Cherenkov radiation in negative index media under EIT conditions

David Ziemkiewicz[1,*] and S. Zielińska-Raczyńska[1]
[1]Institute of Mathematics and Physics, UTP University of Science and Technology, Al. Kaliskiego 7, 85-789 Bydgoszcz, Poland.

Nowadays, there is considerable interest in creating negative refraction index, left handed media (LHM) [1] using atomic vapor [2]. In contrast to the more commonly considered metamaterials, such systems offer many promising characteristics - isotropy, loss compensation by gain and operation at optical wavelengths. One of the means of obtaining negative refractive index with low absorption is application of electromagnetically induced transparency (EIT) [3]. The most remarkable properties of such media are the optical control of its dispersion and possibility of obtaining extremely low group velocity inside the transparency window, leading to the so-called slow light. Due to EIT the conditions for signal propagation in the medium change drastically, i. e. initially opaque medium becomes transparent, and have a significant impact on dynamic phenomena such as Doppler effect and Cherenkov radiation.

An example of the dispersion relation for the medium under EIT condition is shown on the Fig. 1. In the frequency range around $\omega = 0.1$, the refraction index is negative so in this region the medium is left-handed while due to $\frac{dn(\omega)}{d\omega} > 0$ the group velocity of the propagating signal decreases. It has been shown in [4] that the material

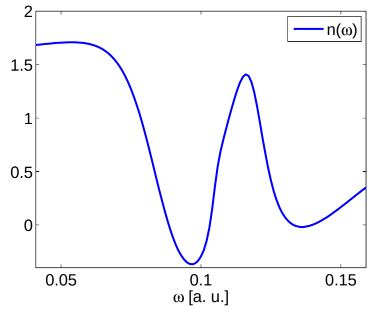

FIG. 1. Real part of refraction index in EIT medium.

dispersion plays an important role in the mechanism of the Doppler shift of frequency for the source moving inside the medium, leading to the so-called complex Doppler effect where monochromatic source generates wave modes of multiple frequencies. For the case of a source having frequency ω_0 and moving with velocity V, the shifted frequency ω can be obtained from the relation

$$\omega_0 = \gamma(\omega - \vec{k}\cdot\vec{V}), \tag{1}$$

where $\gamma = \frac{1}{\sqrt{1-V^2/c^2}}$. For waves emitted in the direction of motion, for any given values of ω_0 and V, the above relation can be solved numerically and the graphical solution is shown on the Fig. 2. One can see that the source is expected to generate wave modes of three distinct frequencies, and one of them is located inside the transparency window, in the region where the medium is left-handed. Therefore, the Doppler effect is expected to be reversed [1] and the small value of the group velocity might lead to a Cherenkov-like radiation pattern where the emitted field is present only behind the source, even at a relatively low source velocity. Moreover, the Cherenkov radiation caused by a moving, charged particle is also expected to be reversed in negative index media and significantly influenced by the material dispersion. These properties of left-handed media might be

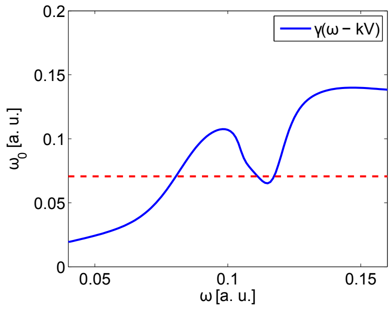

FIG. 2. Graphical solution of the Doppler shift equation for $V = 0.3c$ and $\omega_0 = 0.07$.

advantageous in particle detectors. The unique dispersion relation of the material and possibility of its optical control provide a new layer of flexibility in the design of these devices. We will study the Doppler effect and Cherenkov radiation under EIT conditions, investigating the role of a very small or negative group velocity and time dependent medium properties using the finite difference time domain (FDTD) algorithm, which can be extended to be applicable to the left-handed media and is well suited for simulation of phenomena involving moving radiation source [4].

* david.ziemkiewicz@utp.edu.pl

[1] V. G. Veselago, *Sov. Phys. Usp.* **10**, 509-514 (1968).
[2] Q. Thommen, and P. Mandel, *Phys. Rev. Lett.* **96**, 053601 (2006).
[3] M. Ö. Oktel and Ö. E. Müstecaphoğlu, *Phys. Rev. A* **70**, 053806 (2004).
[4] D. Ziemkiewicz and S. Zielińska-Raczyńska, *J. Opt. Soc. Am. B* **32**, 3 (2015).