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Optics Communications
Volume 505, 15 February 2022, 127583

Limits and possibilities of refractive index in atomic systems

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https://doi.org/10.1016/j.optcom.2021.127583
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Abstract

Manipulation of the refractive index has been of growing interest lately. We consider parameters and possibilities of enhancing the absolute-value limit of the linear index in coherent atomic systems. Starting with a review of how two-level transitions – without and with added coherence effects – do not realistically allow for a significantly enhanced index at fixed atomic density, we discuss a possible way around this using wave mixing. This confirms that the only parameters, besides the medium optical depth/density, that can effectively change the value of the attainable index are the frequencies of the involved transitions.

Introduction

The values of the refractive index most commonly observed in nature are positive and on the order of 1. Finding materials with an unusual refractive index – very high, zero, or negative – has long been a subject of interest; of course, to be of practical use, it should be accompanied by low attenuation. It was proposed that quantum interference effects could be used to create an enhanced index of refraction with no attenuation in Λ-type atoms [1], [2]. However, it was later noted that at the densities required for such methods, quantum corrections such as cooperative effects must be considered [3], [4], [5], which can dramatically diminish the promise of the original proposals. For example, radiation trapping effectively decreases the effects of coherence. Moreover, a new article [6] reveals that densities that are effective for increasing the index of refraction are severely limited due to disorder effects even if the real densities are very high and nonlinear effects are disregarded.

Since then, there have been increasing efforts to modify the index of refraction of a system or to attain a particular value through the design of metamaterials [7], [8], [9] or control by external fields [10], [11], [12], [13]. Unusual values for the index have been suggested for use in various applications; for example, a negative index could be used to implement cloaking [14], [15], [16], [17] or to create a “perfect lens” with infinite resolution [18], [19], while a medium with a large index decreases the wavelength of light traveling through it, which could be useful in optical imaging [20].

Let us briefly clarify what we mean by “high” or “enhanced” index of refraction in the rest of this article: the real part of the atomic electric susceptibility – and thus the index of refraction – are strongly frequency-dependent, especially close to resonance. Thus, the first necessity of finding a very high positive or negative susceptibility is to ensure that the maxima and minima of the susceptibility spectrum are high. This is what is studied in this article. Selecting optimal detuning from resonance and making sure that the respective attenuation value is close to zero would be the second step. This has been treated, however, in depth in the articles cited above.

In theoretical approaches focusing on the use of external fields to control the optical response of a system, parameters can simply be changed in order to modify the index of refraction. However, there are limits to what values of index are possible, considering only the linear part of dispersion, which we systematically study for three increasingly complicated cases.

We start this article by briefly reviewing that changing the (effective) density of the atomic medium seems to be the only way to change the magnitude of the index apart from its frequency. This is most evident in the well known system of a single transition coupled to an external field. We also look at whether coherence effects introduced via an additional transition offer any way around the limitation imposed by density. This is reviewed in the simplest cases, the two standard cases of ensembles of two- and three-level atoms, in the context of enhanced index to illustrate how density is both the only way that the index may be enhanced, and a major limitation.

The main part of the article is devoted to showing how wave mixing, not usually considered in the context of enhanced index, can be used to change the effective frequency and thus the refractive index without changing the density of the gas. With at least four levels, wave mixing can occur, so we include a fourth level to look at this in the most straightforward case. Then, the index depends directly on the frequencies of two atomic transitions as well as the frequencies of the fields coupled to them. The choice of frequencies via choice of level structure gives more freedom in attaining some desired index, which may potentially be enhanced. This offers another avenue besides the density for changing the index. This is the main result of this paper, which suggests that there may still be some possibilities in attaining an enhanced linear index without higher order effects.

The index of refraction of a medium is defined by $n=\sqrt{\varepsilon\mu}$, with relative permittivity $\varepsilon=1+\chi_e$ and relative permeability $\mu=1+\chi_m$ [21], [22], [23]. The electric susceptibility χ_e and magnetic susceptibility χ_m can be complex, resulting in a complex index n, for which the real part is the “conventional” refractive index which represents the amount of refraction, while the imaginary part represents the amount of attenuation or gain. In this paper we assume that $\mu\approx 1$, since magnetic coupling is typically weaker by a factor of $\alpha^2\approx 1/137^2$ for transitions in the visible spectrum, so that $n\approx\sqrt{1+\chi_e}$ (henceforth we drop the subscript “e”).

Although the real part of n depends on a complex χ, in practice, ultimately one would want minimal attenuation, where the imaginary part of χ is negligible. We are here interested only in the best-case scenarios for enhancing the real part of n, so we will focus on the real part of χ in Section 2.

In what follows, we suppose that electric fields of the form $\mathbf{E}(z,t)=\frac{1}{2}\hat{\varepsilon}\mathscr{E}(z)\,e^{i(kz-\nu t)}+\text{c.c.}$, where c.c. denotes the complex conjugate, each couple to one atomic transition with dipole operator $\hat{\mathbf{d}}$ in an ensemble of atoms with number density N, which do not interact with each other. We assume that the independent scattering approximation (ISA) holds and consider only the linear part of dispersion. In this case, the polarization due to such an electric field has the form $\mathbf{P}(z,t)=\frac{1}{2}\hat{\varepsilon}\mathscr{P}(z)\,e^{i(kz-\nu t)}+\text{c.c.}$, and $\mathscr{P}(z)=\varepsilon_0\chi\mathscr{E}(z)$ if the polarization depends on only one field. The susceptibility can be calculated by equating this with $\mathscr{P}(z)=2Nd^*\rho_{ij}$, since $\mathbf{P}(z,t)=N\left\langle\hat{\mathbf{d}}\right\rangle(z,t)$, and solving the optical Bloch equations in the steady state for the relevant density matrix element $\rho_{ij}=\langle i|\rho|j\rangle$, which represents the coherence between levels $|i\rangle$ and $|j\rangle$ [21], [22], [23].

In Section 2, we review the simplest case of an ensemble of atoms with a single transition in the context of enhanced index to point out how density is a limitation. Then we show how coherence effects introduced via a third level do not improve the basic result. In Section 3, wave mixing introduced via a fourth level is considered as a way around the density obstacle.

Section snippets

Basic case — two levels

We start with the most basic result which comes from a two-level atom driven by an external field $\mathbf{E}$ (shown in Fig. 1a) in order to find baseline values for χ and therefore n to which other values can be compared, while considering the natural limitations in attaining them.

The standard result for the susceptibility is [21], [24] $\chi=N\frac{3\lambda^3\Gamma}{4\pi^2}\frac{i\Gamma-2\Delta}{\Gamma^2+4\Delta^2+2|\Omega|^2}$,where λ is the wavelength of the incident light, Γ is the spontaneous decay rate, Ω is the Rabi frequency, and the detuning Δ is typically...

Manipulating refraction using wave mixing

In this section, wave mixing is considered in the context of enhancing the index. In the simplest case, wave mixing occurs with four levels, so we move to the system shown in Fig. 2. So far, the atomic and field properties seen in Section 2 have not been useful in enhancing the index, except for the density, which has the practical limitations noted above. Field frequencies have appeared in detuning parameters, which cannot significantly enhance the index, but the frequencies may be more...

Conclusion

The only parameter that allows to change the amplitude over which the index of refraction can change in a given transition is, in principle, the density of the atomic gas. This is true for atomic gases and any other system. This, however, places severe limits on (three-dimensional, homogeneous) atomic gases due to disorder and dipole–dipole interactions [5], [6], the total achievable index of refraction in an atomic gas seems limited to a small fraction of unity. Coherence effects, such as can...

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper....

Acknowledgments

We would like to acknowledge useful discussions with Marina Litinskaya and funding by the National Science Foundation, United States via grants PHY-1912607 and PHY-1607637....

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