Multicolor coherence-induced negative refraction in three-level atomic system

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Multicolor manipulation of negative refraction in a three-level Λ atomic system is theoretically investigated. Based on multicolor coherence, the negative refractive index can be obtained with reduced absorption. The refractive index can also be controlled by changing the sum of the phases of the sidebands in the trichromatic driving fields. By adjusting the sum phase, the refractive index can be varied between negative and positive in two different frequency bands. Furthermore, the frequency band corresponding to the negative refractive index is widened by increasing the intensity and the frequency difference of the trichromatic field.

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The left-handed material (LHM)\textsuperscript{[3]} has recently been widely investigated because of its counterintuitive properties. In these materials, the inverse Snell law, reverse Cerenkov effect, and reverse Doppler shift can appear. With the remarkable properties of negative refraction, including amplification of evanescent waves\textsuperscript{[2,3]} and photon tunneling\textsuperscript{[4]}, LHM can be used to focus all Fourier components of a two-dimensional image as a perfect lens\textsuperscript{[5]}. LHM is not available in nature: it is artificially manufactured\textsuperscript{[6–12]} by delicately constructing spatial periodic structures\textsuperscript{[13,14]}. Recently, schemes based on quantum coherence and interference have been put forward simultaneously by Oktel et al.\textsuperscript{[15,16]} to achieve negative refraction in a three-level medium. However, in these examples, absorption reduces the resolution of a perfect lens\textsuperscript{[17]}. Numerous proposals have been put forward to reduce absorption\textsuperscript{[18–22]}. Thommen et al. proposed a four-level scheme in which an electric (magnetic) atomic transition was used as an electric (magnetic) resonator to modify the permittivity (permeability), and at the same frequency, to electromagnetically induce left-handed properties\textsuperscript{[18]}. Kastel et al. presented a five-level scheme based on electromagnetically induced chirality, which can achieve negative refractive index without absorption\textsuperscript{[20]}. However, all of the above are examples of materials interacting with monochromatic optical fields. A monochromatic field with a single frequency value exists only in ideal states. By contrast, a multicolor field, a resonant optical field with sidebands, is considered closer to reality. Multicolor coherence in the atomic system could induce many interesting phenomena\textsuperscript{[23,24]}, and manipulate the absorptive and dispersive properties\textsuperscript{[25,26]}. In this letter, we study the negative refraction based on multicolor coherence, where a three-level Λ atomic gas system is coupled with a strong trichromatic driving field and a weak monochromatic probe field. By accurately tuning the frequency difference and three Rabi frequencies of the trichromatic driving field, the negative refraction with reduced absorption can appear resulting from the quantum interference between multi-interaction paths. By considering phase influence in this system, the refractive index is found to depend on the sum of the relative phases of the sideband components. Adjusting the sum phase, the refractive index can be altered between negative and positive in two different frequency bands. In addition, the frequency band corresponding to the negative refraction can be widened by increasing the intensity and the frequency difference of the trichromatic field.

We consider a three-level Λ-type system as shown in Fig. 1\textsuperscript{[15]}, which includes an excited state and two lower states, signed by $|0\rangle$, $|1\rangle$, and $|2\rangle$, respectively. Two lower states, $|1\rangle$ and $|2\rangle$ have the same parity with $\hat{\mu}_{21} = (2)|\hat{\mu}|1\rangle = 0$, where $\hat{\mu}$ is the magnetic dipole operator. The upper state $|0\rangle$ has an opposite parity to the lower states $|1\rangle$ and $|2\rangle$ with $\hat{d}_{10} = (1)|\hat{d}|0\rangle \neq 0$ and $\hat{d}_{02} = (2)|\hat{d}|0\rangle = 0$, where $\hat{d}$ is the electric dipole operator. The $|0\rangle \rightarrow |2\rangle$ transition is coupled with a trichromatic driving field $(\vec{E}_0 + \vec{E}_1 e^{i\delta t} + \vec{E}_2 e^{-i\delta t})e^{-i\omega_{d}t} + c.c.$, and the $|0\rangle \rightarrow |1\rangle$ transition is coupled with a weak monochromatic probe field $\vec{E}_p e^{-i\omega_{p}t} + c.c.$, in which $\vec{E}_i (i = 0, 2, p)$ are the field amplitudes of each component of the driving and probe fields, $\omega_0$ is the central frequency of the driving field, $\omega_p$ is the probe frequency, and $\delta$ is the frequency difference among the three components of the driving field. $\Delta_p = \omega_0 - \omega_p$ and $\Delta_d = \omega_{d2} - \omega_0$ are the detunings of the respective fields from the corresponding transitions. $\gamma_1$, $\gamma_2$, and $\gamma_3$ are the spontaneous emission decay rates respectively corresponding to the $|0\rangle \rightarrow |1\rangle$, $|0\rangle \rightarrow |2\rangle$, and $|1\rangle \rightarrow |2\rangle$ transitions. $\Omega_i = \frac{\Delta_i \vec{E}_i}{\hbar} (i = 0, 2)$ and $\Omega_p = \frac{\Delta_p \vec{E}_p}{\hbar}$ represent Rabi frequencies related to the respective fields. In general, we set the Rabi frequencies $\Omega_0$, $\Omega_p$ to be real. Hence we take $\Omega_f =$
\[ \rho_{jk} = \sum_{n=-\infty}^{\infty} \rho_{jk}^{(n)} e^{\text{in} \delta t} \quad (j, k = 0, 1, 2). \]
driving field is adjusted to be trichromatic, the permittivity and the permeability are simultaneously negative in the area of $3.954\gamma < \Delta p < 3.990\gamma$, thereby corresponding to frequency bandwidth of $\sim 0.36\text{MHz}$ as demonstrated in Fig. 2(c). Furthermore, in this negative refraction frequency band, the imaginary part of refractive index $n_r$ related to the absorption is reduced, as indicated in the insert in Fig. 2(c). This condition is suitable for application. The interference between multi-interaction paths of trichromatic coherence makes it possible to achieve negative refraction in a wide frequency band.

Phase dependence also plays a key role in multicolor coherent effects. We turn to consider the phase influence of the negative refraction in this system. Adjusting the sum phase to be $\Phi = \pi$ with other parameters being the same as in Fig. 2(c), we plot the probe-detuning dependence of the real part of $\varepsilon_r$ (solid line), the real part of $\mu_r$ (dashed line), and the imaginary part of refractive index $n_r$ (dotted line) in Fig. 3. Comparing Fig. 3 with Fig. 2(c), we find that the negative refractive property depends strongly on the sum phase. Altering the sum phase from 0 to $\pi$, the structure of peaks about electric permittivity and magnetic permeability are changed significantly. The frequency band corresponding to both negative permittivity and negative permeability is shifted to $7.756\gamma < \Delta p < 7.848\gamma$, and widened to be $\sim 0.93\text{MHz}$, as described in the enlarged figure (inserted in Fig. 3), which is approximately three times that of Fig. 2(c). However, Fig. 3 shows that in the same negative refractive frequency band corresponding to $\Phi = 0$, the electric permittivity and magnetic permeability simultaneously become positive. Thus, refractive index can be switched between negative and positive in two different frequency bands by adjusting the sum phase$^{[30]}$, which can provide a convenient way to transform the refractive nature of the medium in practical application.

Additionally, we consider the effect of the intensity of the trichromatic field and the frequency difference ($\Omega_0$, $\Omega_1$, $\Omega_2$, $\delta$) on the properties of electric permittivity and magnetic permeability in Fig. 4. By comparing Figs. 4(a) and (b) with Fig. 2(c), we find that simultan-

![Fig. 2. Frequency dependence of the relative dielectric permittivity $\varepsilon_r$, the relative magnetic permeability $\mu_r$ and the refractive index $n_r$ of three-level atoms with $\Phi=0$, and (a) $\Omega_0 = 8\gamma$, $\Omega_1 = \Omega_2 = \delta=0$; (b) $\Omega_0=\Omega_1 = \delta = 8\gamma$, $\Omega_2=0$; (c) $\Omega_0=\Omega_1 = \Omega_2 = \delta = 8\gamma$.](Image 2)

![Fig. 3. Real parts of $\varepsilon_r$ and $\mu_r$, along with the imaginary of $\varepsilon_r$, $\mu_r$, $n_r$ versus frequency detuning $\Delta_p$ for the case of $\Phi = \pi$ and $\Omega_0 = \Omega_1 = \Omega_2 = \delta = 8\gamma$.](Image 3)
Fig. 4. Frequency dependence of the real electric permittivity $\varepsilon_r$ and magnetic permeability $\mu_r$, along with the imaginary of $n_r$ for (a) $\Omega_0 = \Omega_1 = \Omega_2 = \delta = 2\gamma$, and (b) $\Omega_0 = \Omega_1 = \Omega_2 = \delta = 4\gamma$.

taneously increasing the intensity of trichromatic field and the frequency difference $\Omega_0 = \Omega_1 = \Omega_2 = \delta$ can widen the frequency band corresponding to the negative refractive index from 0.32 to 0.34 and 0.36 MHz. The increased negative refractive frequency band has a favorable and practical use for operating.

In conclusion, we study multicolor coherence-induced negative refractive index in a three-level $\Lambda$ type atomic configuration. Based on trichromatic coherence, negative refraction with reduced absorption is achieved. The sum of the relative phases of the sideband components also plays a crucial role in the properties of electric permittivity and magnetic permeability. Negative refraction can be obtained in a different frequency band by changing the sum phase from 0 to $\pi$. The refractive index can be switched between negative and positive by controlling the sum phase in two different frequency bands. Gradually increasing the intensity of the trichromatic field and the frequency difference between the driving field components can further widen the frequency band corresponding to the negative refraction.

References