MICROSCOPIC ANALYSIS FOR NORMAL DISPERSION BASED ON QUANTUM PHOTONICS TREATMENT

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Abstract

In this paper we will introduce a physical model to describe normal dispersion based on Quantum Photonic treatment. We have successfully estimated analytically the time retardation during each photon electron interaction through the transparent media. To do this, we have selected a new organic aromatic material called N-(4-Nitrophenyl)-(L)-prolinol (NPP) which has shown high figure of merit for optical properties. The main advantage of this organic compound is wide frequency transparency at the wavelengths between 0.5μm to 1.3μm which is suitable for wide optical bandwidth transmission systems. The result of simulation in comparison with experimental measurements in macroscopic scales follows successfully. In addition this model can also explain the phenomena in microscopic (submicron) scales, where the macroscopic Electromagnetic theory fails.

Keywords

Photon–electron interaction, Normal Dispersion, Refractive index, Microscopic model, Quantum theory, Organic material: NPP

1. Introduction

New technologies usually bring with them some modifications in the existing approaches to solve the problems which even have well established and widely accepted solutions. However, depending on disruptiveness of the new technology, these modifications could be so radical that the modified approach seems to be completely a new one. Nanoelectronics and in a wider sense Nano technology, are such an emerging and disruptive technologies that oblige to develop new approaches to solve the formerly solved problems but this time in submicron scales [1]. In today photonics and optoelectronics devices, it becomes necessary for optical elements to shrink into submicron scales too, where the macroscopic physical laws do not hold any more or at least must be modified [2,3,4]. One of these macroscopic phenomena is "Dispersion", which concerns the speed of light and its variations with wavelength in dielectric media. Many successful attempts to present the curve of dispersion were made and demonstrated by Cauchy, Sellmeier and Helmholtz equations so far [5].This phenomenon has also been formulated by the Electromagnetic theory of light [6,7]. According to the Maxwell's classical theory, the wave propagation through source free media could be described using wave equation [4,8,9]:

$$\nabla^2 E = \mu\varepsilon \frac{\partial^2}{\partial t^2} E - \mu \frac{\partial^2}{\partial t^2} P_{NL} \qquad (1)$$

For a given homogeneous and isotropic material ε and μ are assumed to be constants. The macroscopic constitutive parameters permittivity (ε) and permeability (μ), loose their validities as device dimensions shrink from micrometers to nanometers and will not be constant values any more. In fact, in submicron scales these parameters fluctuate both in time and space [10, 11].
In what follows, we present a new approach based on quantum theory which takes into account the variations of "n" versus time and space in the media and finally we compare the results with those of Electromagnetic theory

and experimental measurements reported for a nominated aromatic organic material called NPP[12].

So far, this approach has been utilized to study other phenomena such as Refraction [13], Polarization [14], Second Harmonic Generation [15] and Electro_Optic effects in submicron scales [10,11]. In our treatment we consider light as a stream of billions of photons striking the atomic or molecular structure of the media. The photons are assumed to have quantized energies according to the Planck's law:

$$E = \eta\omega \quad (2)$$

And momentum:

$$P = \eta k \quad (3)$$

In section (2) we'll try to estimate photon retardation 'τ' according to Planck's formula, when it travels inside the dense media. In section (3) we'll show the dependency of τ to incident light wavelength 'λ'. We'll also have a result and conclusion sections.

2. Estimation of Index of refraction in terms of photon retardation

The total time which takes for a photon to travel through a transparent media may be assumed as the sum of the time that the photon spends to pass through the intermolecular (inter atomic) empty space and photon-molecule (atom) interactions.

Assuming τ_{di} as the retardation time of the photon with the i'th atomic layer and also considering the velocity of the photon in the intermolecular (inter atomic) space, as speed of light in free space, the whole traveling time can be obtained as follows[13]:

$$T = \frac{L}{C_0} + \sum_{i=1}^{N} \tau_{di} \quad (4)$$

Where L is the media length, C0 is the velocity of light in free space and N is the numbers of interactions. Equivalently, the velocity of light in the media (c) is:

$$c = \frac{c_0}{1 + \frac{c_0}{L}\sum_{i=1}^{N} \tau_{di}} \quad (5)$$

The index of refraction is the ratio of C_0 to the average velocity of the photons in the media for large values of N, so:

$$n = \frac{c_0}{c} = 1 + \frac{c_0}{L}\sum_{i=1}^{N} \tau_{di} \quad (6)$$

If we consider "τ_d" as the mean retardation time per interaction and "d" as the mean free path between two successive interactions, we have:

$$n = 1 + \frac{c_0}{d}\tau_d \quad (7)$$

Where: $\tau_d = \frac{\sum_{i=1}^{N} \tau_{di}}{N}$, $d = \frac{L}{N}$

During the interaction, at first the photon annihilates and gives its energy to the electron in the lowest energy level and perturbs it.

Since the energy of the annihilated photon is not sufficient to transfer the electron to a higher allowed energy state, the perturbed electron returns to its initial orbit after a transient time, which we call (τ_p) ultimately the photon recreate.

Therefore the retardation time (τ_d) may be considered as the sum of photon annihilation time (τ_a), electron perturbation time (τ_p) and photon recreation time (τ_r).

$$\tau_d = \tau_a + \tau_p + \tau_r \quad (8)$$

Generally these quantities can be considered as a function of wavelength but, for simplicity as a first order approximation, we consider τ_a, τ_r as constants.
This assumption is fairly reasonable as we justify later when we compare the results with experimental data in section (IV).

3. Calculation of τ_p as a function of wavelength (λ)

To calculate (τ_p) first of all we use Bohr atomic model: an electron, traveling in a circular path with radius r_0 and tangential velocity V_0 around an effective electric charge (ze) located in the center, so:

$$\frac{ze^2}{4\pi\varepsilon_0 r_0^2} = \frac{mV_0^2}{r_0} \quad (9)$$

Where (m) and (e), are the electron mass and charge respectively. After photon annihilation, the velocity of the electron can be decomposed to a radial component (V_R) and a tangential component (V_θ).

When photon annihilates, its entire energy is transferred to the system, so a fraction of it ($\alpha\eta\omega$), causes the bounded electron to accelerates radially.
According to energy conservation law, at every point in the transient trajectory of electron at a distance r from the center we have (see also Fig 1):

$$\frac{1}{2}m[V_R^2(r) + V_\theta^2(r)] - \frac{KZe^2}{r} = E_P + \frac{1}{2}mV_0^2 - \frac{KZe^2}{r_0} \quad (10)$$

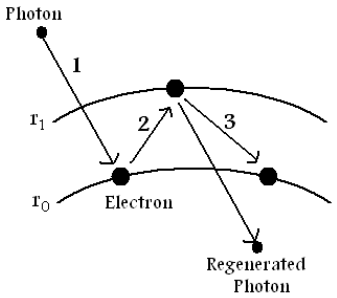

Fig 1: Interaction of photon and electron in transparent media

Where ω is the frequency of the photon and α is the photon-electron energy coupling factor.
The radial velocity gradually decreases as r increases, thus at a maximum radius "r_f", V_R becomes zero:

$$r_f = \frac{r_0}{1-\sqrt{\frac{\omega}{\omega_0}}} \quad (11)$$

Where ω_0 is defined as:

$$\omega_0 \equiv \frac{mV_0^2}{2\alpha\eta} \qquad (12)$$

From angular momentum conservation (neglecting photon's angular momentum in visible band):

$$V_\theta(r) = \frac{r_0 V_0}{r} \qquad (13)$$

Combining (9) and (13) we obtain:

$$V_R(r) = \sqrt{(\frac{\omega}{\omega_0})^2 - (1-\frac{r}{r_0})^2} \qquad (14)$$

So, the electron perturbation time can be calculated as:

$$\tau_d = \int_{r_0}^{r_f} \frac{dr}{V_R(r)} = 2\tau_0 \left[\frac{\sqrt{\frac{\omega}{\omega_0}}}{1-\frac{\omega}{\omega_0}} + \frac{2\tan^{-1}\left(2\sqrt{\frac{\omega}{\omega_0}}\right)}{\left(1-\frac{\omega}{\omega_0}\right)^{3/2}} \right] \qquad (15)$$

Where: $\tau_0 \equiv \frac{r_0}{V_0}$

Therefore, from (8) and (15) we have:

$$\tau_d = \tau_{ar} + \tau_p \qquad (16)$$

Where $\tau_{ar} \equiv \tau_a + \tau_r$. Now we have obtained all parameters in (7), so:

$$n = 1 + \frac{c_0}{d}\left(\tau_{ar} + \tau_p\right) \qquad (17)$$

4. Comparison of the result with the electromagnetic dispersion formula

The electromagnetic relation for dispersion is:

$$n(\lambda) = \left(1 + \frac{S_0\lambda_0^2}{1-\left(\frac{\lambda_0}{\lambda}\right)^2} \right)^{1/2} \qquad (18)$$

Where S_0 and λ_0, are two modeling parameters [12]. In fig.2 and fig.3, we have compared the results of our formula (17) and electromagnetic formula for dispersion with experimental data for N-(4-Nitropheny)-2-prolinol (NPP) which is an aromatic organic material [12].

It is obvious from the figures the proposed relation (15) shows less error than electromagnetic formula.

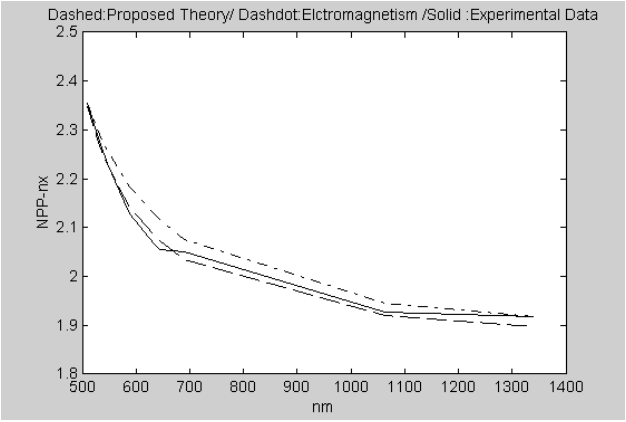

Fig 2: Experimental data, electromagnetic dispersion formula (Eq.15) and Quantum Photonics (Eq.14) for X-polarized light, ω_0=6.18e+15Hz, Z=5

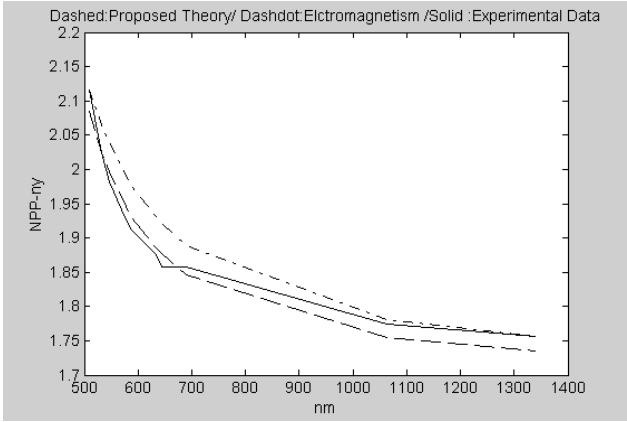

Fig 3: Experimental data, electromagnetic dispersion formula (Eq.15) and Quantum Photonics (Eq.14) for Y-polarized light, ω_0=6290THz, Z=5

5. Conclusion

In this paper we have presented a microscopic physical model for dispersion of light in submicron scales based on quantum photonics approach. We have considered that in the interaction of photon with molecular/atomic structure, first it annihilates and after a transient time, called perturbation time, it recreates. We assumed annihilation and recreation times independent of wavelength for simplicity for a first order approximation. Also, perturbation time calculated in terms of wavelength in section III.

Finally in section IV we compared the result of our formula with electromagnetic results and experimental data for NPP. Our treatment shows error less than %1 in the range of transparency of NPP.

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