Kerim Guseynov, group 113M

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Maximum Refractive Index of an Atomic Medium

Sections I, II, III, IV, and VI (since Sec. V is very technical and, as the paper says, "casual readers can consider skipping" it.)

The text is about 39k symbols.

Vocabulary

reconcile	согласовать	page 1, abstract
dilute gas	разреженный газ	page 1, abstract
implication	последствие	page 1, par. 1 (left)
readily	охотно	page 1, par. 1 (right)
granularity	гранулярность, дискретность	page 2, last par. (right)
exquisitely	изящно	page 2, last par. (right)
retain	сохранять	page 2, Fig. 1 caption
dyadic	состоящий из двух частей	page 3, par. 3 (left)
foster	стимулировать	page 3, par. 2 (right)
encode	представлять	page 3, par. 3 (left)
attenuation	затухание	page 4, par. 3 (left)
decompose	раскладывать	page 4, par. 3 (left)
speckles	пятна	page 4, last par. (left)
prescribe	описывать, определять	page 5, par. 2 (left)
inset	вставка	page 5, par. 2 (right)
necessitate	требовать	page 5, par. 3 (right)
pictorial(ly)	наглядный	page 6, last par. (right)
bulk	большой	page 8, par. 3 (left)

Questions

1. What is the relation between the optical response and scattering cross-section of a single atom and its size?
2. How does the refractive index of a smooth medium behave when its density increases?
3. How can we take into account the local electric field in the smooth medium approximation?
4. Does this modification change the behavior of the refractive index at high densities?
5. What can we do to avoid the indefinite growth of the refractive index at the resonant frequency?

6. Is the optical response of two interacting identical atoms equal to the sum their individual responses?
7. What causes the change in the optical response?
8. How can we use this information to simplify calculations for an atomic medium?
9. How can we verify does the simplification work how exact is it?
10. What interaction remains between the atoms after the iterative simplification procedure?
11. How does the refractive index of an ensemble of identical atoms behave with density increase?
12. What is the ultimate reason for the absence of large refractive indexes of transparent media?

Overview

Transparent materials let the visible light come through differently. Some of their properties include opacity, reflectively, dispersion law, and refractive index. Most of them are related to the optical response of the material, which is its low-level characteristic resulting from the atomic structure. While the optical response of a single atom is easy to calculate, any attempts to derive the refractive index of an atomic medium have led to unrealistic results. This paper presents a completely new approach to calculating the optical response and the refractive index of an atomic medium and throws light on the mystery of why refractive indexes are of the order of unity.

To understand the problem, we should first follow the conventional approach and find its weak point. To avoid very complex and time-consuming calculations, atoms are approximated as semi-classical two-level systems. This is fairly precise and incorporates the most important characteristics of the atom. The reaction of a single atom is well known, so our work is to apply it somehow to a system of many atoms. The conventional way is to forget about the atomic, discrete, granular structure of the matter, introduce its collective characteristics such as density, polarizability, etc., and operate in terms of a continuous medium. At this point you may have already gotten the largest weakness of the approach, but we should still reach its result. One distinction of a continuous medium is that the electric field traversing it is always and constantly influenced by it, thus making it impossible to experience multiple scattering and interference. The result of that is that the refractive index in the leading order is just the index of a single atom scaled by a factor proportional to the square root of the number of atoms divided by the volume. So at the resonance, the refractive index just grows indefinitely with density, what is obviously not observed in real life.

The approach suggested in this paper, however, does not forget about the atomic nature of any medium. It is implemented for an ensemble of perfectly identical atoms, each of which has the same resonant frequency, but remains a distinct and point-like particle. The main reason why theoretical studies have always considered the smooth medium approximation is that it dramatically simplifies all formulas and even lets one achieve the result analytically. To keep the atomic structure, one has to calculate large sums over all atoms including the values of the electric field at each atom's position. To make matters worse, in the correct, quantum approach, one has to take into account the mixing of atomic states due to the Pauli principle, which adds an N x N determinant to every equation, making it exponentially more time-consuming for larger systems. And for N even about $10\hat{3}$, it takes an enormous amount of time and work. The fact that in the system considered atoms have only two energy levels makes things easier, but not enough for a complete large-scale study. However, an elegant way out is also suggested by the authors. I will explain it in a minute, but first, you should understand how two atoms behave under a incident plain electromagnetic wave.

If there are two perfectly identical atoms with the resonant frequency omega zero that interact with each other, their optical response is not a Lorentzian centered at omega zero with the height twice as large as for a single atom. Instead, the response is two substantially distant Lorentzian peaks of normal height centered at shifted frequencies of omega zero plus-minus delta omega, where delta omega depends on the distance between the atoms and their interaction strength. Based on the optical response, which defines the reaction of the system to visible light, two identical atoms behave almost like two atoms whose resonant frequencies are slightly shifted from the original atoms' frequency.

This way, one can expect that a set of identical atoms can be approximated by a set of different atoms with effective resonant frequencies depending on spatial parameters of the original system. And indeed, as the authors compare the simplification with a straightforward calculation of the aforementioned large formulas for smaller densities, this test shows good agreement between them. And it also shows that the refractive index n of an atomic medium approaches a limit as the density increases. For larger densities, only the simplified technique is applicable, but it confirms that the index saturates and reaches a value of about 1.7, which is of the order of unity.

The result of the study explains the universal rule that the refractive index is always of the order of unity. It is because of the granularity and atomic structure of everything in the Universe.

So, thank you for your attention. I hope you enjoyed my talk and will probably enjoy looking through the article. Goodbye.