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DIELECTRIC TENSOR OF PHOTOINDUCED POLARIZATION CONVERTORS IN OPTICAL FIBERS

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Abstract

We show that unusual forms of dielectric tensor, leading to novel polarization convertors, can be induced in fibers by interferometric exposure to orthogonally polarized UV beams.

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In this paper, the general form of the dielectric tensor induced in glass by interferometric exposure to light of arbitrary polarization is derived using a Hamiltonian approach for one and two-photon absorption. Considerable research effort has been devoted to the fabrication of polarization convertors in optical fibers using anisotropic photosensitivity [1-4], partly because of their potential applications in distributed sensing. The analysis of these devices has been conducted by writing down the dielectric tensor using phenomenological arguments. A rigorous development of the complete dielectric tensor starting from the microscopic origins has been lacking in the literature. We discuss the physical origins of anisotropic photosensitivity and develop a model based on preferential ionization to arrive at the form of the dielectric tensor under general exposure conditions. Both single and two-photon processes can be treated, making the formulation valid for both UV side-writing and in-core filter writing with blue/green guided modes. In addition to elucidating the dielectric tensor of polarization convertors, the treatment predicts that a special new type of light tap will form during single-photon side-writing with waves of linear but orthogonal polarization states.

Although the germanosilicate glass matrix of a standard fiber core is isotropic on a macroscopic scale, the individual molecular bonds are highly anisotropic. That is, an electric field along the direction of the bond axis induces a much larger dipolar moment than a field perpendicular to the bond axis. This anisotropic polarizability leads to preferential ionization of bonds oriented along the electric field of linearly polarized light. In germanosilicate glasses the band gap of the material is much higher and $\equiv Si-O-$ or $\equiv Ge-O-$ cannot be broken by visible light. Certain anisotropic defects, however, such as oxygen vacancies, are ionizable by two-photon absorption of blue/green light or one-photon absorption of UV in a band around 240 nm. Preferential ionization will then reduce the polarization along bond axis; the released electron is likely to be trapped with equal probability in a host of randomly oriented sites. The negative birefringence predicted by this picture has been observed by Bardal *et al.*[5] and Lauzon *et al.* [6].

In our mathematical analysis we will assume for the sake of simplicity that the anisotropic defects are negligibly polarizable in the direction orthogonal to the bond axis. If the defect axis is lined along the unit vector $\hat{\mathbf{u}} = (u_x, u_y, u_z) = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$ and the linear polarizabilty of the bonds is β, then the above assumption allows us to write the contribution of this bond to the linear susceptibility as $\delta\chi_{ij} = \beta u_i u_j$. The macroscopic change in the linear susceptibility then takes the form:

$$\Delta\chi_{kl} = \beta \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} \Delta N(\theta,\phi)\ u_k\ u_l\ \sin\theta\ d\theta\ d\phi. \quad (1)$$

where $\Delta N(\theta,\phi)$ is the change in the angular distribution of the bonds due to exposure to light. The $\{x,y,z\}$ coordinate system used throughout the article is illustrated in Fig. 1. To calculate $\Delta N(\theta,\phi)$ we turn our attention to the interaction of the illuminating optical field with the glass matrix. The total vector electric field may be written as:

$$\mathbf{E} = \frac{1}{2}\{\mathbf{E}_1\exp(i\mathbf{k}_1\cdot\mathbf{r}) + \mathbf{E}_2\exp(i\mathbf{k}_2\cdot\mathbf{r})\}\exp(j\omega t) + \text{c.c.} \quad (2)$$

This optical field interacts with a distribution of anisotropic defects randomly oriented in angle space via the following interaction Hamiltonian :

$$H_{int} = \boldsymbol{\mu}\cdot\boldsymbol{E} + \boldsymbol{\alpha} : \boldsymbol{EE} \quad (3)$$

where μ is the molecular dipole moment operator and α the second rank polarizability tensor. The one-photon term applies to side-writing with UV and the two-photon term applies to in-core writing with blue/green. Since the bonds are predominantly polarizable along the bond axis, the inverse lifetime of a single bond under the action of UV light from the side is predicted by:

$$w = \frac{\mu_0^2}{4\hbar^2}\ g(\nu-\nu_0)\ u_k u_l\ E_k E_l^* \quad (4)$$

where μ_o is the expectation value of the dipole moment operator and

$$\int g(\nu-\nu_0)\,d\nu = 1. \quad (5)$$

For brief exposures to light which do not significantly deplete the population of the anisotropic defects, i.e. for small times Δt, $w(\theta,\phi)$ may be related to the population change $\Delta N(\theta,\phi)$ via the simple relationship

$$\Delta N(\theta,\phi) = \frac{N_o}{4\pi}\ w(\theta,\phi)\ \Delta t \quad (6)$$

where $N_o/4\pi$ is the initial isotropic distribution of defects. Substituting the above expression into Eq. 1 and integrating yields

$$\Delta\chi_{ij} = C_o\ Q_{ijkl}\ E_k\ E_l^* \quad (7)$$

where

$$C_o = \left(\frac{\mu_0}{4\hbar}\right)^2 \frac{N_0 \beta \, \Delta t}{\pi} \, g(\nu - \nu_0), \tag{8}$$

and the quantities Q_{ijkl} are defined by the integrals:

$$Q_{ijkl} = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} u_i u_j u_k u_l \sin\theta \, d\theta d\phi \; . \tag{9}$$

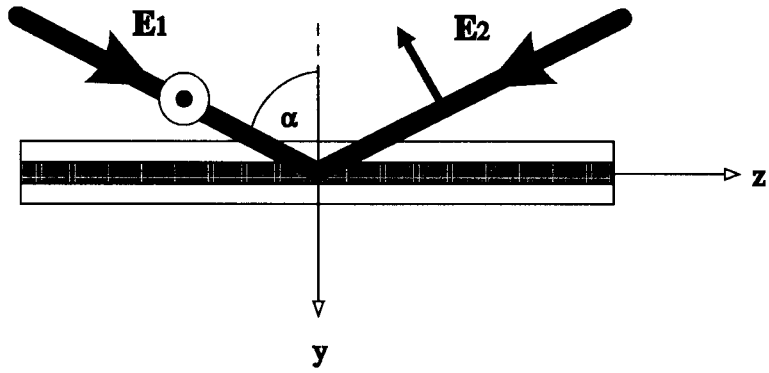

Figure 1. Interference of two beams with linear but orthogonal polarization states. $\mathbf{E}_1$ is polarized along the x-axis and $\mathbf{E}_2$ is polarized in the y-z plane. The propagation vectors of the two beams are in the y-z plane and make an angle α with the y-axis.

The above analysis can be applied to predict the dielectric tensor due to interference of arbitrarily polarized beams. In this summary, however, we will limit our discussion to the situation illustrated in Fig. 1. Substituting linear but orthogonal polarization states of Fig. 1 in Eq. 2, we obtain the following dielectric tensor:

$$[\Delta\chi] = \Delta\chi_0 \times$$

$$\begin{bmatrix} 3E_1^2+E_2^2 & -2E_1E_2 \sin\alpha \cos\mathbf{K}\cdot\mathbf{r} & 2E_1E_2 \cos\alpha \cos\mathbf{K}\cdot\mathbf{r} \\ -2E_1E_2 \sin\alpha \cos\mathbf{K}\cdot\mathbf{r} & E_1^2 + E_2^2(1+2\sin^2\alpha) & -E_2^2 \sin 2\alpha \\ 2E_1E_2 \cos\alpha \cos\mathbf{K}\cdot\mathbf{r} & -E_2^2 \sin 2\alpha & E_1^2 + E_2^2(1+2\cos^2\alpha) \end{bmatrix} \tag{10}$$

with $\Delta\chi_0 = 4\pi C_o/15$ and $\mathbf{K} = \mathbf{k}_1 - \mathbf{k}_2$.

The perturbations to the on-diagonal elements of the dielectric tensor are purely dc; hence, no Bragg grating has been induced. The asymmetry in χ_{xx} and χ_{yy}, however, does lead to a uniform photo-induced birefringence. It is the periodic modulation in χ_{xy} and χ_{yx} terms, which couple x- and y- polarized modes, that is responsible for phasematched energy transfer to the orthogonally polarized counterpropagating mode within a narrow band of frequencies. The periodicity in χ_{zx} can act as a special light tap. Unlike the blazed-grating isotropic-light tap, which provides phasematching for conversion from guided modes to radiation modes, this light tap sets up a polarization which cannot radiate light along the guided direction when the incident guided mode is x-polarized. In large core fibers leakage of light is suppressed because of a large phasemismatch, but substantial leakage may occur in small core high NA fibers.

In order to predict more precisely the magnitude of the perturbations an accurate knowledge of β and μ_0 is required. However, an order of magnitude estimate of the birefringence that can be induced is possible by making some assumptions. We assume that the linear polarizability β of the anisotropic defects is approximately the same as the linear polarizability of the $\equiv Si-O-$ bonds. Since the anisotropic defects have lower ionization potential than $\equiv Si-O-$ bonds, their polarizability is likely to be larger and not smaller. Now if 1% from a total number of 10^{19} cm^{-3} are depleted along one of the axes then a birefringence of approximately 10^{-6} to 10^{-5} can be induced.

In conclusion, we have presented a simple but general formalism for predicting the dielectric tensor of any device based on anisotropic photosensitivity. Although in this summary the formalism was only illustrated for the side-writing case with linearly polarized UV beams, in-core writing with blue/green light can be easily handled using the two-photon term in the interaction Hamiltonian and the dielectric tensor of filters fabricated using circularly polarized beams can also be obtained. These will be fully presented in a future paper.

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