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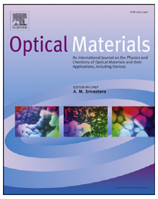

Spectral analysis techniques for characterizing cadmium zinc telluride polarization modulators

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ABSTRACT

The low frequency electro-optic characteristics of cadmium zinc telluride are demonstrated in the mid-infrared, in the spectral range 2.5–11 μm. Conventional methods for characterizing the dynamic response by monitoring the amplitude of the time-varying light intensity do not account for spatial variation in material properties. In such cases, a more revealing method involves monitoring two distinct frequency components in order to characterize the dynamic and static contributions to the optical retardation. We demonstrate that, while this method works well for a ZnSe photo-elastic modulator, it does not fully capture the response of a cadmium zinc telluride electro-optic modulator. Ultimately, we show that acquiring the full waveform of the optical response enables a model to be created that accounts for inhomogeneity in the material that results in an asymmetric response with respect to the polarity of the driving voltage. This technique is applicable to broadband and fixed-wavelength applications in a variety of spectral ranges.

1. Introduction

Many applications of electro-optic materials, such as fast-switching light valves [1], Q-switches for pulsed lasers [2], and polarization modulators [3] require a material to display a voltage-dependent refractive index difference in response to a pulsed or sinusoidal waveform. In such devices, the objective is generally to modulate the device optical property between no optical retardation and either a quarter-wave or a half-wave retardation. Quarter-wave retardation can be used to create a precise arbitrary polarization state [4–6], including circularly polarized light, from linearly polarized source. Half-wave retardation can be used to rotate the azimuth of linearly polarized light by 90°, which results in light which would be transmitted by a polarizer to instead be blocked. While fast-switching electro-optic modulators are widely available in the form of liquid crystal variable retarders [7,8], fewer options for materials exist in the mid-infrared. One available option is the photo-elastic modulator (PEM). In this device, an AC voltage is applied to a piezo-electric crystal (such as quartz) at its resonant frequency, causing it to undergo mechanical strain, coupled to a IR-transparent material such as ZnSe to induce a time-varying birefringence.

Pockels cells provide another option for the mid-infrared, from materials including ammonium dihydrogen phosphate (ADP), potassium dihydrogen phosphate (KDP), and potassium dideuterium phosphate (DKDP) [9,10]. More recently, compounds of Group II and Group VI elements, known as II-VI compounds, have been used for this application, featuring wider band gaps and higher density. II-VI compounds have a zinc-blende crystal structure, and the only non-zero electro-optic coefficient is r_{41}. Retardation depends on the electric field according to

$$\delta = \frac{2\pi}{\lambda} n_0^3 r_{41} E \ell \qquad (1)$$

where λ is the wavelength, n_0 is the refractive index, E is the field strength, ℓ is the length of the material along the propagation axis of the light, and the retardation δ is in radians. The material with the highest EO coefficient of all measured II-VI compounds is cadmium telluride (CdTe) [11], with r_{41} reported at 6.8×10^{-12} m V^{-1} at both 3.39 μm and 10.6 μm [12], though more recent measurements indicate a value of $5.5 - 5.9 \times 10^{-12}$ m V^{-1} at 10.6 μm

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Applying AC voltage requires consideration of the frequency dependence of the electro-optic response. Every Pockels material must have a non-centrosymmetric crystal structure, which also brings about the piezo-electric effect. Thus as voltage is being applied, the material is being mechanically deformed by the inverse piezoelectric effect as well as electronically modulated by the electro-optic effect. At sufficiently low frequency, the changes effected in the material can occur at the same rate as the time-varying voltage. At a resonant frequency pertaining to the specific properties and dimensions of the sample, the piezo-electric effect is amplified. Frequencies below this region are referred to as being in the unclamped region, as the material is free to deform along with the applied voltage. At frequencies far higher than the resonant frequency (unclamped region), the material cannot mechanically deform at a rate fast enough to keep up with the applied voltage, and the result of this is that it does not deform significantly as the voltage switches.

Cadmium zinc telluride (CZT) is a pseudo-binary alloy of cadmium telluride (CdTe) and zinc telluride (ZnTe), which have found applications in nuclear radiation detection. CZT has the same zinc blende crystal structure and belongs to the cubic crystal class $\bar{4}3m$. It also displays the Pockels effect [16], which has not yet been quantitatively characterized in the literature for the mid-infrared region. For this crystal class, the only non-zero electro-optic and piezo-electric coefficients are r_{41} and d_{14} respectively. These are correlated in that when voltage is applied on the $[\bar{1}10]$ direction, r_{41} dictates a proportional retardation with an optical axis in the [110] direction, while d_{14} dictates a proportional shear strain in the plane normal to this applied voltage. The r_{41} coefficient specifies that the optical axis is created along the diagonal from one corner of the adjacent crystal face to the opposite corner, while the piezo-electric effect lengthens the distance along this optical axis and shortens the orthogonal distance. Thus unclamped, the material is expected to have a more pronounced electro-optic effect. The electro-optic coefficient of CdTe has been studied by Herrit and Reedy at 10.6 μm at a range of AC frequencies spanning the resonant frequency [13]. Applying frequencies above and below the resonant frequency of the sample, the unclamped and clamped r_{41} were reported to be 5.5×10^{-12} m V^{-1} and 4.1×10^{-12} m V^{-1}, respectively. In that study of CdTe, a 10.6 μm laser was used as the source, and the determination of the electro-optic coefficient was performed using a crossed-polarizer system. The transmitted intensity was analyzed by a root mean square (RMS) meter, and the value of the RMS current from the detector was used to elucidate the electro-optic coefficient. This method relies on a predictable relationship between the electro-optic coefficient and the RMS signal in the case of ideal behaviour of the material. In this work, we apply a low-frequency sinusoidal voltage up to 3.4 kV to a CZT crystal. We discuss ideal behaviour of the response to this voltage, and aim to develop a method to completely characterize the response of CZT in the unclamped region across the mid-IR wavelength region. We develop a model that may be applied to any optical modulator that accounts for the retardation and depolarization effects in the presence of material inhomogeneity.

2. Experimental

For this work, the CZT electro-optic modulator working in the transverse geometry was cut from a $Cd_{1-x}Zn_x$ Te single crystal boule with x nominally 0.1, grown at Redlen Technologies by a travelling heater method [17]. All six faces of the bar were sized by standard lapping methods and given a 0.3 μm polish as the final finish. Two of the long sides opposite one another were metallized with indium electrodes, and gold wires attached to one end of each metallized face.

We present two schemes for measuring the Pockels retardation of the crystal, the first selecting specific frequencies using lock-in amplifiers, and the second employing an oscilloscope (Tektronix DPO4034) to capture the complete waveform of the optical response. Using a Fourier transform infrared spectrometer (FTIR, Bruker Vertex 70) operating in step-scan mode with a globar source, we can perform broadband measurements in the mid-IR together. The choice of some optics (beam splitter, windows, etc) in the beam path limit our wavelength range for analysis to 2.5–11 μm. A schematic of the setup is shown in Fig. 1. A custom-built 60 Hz variable power supply can supply up to 3.4 kV amplitude at 60 Hz. The CZT crystal rests in a specially-designed enclosure free of pressure. The crystal is placed between two parallel polarizers, with its optical axis oriented 45° with respect to the polarizer transmission axes. The beam emerges from the FTIR roughly collimated with a diameter approximately 25 mm. It is brought to a gentle focus in the middle of the CZT bar using a 500 mm focal length mirror, and the beam spot is further restricted by an iris to ensure that all light reaching the HgCdTe detector (Kolmar Technologies, Newburyport MA) has passed through the sample. We estimate that the beam diameter is between 1 and 3 mm throughout the length of the crystal. Since the metal electrodes were indium, which has a work function (4.1 eV [18]) lower than that of CdTe, we expect that the Schottky barrier height is minimized at the metal-semiconductor junction. If a uniform electric field is achieved within the crystal, then $E = V/L$, where L is the distance between the electrodes, and the electro-optic coefficient can be obtained via the optical retardation using Eq. (1).

As shown in Fig. 1, an optical chopper introduces a low frequency (300 Hz) modulation to provide a more robust means for measuring the DC component of the signal. The photocurrent from the detector is passed to three lock-in amplifiers (Signal Recovery 7265) along with a reference frequency from the chopper and the AC power supply. The lock-in amplifiers analyze the chopper frequency component of the signal, as well as the fundamental frequency component and second harmonic of the driving AC voltage.

3. Results and discussion

3.1. Lock-in amplifier measurements

In the first measurement scheme, we follow a methodology commonly used to characterize and calibrate photoelastic modulators (PEM) [19–21]. When AC voltage is applied, the retardation varies with time, modulating the transmittance through the polarizer-sample-analyzer configuration. For instance, when the

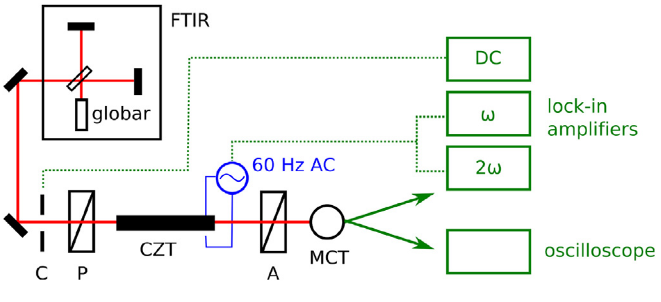

Fig. 1. Incident light from an FTIR in step-scan mode is modulated by an optical chopper (C) and polarized at 0° (P), and after encountering the sample (CZT) with optical axis at 45°, passes through another polarizer (A) at 0° to reach the detector (MCT). In one scheme, three lock-in amplifiers demodulate the signal at three frequencies of interest. In the second scheme, the signal waveform is collected at each FTIR mirror step by an oscilloscope.