Analysis and Design of an Organic High Speed Digital Electro-Optic Switch

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Abstract

We have analyzed and designed an organic high speed digital optical switch (DOS) based on transverse electro-optic effect. In analysis section, we proposed a quantum photonic model (QPM) to explain linear electro-optic (EO) effect. This model interpret this effect by photon-electron interaction in attosecond regime. We simulate applied electric field on molecule and crystal by Monte-Carlo method in time domain. We show how a waveguide response to an optical signal with different wavelengths when a transverse electric field applied to the waveguide. In design section, we configure conceptually a 2 × 2 EO switch with full adiabatic coupler. In this DOS, we use a rib waveguides that its core has been constructed from NPP crystal. This switch is smaller at least to one-half of similar DOS in dimensions.

Keywords: Quantum-photonic model(QPM), π-electron system, photon-electron interaction, attosecond regime, electro-optic (EO) effect, digital optical switch (DOS), 2 × 2 organic EO switch, NPP crystal.

1 Introduction

High-speed and high-performance optical switches are vital for optical communication networks and optical signal-processing systems. Among these, optical switches based on the electro-optic(EO) effect are promising for applications that require high-speed low-loss switching such as: optical burst switching, optical packet switching or EO beam deflector switching [1]-[15]. MachZehnder interferometer (MZI) switches and directional coupler(DC) switches have been under intensive investigation for a long time, but they both have very limited fabrication tolerance. Furthermore, bias control networks and precise switching voltages are needed in MZI switches and DC switches to achieve high performance [1, 14]. Electro-optic polymers are particularly interesting for new device design and high-speed operation [1]-[7]. Organic optical materials like MNA, NPP, MAP have a high figure of merit in optical properties in comparison with inorganic optical materials such as BBO, LiNbO3, [17]. 2-methyl-4-nitroaniline (MNA) and N-(4-nitrophenyl)-L-prolinol (NPP) have the highest figure of merit between organic nonlinear optical materials [18]. Thus they are used for electro-optic and nonlinear optic applications[17]-[31]. Because of the large electro-optic coefficient of organic material, a certain amount of refractive index (RI) change can be realized with lower driving voltage than in other EO materials(1.5V/µm for NPP,[19]). Since there is better optical/RF velocity matching inside the EO organic, high-speed switching can be achieved eas-

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ily. Digital optical switches (DOSs) are based on adiabatic propagation or modal evolution effect [8]. These switches are wavelength-polarization insensitivity and electronics for control of these devices are simple. These switches can be applicable in optical network of phase array radar systems. Their structure of waveguides can be chosen the buried-type waveguide or rib-type (ridge-type) waveguide. In this paper we analyze and design an organic DOS that is based on EO phenomenon. Our favorite organic molecule is NPP. In analysis, we use QPM, to explain linear optical phenomena in molecular scales. We show that the phase retardation of input light with different wavelengths is distinctive, when it travels through the waveguide. In design we design a $2 \times 2$ DOS with adiabatic couplers. The main advantages of this switch are wide optical bandwidth, low power consumption and high speed data transmission.

2 Analysis

Some approaches are used to analyze and design optical switches in micrometer and nanometer sizes by quantum mechanics (QM) [32]. In this paper an EO switch has been analyzed using QPM. This model gives us a constitutive vision about phenomena and real materials [33]-[36]. This approach is based on four elements: 1-Quasi-classic principle for justification of optical phenomenon in molecular scales, 2-Knowledge of crystal network and its space shape, 3-Short range intramolecular and intermolecular forces, 4- Monte-Carlo time domain simulation. In this model we suppose a laser beam is a flow of photons while passing through single crystal film, interacts with delocalization $\pi$-electron system of organic molecule and delays the photon in every layer [36]. By precise calculation of these retardation in every layer, we obtain RI in specific wavelength and explain EO effect too. After one, we apply an external electric field to crystal to change its RI a little to switch specific wavelength to identified channel.

2.1 Crystal and Molecular Structure of our Favorite Organic Compound

NPP ($C_{11}H_{14}N_2O_3$) crystallizes in the solid state in an acentric monoclinic (with space group $P2_1$) structure and their parameters are: $a=5.261\text{Å}, b=14.908\text{Å}, c=7.185\text{Å}, \beta=105.18^\circ$ and in the wavelength range of 0.5 to 2μm is transparent. The most interesting property of NPP crystal is the proximity of the mean plane of molecule with the crystallographic plane (101); the angle between both of these planes being $11^\circ$. Nitro group of one molecule in downward connects to Prolinol group in upper by hydrogen bonding. The angle between b orientation of crystal and N(1)-N(2) axis (charge-transfer axis) is equal to $58.6^\circ$ [17]. Fig.1 shows the molecule and crystal packing of the NPP. For accurate and valid simulation, these properties and angles have to be exerted. For benzene molecule, benzene ring is a circle (see fig.2): In NPP molecule, nitro group acts as an acceptor and the other main groups on the other side of benzene ring acts as a week donor (see Fig.1). Fig.3 demonstrates the bond lengths and angles of the NPP molecule. As we see in this figure the bond lengths in benzene ring are not same. In our simulation, for similarity we
consider an ellipse correspond to circle for electron cloud. We obtained $\varepsilon = 0.26$ for the ellipse of NPP from simulation.

2.2 Our Model for Electro-Optic Effect

Assume that single crystal film lies in x-y plane and light propagation is in the z direction; therefore in the presence of an electric field the equation of index ellipsoid by assuming crystal symmetry will become:

$$[(\frac{1}{n^2}_x + r_{12}E_y)x^2 + (\frac{1}{n^2}_y + r_{22}E_y)y^2 + 2r_{61}E_xxy = 1]$$

(1)

that $E_x$ and $E_y$ are transverse electric field components, [19]. With appropriate rotational transformation, these relations can been simplified. In NPP, $r_{12}$ and $r_{22}$ are large coefficients. Therefore $n_x$ and $n_y$ simplified to $n_x - (1/2)n^3_3 r_{12}E_y$ and $n_y - (1/2)n^3_3 r_{22}E_y$ respectively. The phase retardation $\Gamma$, with an applied electric field in a typical linear transverse electro-optic modulator will be obtained as follows, [38]:

$$\Gamma = \phi_y' - \phi_x' = \frac{\omega L}{c} \left| n_y - n_x - \frac{1}{2} (n^3_3 r_{22} - n^3_3 r_{12}) E_y \right|$$

(2)

The total phase difference between two perpendicular polarization of light (in our example $E_x$ and $E_y$), is

$$\Delta = \Delta_0 + \delta$$

(3)

where $\Delta_0$ is due to linear birefringence and $\delta$ is due to linear electro-optic effect. In this case $\delta$ is much smaller than $\Delta_0$.

In sub-micron space scales and sub-femtoseconds time scales, the optical constants loses its stabilization and classical equations for linear and nonlinear optical phenomena are not useful [36].

Now, we suggest a microscopic model for linear electro-optic phenomenon. That would be assumed only linear optic phenomenon exist and nonlinear optic phenomenon do not exist, approximately. Because laser watt is not much, one photon interacts with any NPP molecules. In each interaction between photon and electron in every layer of crystal, we suppose a delay time equal to $\tau_i$ (ith layer of the crystal). Total delay time for m layers in crystal region is equal to:

$$\sum_{i=1}^{m} \tau_i$$

Consequently required time for photon transmission in L length of crystal is equal to $\tau$, achieved from relation:

$$\tau = \frac{L}{c} = \frac{nL}{c_0} = \frac{L}{c_0} + \sum_{i=1}^{m} \tau_i$$

(4)

where $c_0$ is velocity of light in vacuum. By using this relation, we can relate macroscopic quantity $n$ to microscopic quantity $\tau_i$. In biaxial crystals, $\tau$ and consequently $n$ depends on polarization direction of incident light. Because dipole-field interaction conclusion is different for any direction of molecule. If $\tau_x$ would be a microscopic delay for interaction of x-polarization field with dipole (or charge transfer action) and $\tau_y$ would be a microscopic delay for interaction of y-polarization field with dipole then the final phase difference between these two fields (named phase retardation) will be:

$$\Delta \phi = \omega \cdot (\tau_x - \tau_y) = \omega \cdot \sum_{i} (\tau_{x_i} - \tau_{y_i})$$

(5)
Of course this relation give $\Delta_0$ of (6). We justify $\delta$ from our model in later subsections.

### 2.3 Photon-Electron Interaction in Attosecond Regime

It can be shown that for absorption or emission of photons the material has to perform a transition between two eigenstates $E_m$ and $E_p$ of the material and thus the photon energy $E_{\text{photon}}$ has to fulfill the resonance condition:

$$E_{\text{photon}} = \hbar \nu_{\text{photon}} = |E_p - E_m|$$  \hspace{1cm} (6)

But for our linear phenomenon, the photon energy is about 2eV (in $\lambda = 630nm$). If electron would be in HOMO (Highest Occupied Molecular Orbital), this electron do not go to LUMO (Lowest Unoccupied Molecular Orbital) or exited state by interaction. This phenomena is named nonresonant phenomenon.[18, 40, 41] (nonresonant phenomena is not exclusive for nonlinear optical phenomena). Therefor electron after interaction, go to quasi states that their life times is very short, then this electron go back to primary state after very short time. The nonresonant lifetime is determined by the uncertainty principle and the energy mismatch between photon energy in second time and the input photon energy. We can assume that the characteristic response time of this process is the time required for the electron cloud to become distorted in response to an applied optical field. This response time can be estimated as the orbital period of the electron in its motion around the nucleus which is about $\tau \approx 10^{-15}s$ or 100as.[41]

We can estimate this characteristic response time according to (4) if, $n = 3, L = 3\mu$. Consequently $\Sigma \tau$ is equal to $10^{-14}$sec. Because in b direction of crystal in $3\mu$m length, approximately 4024 molecules exist, therefore the average quantity of $\tau$:

$$\bar{\tau} = \frac{\sum \tau}{N}$$

is in order of $10^{-18}s$ or 1 as. The perturbation in this very short time can assume semiclassically. In linear phenomenon in this short time, just one photon interacts with one molecule. Because NPP molecule has delocalization electrons,(or $\pi$-electron system), in benzene ring, that photon interacts with this electron type.[42] and it is annihilated[38]. We call this photon, a successful photon, (that does not produce phonon).

To obtain $\pi$-electron wavefunction for benzene molecule the Schrödinger equation may be solved. Since this is very complicated process, it cannot be done exactly, an approximated procedure known as Hückle method must be employed. In this method, by using Hückle Molecular-Orbital (HMO) calculation, a wave function is formulated that is a linear combination of the atomic orbitals (LCAO) that have overlapped[37] (see Fig.3):

$$\Psi = \sum \Phi_i C_i$$  \hspace{1cm} (7)

where the $\Phi_i$ refers to atomic orbitals of carbon atoms in the ring and the summation is over the six C atoms. The $|C_i|^2$ is the probability of the $\pi$-electron at $i$th atom. Thus:

$$|C_1|^2 + |C_2|^2 + |C_3|^2 + |C_4|^2 + |C_5|^2 + |C_6|^2 = 1$$

In the case of Benzene molecule:

$$|C_i|^2 = \frac{1}{6}$$

as followed from the symmetry of the ring[44, 45]. But NPP molecule isn’t such as Benzene molecule. NPP is polar molecule. Nitro ($NO_2$) is more powerful electronegative compound than prolinol and pulls $\pi$-electron system; consequently, the probability of finding $\pi$-electron system at various carbon atoms of main ring isn’t the same and the probability of finding $\pi$-electrons near the Nitro group is greater than near the prolinol group. Therefore there is no symmetry for NPP and electron cloud is spindly or oblong, (similar to dom-bell) (Fig.4). We estimate this form of electron cloud by an ellipse that our calculations would be uncomplicated. We assume effective positive charge that is located in one of focal points of ellipse. The quantity of this effective positive charge is determined by semiclassical arguments. For attaining probability of electron presence on an orbit.
(Fig. 5), we say, T time is required by radial vector to sweep total $\pi u v$ interior area of ellipse ($u$ and $v$ are semimajor and semiminor axis of ellipse respectively), in t times, this radial vector sweeps:

$$\pi u v \frac{t}{T}$$

area of ellipse, (see Fig. 5). If t is the time, that electron sweeps $\theta$ radian of orbit then t is obtained from this relation (8):

$$t = \frac{T}{2\pi} \left[ 2 \arctan \left( \sqrt{\frac{1 - \epsilon}{1 + \epsilon}} \tan \left( \frac{\theta}{2} \right) \right) - \frac{\epsilon \sqrt{1 - \epsilon^2} \sin(\theta)}{1 + \epsilon \cos(\theta)} \right]$$

(8)

Where $\epsilon$ is ellipse eccentricity. By using this relation, we attain the required time (t) for electron to traverse from $\theta$ to $\theta + d\theta$ and it is divided by total time T. By this approach, we can determine the PDF (Probability Density Function) approximately. The PDF in apogee (near the Nitro group), is maximum and in perigee (near the Prolinol or Methane) is minimum. Therefore PDF is correlated to $\theta$ from (8) and seen in Fig. 6. The $\tau$ quantity is correlated to $\theta$ from (8) and seen in Fig. 6. The $\tau$ quantity is correlated to $\theta$ and consequently, $\tau$ quantity is correlated to presence probability of $\pi$-electron system.

The angle between Y vector and charge transfer action (N$_1$-N$_2$) is 58.6° and X and Z axis is perpendicular to Y (Fig. 6). We consider propagation along Z direction. We spot a photon interacts with $\pi$-electron of NPP in first layer. After interaction, this photon gives its energy to electron and is annihilated. Electron absorbs energy and digresses in direction of photon momentum. Electron with photon energy, may not be unbounded and after arriving to apogee of digression, it returns back to ground state, because the photon energy is equal to $h\nu = 1.96ev$ (h is Planck’s constant and $\nu$ is frequency of laser beam) whereas energy for excitation is greater than $3ev$. When electron returns to ground state one photon is produced. The time coming up and down is $\tau$ delay time. This photon after freedom goes to second layer in direction of annihilated photon (nonce, we assume the polarization doesn’t change), in second layer this photon interacts with another delocalization $\pi$-electron certainly, because the effective interaction range of photon is approximately equal to its wavelength and is very greater than the distance between molecules. This molecule is nearest to photon effective central. This action is repeated for each layer. The location of photon-electron interaction is significant in every molecule and it is effective on $\tau$ quantity directly. We assume that interacting photon has circle polarization and electron subject to virtual positive charge center. The phase retardation between $E_x$ and $E_y$ (2) can be obtain from this relation (9):

$$\Delta \phi = \frac{\omega \sqrt{2\hbar \nu m}}{KZe^2} \sum_{i=1}^{m} [\cos(\theta_i) - \sin(\theta_i)] r_i^2$$

(9)

that

$$r_i = \frac{(1 - \epsilon^2)u}{1 + \epsilon \cos(\theta_i)}$$

where $\epsilon$ is the elliptical eccentricity and $u$ is the semimajor axis of the ellipse. By applying an external transverse electric field to organic crystal (in the range of several volts per micron) the shape of $\pi$-electron system will be deformed slightly and we would expect some noticeable variations in microscopic delay parameters $(\tau_x, \tau_y)$ and phase retarda-
Figure 7: Phase retardation between $E_x$ and $E_y$ of optical signal with different wavelength by applied external electric field. As we see; by applied electric field, the virtual ellipse eccentricity change (electron in electrical field). With eccentricity variation, the microscopic delay ($\tau_x, \tau_y$) change and consequently phase retardation is modified. 

2.4 Variation Analysis of Phase Retardation versus Applied Electric Field

We simulate phase retardation of 3µm-length NPP crystal by Monte-Carlo method, then we generate random number using $MATLAB$ program. This program produces PDF quantities was explained in before subsection and relates each of them to every molecule. These values are indexing $\pi$-electron positions in each layer, by assumption a reference point (see Fig.5). Additionally we have used a $MATLAB$ program for Monte-Carlo simulation. The inputs of this program are:

1. The wavelength of incident optical beam in which we want to design DOSs;
2. $h, m, q, k = \frac{1}{4\pi^2 c_0}$ that are Planck’s constant, electron rest mass, elementary charge, Coulomb constant and speed of light respectively.
3. Unit cell parameters of NPP crystal: $a, b, c, \beta$ and its other parameters that have given in subsection (A).
4. L: crystal thickness that in our simulation it is 3µm.

And the outputs of $MATLAB$ program are: phase retardation in each wavelength.

System calibration is done semiclassically by experimental refractive index data. In this method that we obtain three refractive indexes with $x$-polarization in threea with $\epsilon$ (eccentricity), $u$ (seminajor axis of ellipse) and $Z$ (equivalent positive charge) in a way that refractive indexes in three wavelengths are very close to experimental data. Then we would see that refractive index in other wavelengths and other polarization with same $\epsilon$, $u$ and $Z$ will be achieved. Of course these values, $\epsilon$, $u$ and $Z$ would be close to experimental structure of crystal, for example $u$ would be greater than and smaller than minimum and maximum sizes of six lengths of benzene hexagonal respectively, or $\epsilon$ would be small but greater than zero. In other hand these values must be logical. From this method in our simulation we have obtained $\epsilon = 0.26, Z = 3.9, u = 1.4A^0$ that is very close to experimental and structural data.

Xu and co-workers [19, 20], have done some electo-optic experiment about single crystal film of NPP. They have obtained $|n_x r_{12} - n_y r_{22}| = 340pm/V$ and $r_{12} = 65pm/V$ in an optical beam with 1064nm wavelength. They have studied phase retardation between $E_x$ and $E_y$ of optical beam as a function of angle between electric field and charge transfer action of NPP. They have concluded that the maximum phase
Figure 8: The typical waveguide that is used for our switch. The core of this waveguide is NPP and the cladding of it, is the poly(tetrafluoroethylene) (PTFE)[27]. We assume input light that has xy-polarization and travel in zy-plane.

The retardation was observed for the field oriented along the charge-transfer axis which was parallel to the film surface. The electro-optic effect or phase retardation was negligible when the electric field was applied perpendicular to the charge-transfer axis. This concept could be justified by our model in previous subsection. When the angle between charge-transfer action and external electric field change, the ellipse eccentricity modify and consequently, the phase retardation alter. Obviously, from Fig 4 when the external electric is parallel to charge-transfer axis, the ellipse drag more and the ellipse convert to a line. Therefor, ellipse eccentricity arise and from Fig 7 the phase retardation growth. In the other hand, from Fig 5 when the angle between external electric field and charge-transfer axis change, the ellipse is gathered and convert to circle and the eccentricity decrease to zero. Thus from Fig 7 the phase retardation is lowered.

3 Design

In this section, we design an organic $2 \times 2$ DOS that is based on EO phenomenon with adiabatic coupler. The adiabatic coupler has some advantages such as: a more evenly split power can be achieved in the switch and comparably longer electrodes can be used for the same device length, which leads to either lower driving voltage or more compact device design[3]. The basic theory of this switch was explained in previous section. In this switch we use a waveguide that has been shown in Fig[8] The core of this waveguide is NPP and the cladding of it, is the poly(tetrafluoroethylene) (PTFE)[27]. We assume input light that has xy-polarization and travel in zy-plane according to Fig[8].

In Fig[9] the layout of our $2 \times 2$ DOS with a full adiabatic coupler has been shown. The input and output waveguides do not have been shown. Driving electrodes are on the top of the waveguides in the interaction region. By applying voltage on the electrodes, we can change the refractive index in one or both waveguides. If the refractive index difference between the two arms in one side is large enough, the power will output from the waveguide with higher refractive index. For these EO devices, the material is poled in the vertical direction (see Fig[10]. Consequently, the driving electric field should be in the vertical direction, which is from the top driving electrode to the bottom electrode, to have a larger EO effect. To ensure the electric field has a larger component in the vertical direction than the horizontal, the spacing between the electrodes should be no less than the thickness of the device. The spacings in our devices are...
about 10\(\mu\)m. Because the NPP material has large linear electro-optic effect, \((r_{12} = 65\text{pm/V})\), that is two times of linear electro-optic effect of nonorganic material) by smaller change of applied voltage, the optical power can switch to the neighbor waveguide, or we can shorten the electrode length\[4\]. Therefore we would have expected that our switch is smaller than a switch with nonorganic material. The full angle between the two neighbor waveguides, \(\Delta \theta\) is about 1mrad. From Fig.\ref{fig:10} we see that the phase retardation change for different wavelengths, with same applied electric field. Therefore we can switch two optical beam with different wavelengths to two output waveguides. By suitable choice of step-like voltage(using an analogue to digital converter(ADC) and choosing two of four electrodes), we can switch specific beam with optional wavelength to specific output channel.

The cross section of the EO DOS in the interaction region is shown in Fig.\ref{fig:10}. As we see, the rib waveguide is used for this switch.

4 Conclusion

We analyzed and designed a novel 2 \(\times\) 2 DOS that is based on transverse EO effect. In analysis we justified linear EO phenomenon by QPM. This suggested physical model could be a powerful tool for analyzing and explaining processes that happen in waveguides with microscopic and nanoscopic sizes. We showed how the phase retardation between different arguments of an optical field with distinctive wavelengths can take place. In design, we configured a DOS with full adiabatic coupler. We used a ridge waveguide that has been constructed from NPP crystal as core. By using an ADC and applying four proper voltages on four electrodes, one could switch an input optical beam with specific wavelength to certain output channel.

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