamma_i = \sum_{k=1}^{4} \gamma_{ik}$ is the decay rate of level $|i\rangle$ and γ_{ik} $(i = 1–4)$ is the spontaneous emission decay rate from state $|i\rangle$ to state $|k\rangle$. In our scheme, the EIT approximations are used. These include the atoms are initially in state $|1\rangle$ and $|3\rangle$ and the strong pump approximation $\Omega_p < \Omega_c \ll \Omega_s$.

In the following, we will discuss the electric and magnetic responses of the medium to the probe field. The induced complex electric dipole moment of the atom is given by $\vec{p}(\omega_p) = \mathrm{Tr}\{\hat{\rho}\hat{\vec{d}}\} = \vec{d}_{21}\rho_{12}$, which is related to the complex atomic polarizability tensor α_e as $\vec{p}(\omega_p) = \varepsilon_0\alpha_e(\omega_p)\vec{E}_p(\omega_p)$. Here, we choose $\vec{E}_p$ parallel to the atomic dipole $\vec{d}_{21}$ so that α_e is a scalar. Then the electric polarizability for the probe field is

$$\alpha_e = \frac{d_{21}\rho_{12}}{\varepsilon_0 E_p}. \tag{4}$$

Similarly, the magnetic response of the medium to the probe field is relative to the coherent term ρ_{43} and the magnetizability can also be a scalar expressed as

$$\alpha_m = \frac{\mu_0 c\mu_{34}\rho_{43}}{\eta E_p}, \tag{5}$$

where μ_0 is the permeability of vacuum, c is the speed of light in vacuum and η is a unitary complex number depending on the polarization of the probe field $\vec{E}_p$.