ELECTRON BOMBARDMENT OF ZnTe EO BUNCH CHARGE DETECTOR FOR SIGNAL LIFETIME STUDIES IN RADIATION ENVIRONMENT

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Abstract

Electro-optic(EO) detection of bunch charge distribution utilizing the nonlinear Pockel's and Kerr effect of materials has been implemented at various facilities as a method of passive detection for beam preservation throughout characterization[1-12]. Most commonly, the inorganic II-VI material ZnTe is employed due to its strong Pockel's EO effect and relatively high temporal resolution (~90 fs)[2]. Despite early exploration of radiation damage on ZnTe in exploration of semiconductor materials in the 1970's, full characterization of EO response over radiation exposure lifetime has yet to be performed. The following paper presents a technique for ZnTe crystal characterization studies throughout radiation exposure at various energies and dosages by analyzing the changes in index of refraction including bulk uniformity, and THz signal response changes.

INTRODUCTION

The development of non-invasive charge distribution detectors based on the electro-optic properties of materials has seen various implementations at electron accelerators [1-4], and particularly in free-electron laser facilities. Though there are various electro-optic detector arrangements that range in method of data encoding and measurement, the typical electro-optic bunch detector is arranged to measure the passing profile of the electric field of relativistic electron bunches by probing the polarization shift in the electro-optic material with a synched laser. This polarization shift arises out of the electro-optic effect induced in a particular material (e. g. ZnTe, GaP, DAST, etc) by the strong electric field of the passing bunches. These EO-materials have a high 1st order non-linear coefficient, resulting in an index of refraction anisotropy that is linearly proportional to the applied field.

In contrast to the previously referenced facilities which employ EO detectors, the JLab and CSU facilities operate at a higher average current. It is suspected that this higher average current environment may present a greater hazard to the crystals. Studies that look into damage induced by either the probing laser beam or radiation environment seen by the materials within the accelerator vacuum are limited [5] and thus so is a direct correlation between detector signal and crystalline lattice defects induced while in operation. In order to develop a thorough understanding of signal properties throughout an EO material's lifetime, studies of material lattice properties

(index of refraction, electro-optic coefficient, etc) before and after bombardment by electrons of various energies and at varying doses is laid out in this paper.

METHODS

It is planned that a picture of the material properties throughout its lifetime within an accelerator environment can be simulated through exposure of the materials to electron beams of various energies (2-16 MeV) at varying doses. The exposed materials will be characterized before and after exposure using an assortment of optic analysis tools to get a thorough picture of the complex index of refraction, electro-optic coefficient, and any other perturbations of the original material properties. This information will help develop an accurate picture of material response throughout its lifetime and help to deconvolve signal error arising from defects within the material itself or other sources.

Exposure Procedure

Exposure is planned on an operational cancer therapy machine with available electron beam energies between 2-16 MeV and various dosing rates. The crystals will be placed at a proper distance and covered by a suitable amount of material to deposit the beams' energy at the desired location within the crystals.

As different defects may arise at different energies and intensities, a different crystal sample will be exposed for each electron beam energy. After each dosing, optical characterization of the materials will help paint a picture of material properties over lifetime within a radiation environment.

Material Characterization

Prior to exposing these materials, a complete picture of material optical properties will be assessed using an assortment of optical diagnostics. The complex index of refraction, its homogeneity throughout the material, absorption and luminescence spectra, and electro-optic response are to be measured using an ellipsometer, Mach-Zehnder interferometer, absorption and luminescence spectrometers, and a THz-kit, respectively. The purpose and data produced by the various devices is outlined below:

- **Ellipsometer -**Produces a map of the complex index of refraction for the materials over a range of wavelengths (200-2000nm). Both transmission and reflection geometries for both faces is planned. Changes in the complex index of refraction may be

indicative of both signal propagation and intensity changes to be expected in detector lifetime.

- ***Mach-Zehnder Interferometer -*** Produces a picture of the homogeneity of refractive index along the direction of the probing laser. As the phase shift induced in the interferometer arm containing the crystal samples is the total shift in the propagation direction, interferograms produce a picture of lattice index of refraction homogeneity. Inhomogeneity, as seen in Figure 1 below, results in deviations in the linearity of fringes. Additionally, this can be used in conjunction with the THz-kit as another method to measure electro-optic coefficient.

Figure 1: An interferogram of a ZnTe crystal with a physical defect. The curvy fringes are indicative of inhomogeneity of index of refraction through the material.

- ***Absorption Spectrometer -*** Absorption spectra over a broad wavelength range is measured. A shift in absorption spectra may be indicative of a band gap shift related to induced lattice defects.
- ***Luminescence Spectrometer -*** The luminescence produced by the sample is measured during pumping with a high frequency laser. The luminescence produced may be indicative of signal spectral and time structure replication errors resultant from damage.
- ***THz-kit -*** Using an ultra-fast laser, an air-plasma created in an AC-bias creates a broadband THz beam. When the THz beam is propagated through a properly oriented EO-crystal collinearly with a probing laser, this can be used to measure electro-optic response of the material [13].

EXPECTED RESULTS

Energetic electrons and photons interacting with the crystalline lattice will cause shifts in lattice structure and induce lattice defects that may shift the complex index of refraction and electro-optic coefficient, thus affecting the signal produced by the detector. The energy required to displace the lattice constituents of one of our focus materials, ZnTe, was measured separately in [14,15]. What these ion shifts represent for optical signals depends on the types of defects produced.

The typical defects arising out of ion lattice displacement would be vacancies, divacancies, interstitials, non-stochiometric atoms within the lattice, and combinations of the above [14-16]. How these may affect the signal spectra depends on how they may affect the complex index of refraction and electro-optic coefficient. A change in electro-optic coefficient as a result of crystalline lattice deformity should be expected, as phonon resonance will be affected by their ability to propagate within the material. An increase in absorption or shift in absorption spectra arising from induced defects will shift the signal if the portion of the spectrum in question lies in the regime of the probing laser or electron-bunch.

Some defects may be transient at room temperature [16], and thus, undetectable in our current measurement scheme. Future experiments aimed at measuring defects during exposure to electron beams is being considered with the goal of best completion of signal errors created in situ.

CONCLUSION

In order to develop a thorough understanding of EO detector lifetime within an accelerator environment, an electron beam exposure and subsequent optical characterization technique is planned and was discussed above. It is hoped that this information will improve bunch detector signal analysis to create a lasting accurate picture of electron bunches in a non-invasive manner.

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REFERENCES

[1] S.P. Jamison, et al., "Femtosecond Resolution Bunch Profile Measurements," EPAC'06, Edinburgh, Scotland, July 2006, TUYPA01, p. 915-919 (2006).

[2] G. Berden, et al., Phys. Rev. Lett. 93 (2004) 11.

[3] M. Veronese, et al., "First Operation of the Electro Optical Sampling Diagnostics of the FERMI@ELETTRA FEL," IBIC'12, Tsukuba, Japan, 2012, TUPA43, pp. 449-452 (2012).

[4] X. Yan et al., Phys. Rev. Lett. 85 (2000) 16.

[5] Y. Okayasu, et al., "Progress Report of the Spectral Decoding Based EOS with Organic Pockels EO Crystals", IBIC 2013, WEPC35 (2013).

[6] H. Loos, et al., "Electro-optic Longitudinal Electron Beam Diagnostic at SDL," May 2003, PAC'03, Proceeding of 2003 PAC.

[7] B. Steffen, et al., "Spectral Decoding Electro Optic Bunch Length and Arrival Time Jitter Measurements at the DESY VUV-FEL," FEL'05, Palo Alto, USA August 2005.

[8] B. Steffen and S. Casalbuoni, et al., "Electro Optic Bunch Length Measurements at the VUV-FEL at DESY," PAC'05, Knoxville, TN, May 2005, Proceedings of 2005 PAC.

[9] G. Berden, et al., Phys. Rev. Lett. 99 (2007) 11.

[10] A. L. Cavalieri, et al., Phys. Rev. Lett. 94 (2005) 11.

[11] H. Schlarb, et al., "Comparative Study of Bunch Length and Arrival Time Measurements at FLASH," EPAC'06, Edinburgh, Scotland June 2006, TUPCH024, pp.1049-1051 (2006).

[12] N. Hiller, et al., "Electro-Optical Bunch Length Measurements at the ANKA Storage Ring," IPAC'13, Shanghai, China, May, 2013, MOPME014, pp. 500-502 (2013).

[13] Newport Corporation, "Application Note 44: Terahertz Spectrometer based on Generation of Ultrafast Terahertz Pulses in Air Plasma", (2011).

[14] J. M. Meese "Zn Displacement Threshold in ZnTe", Applied Physics Letters 19, 86(1971).

[15] F. J. Bryant, A. T. J. Baker, "Threshold energy for tellurium displacement in zinc telluride", J. Phys. C:Solid State Phys. Vol. 5 (1972).

[16] A T J Baker, F J Bryant, W E Hagston, "Time Resolved Spectroscopy Involving Multiply Ionizable Donor-Acceptor States", J. Phys. C: Solid State Phys., Vol. 6 (1973).