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Self-modulation of infrared waves in rutile

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Abstract

Electromagnetic waves carry angular and linear momentums and exert torques on anisotropic dielectrics, arising from the fact of the tensor property of the dielectric constant, that is, the direction of electric displacement is not parallel to the electric field vector of the incident light. The torque per unit volume exerted on a wave plate is given by $\boldsymbol{P} \times \boldsymbol{E}$, where $\boldsymbol{P}$ is the polarization and $\boldsymbol{E}$ is the electric field, which induces the rotations of eigenvibration direction in the crystals. The rotation angles increase with the intensity of the incident light and the dielectric constant of the crystals. Because of the large dielectric constants, self-modulation of the incident light in the infrared frequency region was clearly demonstrated in the infrared transmission spectra of ferroelectric and piezoelectric crystals. Rutile (TiO_2) is a non-ferroelectric and non-piezoelectric crystal, but it also has the large dielectric constants. Rotations of the vibration direction of the ordinary (*o*-ray) and the extraordinary (*e*-ray) waves were shown in the infrared transmission spectra recorded by incidence of the plane-polarized light and transmission through a rutile plate. Interference of the *o*-ray and the *e*-ray waves transmitted through the crystals confirms the rotations of eigenvibration direction, a self-modulation effect of light in the crystal of large dielectric constants and large birefringence in the infrared range.

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1. Introduction

Light incident onto the wave plate of an anisotropic crystal is divided into two plane-polarized waves of eigenvibrations, propagating with different velocities in the crystal and hence different indices of refraction [1]. According to the principle of the classical optics of crystals, the two perpendicularly polarized waves do not produce interference, even if there exists a phase difference between them after passing through a phase plate [1]. On the other hand, electromagnetic waves carry momentums (angular and linear parts) and hence exert forces and torque on anisotropic crystals [2–4]. The torque arises from the fact of the tensor property of the dielectric constant, that is, the direction of electric displacement is not parallel to the electric field vector of the incident light. The torque per unit volume exerted on a wave plate is given by $\boldsymbol{P} \times \boldsymbol{E}$, where $\boldsymbol{P}$ is the polarization and $\boldsymbol{E}$ is the electric field of the incident light, which induces the rotations of eigenvibration direction in the crystals [4]. The rotation angles hence increase with the intensity of the incident light and the dielectric constant of the crystals. Recently, we proposed the relationships to describe the rotation of the induced dipole in the perpendicular electric fields of the incident light [4]. The directions of eigenvibration of the ordinary (*o*-ray) and extraordinary (*e*-ray) waves are no longer perpendicular in this sense. Therefore, there exist always the parallel or anti-parallel subcomponents of the transmitted electric field, which may be brought to interference after passing through the wave plate because of the phase difference [4,5].

The remarkable feature of ferroelectric crystals and rutile (TiO_2) is the large dielectric constants in the microwaves and lower-frequency parts of electromagnetic spectrum [6]. The dielectric constant of most common ferroelectric crystals is usually in the range of $\sim 10^2$ to $\sim 10^4$. Rutile is not ferroelectric but it also has large dielectric constants. The determined dielec-

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tric constants ε_o and ε_e at the wavelength of 1030 μm are 84 and 165 for the *o*-ray and the *e*-ray waves [7], whereas the determined dc-values are 86 and 170, respectively [8]. However, in contrast to the large values, the dielectric constants of most materials are below 10 in visible range ($\varepsilon = n^2$, n: the refractive index). Therefore there exists a transition region in the infrared range [4]. The process in which the dielectric constant changes from ε_∞ (the optical dielectric constant) to ε_s (the static dielectric constant) is of fundamental interest [4,9]. Three fundamental resonance frequencies (500, 388, and 183 cm^{-1}) in the infrared range have been evaluated by infrared reflection measurement on a rutile plate [6]. It has been suggested that the strongest resonance frequency near 183 cm^{-1} is associated with the large dielectric constants of rutile at low frequencies [6]. Because of the large dielectric constants and large birefringence ($n_e - n_o \approx 0.25$ in the wavelength range from ∼ 1 to ∼ 4 μm) [10], it is suggested that significant rotations of eigenvibration direction and hence the clear interference of the *o*-ray and the *e*-ray waves can be induced by incidence of the plan-polarized infrared waves through rutile plate, according to the recently proposed relationships [4], which may be observed in the infrared transmission spectra. Such observations are important for device applications in the infrared and microwave region.

2. Experiment and results

The y-cut (10.0 mm × 10.0 mm in the x-axis and z-axis) used in the present measurements was prepared from the synthesized single rutile crystal. The thickness of the plate is 0.52 mm in the y-axis. Two sides of the plates are optically polished, with flatness $\lambda/8$ @ 632.8 nm. To produce the plane-polarized incident light, a rotatable TlBr-polarizer was placed between the light source and the sample. The azimuth angle of the plane-polarized incident light is denoted as the angle between the transmission direction of the polarized and optic axis (z-axis) of the plate. For every azimuth angle, the measurement of the background was carried out. The transmission spectra reported in the present work were obtained by averaging 100 scans of a Fourier transform spectrophotometer (Perkin–Elmer, Spectrum GX). The resolution was selected to be 8 cm^{-1}.

Fig. 1 shows the representative transmission spectra of the rutile plate obtained by incidence of the plane-polarized light, at several azimuth angles of 45°, 30°, 15°, and 0°. Successive interference fringes are shown in the transmission spectra, which disappear at the azimuth angles of 0° and 90° corresponding the incident *e*-ray and *o*-ray waves, respectively. The modulation amplitude ($T_{\max} - T_{\min}$) exhibits a maximum near the azimuth angle of 45°, as shown in Fig. 2. Evaluating the positions of the interference fringes, we can determine the birefringence $n_e - n_o$. The determined birefringence for rutile is 0.2585 at the wavelength near 2.38 μm, in good agreement with the reported birefringence in the investigated wavelength region [10]. These observations indicate that the interference fringes shown in Fig. 1 are resulted from the interference of the *o*-ray and the *e*-ray waves.

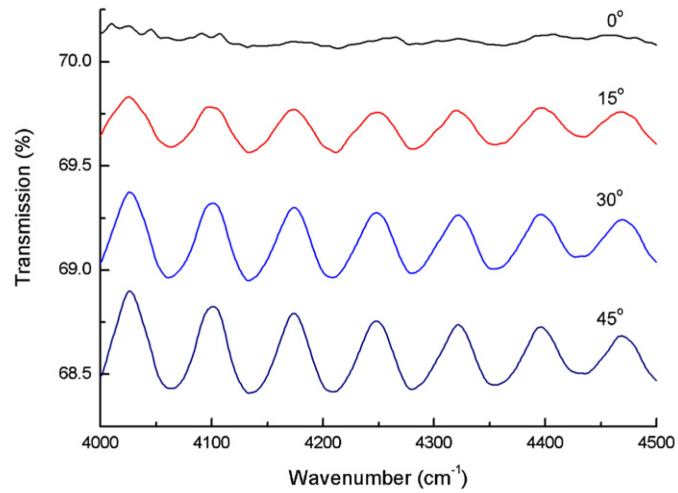

Fig. 1. Representative transmission spectra of the rutile plate (y-cut, 10.0 mm × 10.0 mm in the x-axis and z-axis, thickness: 0.52 mm in the y-axis) obtained by incidence of the plane-polarized light at different azimuth angles of polarization with respect to optic axis. The polarized light is incident normally onto the xz-plane and propagates along the y-direction.

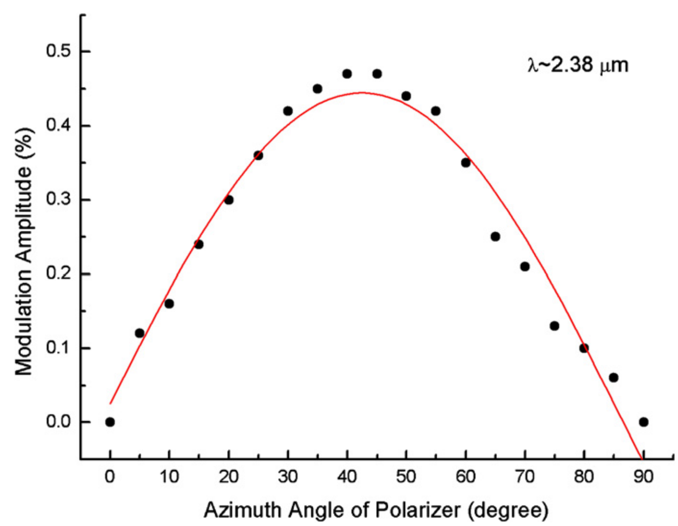

Fig. 2. Modulation amplitude ($T_{\max} - T_{\min}$) of interference fringes shown in the infrared transmission spectrum of rutile plate near wavelength 2.38 μm, and its dependence on the azimuth angle of the plane-polarized incident light. The symbols represent the experimental data and the curve is the fitting result obtained by Eq. (9).

3. Discussion

Light incident onto the wave plate of an anisotropic crystal is divided into two plane-polarized waves of perpendicular eigenvibrations, producing polarizations in the two principal directions [1]. Suppose the incident plane-polarized light propagates in the y-axis. The incident plane-polarized electric field $\boldsymbol{E}$ is divided into two components $\boldsymbol{E}_x$ and $\boldsymbol{E}_z$, vibrating in the x- and z-directions and propagating with different velocities. Let φ be the azimuth angle of the field $\boldsymbol{E}$ with the z-axis. The components $\boldsymbol{E}_x$ and $\boldsymbol{E}_y$ are given by [4]

$$\boldsymbol{E}_x = E\sin(\varphi)\exp\big[i(\omega t - \delta_x)\big], \tag{1}$$

$$\boldsymbol{E}_z = E\cos(\varphi)\exp\big[i(\omega t - \delta_z)\big], \tag{2}$$