Optik 127 (2016) 6682–6687

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

On the refractive index and photon mass

A.I. Arbab*

Department of Physics, College of Science, Qassim University, P.O. Box 6644, 51452 Buraidah, Saudi Arabia

ARTICLE INFO

Article history:
Received 15 February 2016
Accepted 13 April 2016

PACS:
41.20.Jb
78.20.Ci
42.25.Bs

Keywords:
Refractive index
Massive photon
Longitudinal wave

ABSTRACT

A new theoretical law for the refractive index is proposed. The law provides a limit to the photon mass inside optical materials. Experimental data reveal that the rest-mass energy of the photon inside a semiconductor or an insulator is found to be a few eV ($m_0 \sim 10^{-6}\, m_e$). This energy could be related to the band gap energy of the material. The electric (optical) conductivity of the material is found to be related to the photon mass. The photon kinetic energy inside the material, with a refractive index n, and rest-mass m_0c^2 energy is, $E_K = m_0c^2\left(\frac{n-\sqrt{n^2-1}}{\sqrt{n^2-1}}\right)$. The skin depth inside the medium is $\delta_+ = (\hbar\sqrt{\varepsilon\mu}/m_0)$ at very high frequency, and $\delta_- = (\sqrt{2}\,\hbar/m_0c)$ at very low frequency.

1. Introduction

The refractive index is a quantity that tells how a material deflects light when passes into. It is defined as the ratio between the velocity of light in vacuum to the phase velocity (v_p) of light in a medium, *viz.*, $n = c/v_p$. When light enters a medium its wavelength (λ) changes. The refractive index of materials varies with the wavelength. Recall that when white light is incident on a prism the refracted light has several colors. That means each color (wavelength) has a different refractive index, and hence refracted differently. There are two scenarios defining the wavelength in the medium by $\lambda' = n\lambda$, which is due to Abraham, and the second one defining $\lambda' = \lambda/n$, is due to Minkowski [1,2]. It is recently shown that the two scenarios are correct where the former is related to the kinetic momentum, while the latter is related to canonical momentum of light in the medium [3]. The refractive index for visible light is generally greater than unity. Transparent media for visible light have refractive indices in the range between 1 and 3. It is generally understood that the refractive index cannot be lower than 1. However, in the X-ray regime the refractive indices are lower than but very close to unity. This may appear problematic with the theory of special relativity. For an electron transiting between the maximum of the valence band and the minimum of the conduction band, or vice versa, the conservation of momentum, however, cannot be fulfilled with the absorption or emission of a photon alone in an indirect semiconductor that because the magnitude of the momentum of a photon is several orders of magnitude smaller than that of an electron in a semiconductor. This conservation can be reconciled if the emitted phon had mass. We all understand that the photon behaves like a particle in the photoelectric and Compton effects, but no mass is introduced to it.

Thus, the particle nature of the photon is only apparent if the photon exists inside a medium and not in vacuum (free space) where it is massless. The rest-mass of the photon depends on the properties of the medium (*e.g.*, refractive index) in which it exists. It is thus influenced by gravitational interactions while traveling inside the medium. Therefore, if we do

* Tel.: +966 550790379.

http://dx.doi.org/10.1016/j.ijleo.2016.04.040
0030-4026/

not live in a complete vacuum, photons would contribute much to the total mass of the universe. With this minute mass, massive photons could resolve the dark matter and dark energy problems inflicting our present theories of gravitation.

In 1931 Yakov Frenkel proposed the idea of an exciton that is a bound state of an electron and a hole that are attracted to each other by the electrostatic Coulomb force [4]. It is an electrically neutral quasiparticle that exists in insulators, semiconductors and in some liquids. It is considered as an elementary excitation that can transport energy but not electric charge. It is formed whenever a photon is absorbed by a semiconductor or an insulator. It thus excites an electron from the valence band into the conduction band. It travels in a particle-like manner through the lattice.

Thus, the idea of massive photon could replace that of an exciton where the binding energy of the exciton is equal to the rest-mass of the photon. The dynamics of the massive photon is shown in [5] and the references there in. One can define an effective classical radius of massive photon as $r_0 = (ke^2/m_0c^2)$, where k is the Coulomb constant, which for a typical photon rest-mass energy is of the order of some few nanometers.

We derive in this paper a dispersion law relating the refractive index to the wavelength of the incident light and the rest-mass energy of the photon. This law relies on the hypothesis that the photon has a non-zero effective mass inside the medium. The band gap of the material can be related to the photon rest-mass. Other optical properties resulting from this law are investigated. We make comparison with the predicted values and the experimental data. We also outlined some competing laws (models) relating the refractive index with the band gap energy.

2. Cauchy and Sellmeier equations

Optical materials can be properly designed by knowing its refractive index and the parameters related to it. Cauchy had introduced an empirical formula for the refraction index of a medium, and its relation to wavelength of the incident light, as [6]

$$n = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} + \cdots, \tag{1}$$

where A, B and C are constants to be determined from the experiment. This formula works quite well for visible light. More generally, for a transparent optical material a better relation applicable only to the transparent wavelength region, where the absorption is negligible, is described by Sellmeier equation [6,7]

$$n^2 = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_1\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}, \tag{2}$$

where B_1, C_1, B_2, C_2, B_3, C_3 are constants. The refractive index of a material changes also with temperature, pressure, etc. Note that Sellmeier data are very useful for evaluating the chromatic dispersion of a material. The Sellmeier model is an empirical model, which is basically used to describe the dependence of the refractive index in the transparent region. The model assumes κ to be zero so that [6,7]

$$n^2 = A + \frac{A\lambda^2}{\lambda^2 - B}, \tag{3}$$

where A and B are constants.

The wavelength dependence of the refractive index in optical wavelengths for various materials is often given by Feynman as [8]

$$n = 1 + \frac{Ne^2}{2\varepsilon_0 m_e(\omega_0^2 - \omega^2)}, \tag{4}$$

where ω_0 is a resonant frequency of an electron bound in an atom, and N is the charge number density. Light is absorbed by the medium if its frequency is resonant with the transition frequencies of the atoms in the medium. If the light with intensity I_0 incident on the sample with thickness d, the intensity that is transmitted is expressed by the Lambert–Beer–Bouguer Law as [9]

$$\alpha = \frac{1}{d}\ln\left(\frac{1}{T}\right), \tag{5}$$

where T is the transmittance that is related to the reflectance by the relation $T = 1 - R$. However, the transmission coefficient is found experimentally by the relation [10–12]

$$\alpha = \frac{1}{d}\ln\left(\frac{(1-R)^2}{T}\right). \tag{6}$$

The dielectric constant of the material can be written as

$$\varepsilon = \varepsilon_1 \pm i\varepsilon_2 = (n \pm i\kappa)^2, \quad \varepsilon_1 = n^2 - \kappa^2, \quad \varepsilon_2 = 2n\kappa, \tag{7}$$