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Investigation of CdZnTe and $LiNbO_3$ as electro-optic neutron detectors

Kyle A. Nelson [a], Nathan Edwards [a], Mark J. Harrison [b], Alireza Kargar [a], Walter J. McNeil [a], Ronald A. Rojeski [c], Douglas S. McGregor [a,*]

[a] S.M.A.R.T. Laboratory, Mechanical and Nuclear Engineering Department, Kansas State University, Manhattan, KS 66506, USA
[b] Nuclear and Radiological Engineering, University of Florida, 202 NSB, Gainesville, FL 32611, USA
[c] Cymer, Inc., San Diego, CA 92127, USA

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A B S T R A C T

An alternative method for the detection of thermal neutrons has been investigated utilizing the Pockels effect with CdZnTe and $LiNbO_3$. A photodiode was used to indicate a change in light intensity transmitted through an assembly consisting of polarizer, Pockels cell, and analyzer. Ionization due to neutron reaction products can perturb an established electric field within the cell, thus changing the transmitted light intensity through the assembly. The CdZnTe cell demonstrated a repeatable change in transmitted light intensity, increasing with neutron flux, marking the first recorded use of this technology to detect neutrons. However, the $LiNbO_3$ cell gave no response to neutron irradiation, and is assumed to be a result of the extremely short carrier lifetimes found in the material.

1. Introduction

The Pockels effect has been utilized as a new method for detecting radiation and may hold some unique advantages for certain applications. The technique involves transmitting laser light through a Pockels cell, sandwiched between two cross-polarizers, and onto a photodiode. The amount of rotation of the polarized light caused by the Pockels cell depends on the electric field established within the crystal. Radiation interactions causing extensive ionization within the cell can change the electric field slightly. This disturbance changes the polarized light rotation, which also changes the light transmission through the second polarizer and consequently the current (or voltage) output of the photodiode. The conceptual arrangement is shown in Fig. 1.

One unique characteristic of this detection system is the ability to measure sensor response with no physical electronic connection to the sensor. All sensing equipment can be located at some distance away from the crystal sensor. The system operates in a “current mode”; hence pulse processing electronics were not necessary. Instead, an electrometer with nanoampere range sensitivity was used to measure the photodiode response. CdZnTe and $LiNbO_3$ are both birefringent crystal materials and are commonly used as Pockels cells. They were considered for neutron detection because each material contains a natural abundance of a highly absorbing neutron reactive constituent, those being ^{113}Cd in CdZnTe and ^{6}Li in $LiNbO_3$.

2. Theoretical considerations

In a Pockels cell, the intensity of transmitted light through crossed polarizers is a function of the applied electric field,

$$I = I_0 \sin^2\left(\frac{\pi n_0^3 r d}{\lambda} E\right) \tag{1}$$

where I_0 is the maximum light intensity transmitted through uncrossed polarizers, n_0 is the zero bias refractive index, r is the Pockels electro-optic coefficient for the crystal, d is the path length of light transmitted through the crystal, λ is the wavelength of incident light, E is the electric field perpendicular to the optical path and I is the transmitted light [1]. From Eq. (1), the transmitted light intensity reaches its maximum at mid-wave. The maximum change of light intensity per unit applied potential can be found by analyzing the second derivative of Eq. (1), which indicates that the largest intensity change occurs at 1/4 wave. Hence, the change in response for this experiment is maximized at 1/4 wave for slight changes in electric field and marks an optimal operational environment.

^{113}Cd and ^{6}Li have neutron absorption cross sections of 20,000 b and 940 b with natural abundances of 12% and 7.5%, respectively [2–4]. The neutron reactions of interest in the present are [3,5,6],

$$^{113}\mathrm{Cd} + \mathrm{n} \rightarrow {}^{114}\mathrm{Cd} + \gamma_1(558.6\,\mathrm{keV}) + \gamma_2(651.3\,\mathrm{keV}) + \gamma' \mathrm{s} \tag{2}$$

* Corresponding author.
E-mail address: mcgregor@ksu.edu (D.S. McGregor).
URL: http://www.mne.ksu.edu/research/centers/SMARTlab (D.S. McGregor).

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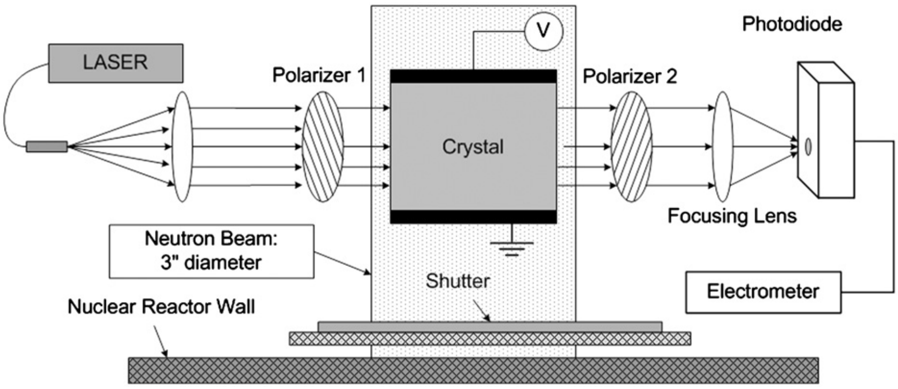

Fig. 1. Depiction of the Pockels cell experimental arrangement in the thermalized neutron beam.

and

$$^{6}\mathrm{Li}+\mathrm{n}\rightarrow{}^{3}\mathrm{H}(2.73\,\mathrm{MeV})+{}^{4}\mathrm{He}(2.05\,\mathrm{MeV}). \quad (3)$$

The reaction products, when absorbed in the Pockels cell, create ionization charge clouds. At high enough interaction rates, the ionization rate increases the steady state free carrier concentration to high levels. The application of a bias voltage across the Pockels cell, the usual operating condition, can cause these free charges to drift to their respective electrodes (electrons to the anode, holes to the cathode), and by doing so create a smaller internal electric field opposing the externally applied electric field. In other words, the space charge associated with the high concentration of free charge carriers changes the electric field distribution in the device. This change in the Pockels cell electric field will also alter the polarization of light passing through the cell. Consequently, the amount of light passing through the second polarizer will also change, which can be detected with a photodiode placed beyond the radiation field. Because the intensity is a function of the electric field, the change in intensity, or current measured at a photodiode, when exposed to radiation versus no exposure, can be measured, and responds directly to the intensity of the radiation field.

3. Experimental procedure

A polished $2\times10\times10$ mm CdZnTe crystal with the 10×10 mm faces coated with Au was used as the Pockels cell. Three fundamental structures were investigated, those being a simple planar device, a device with a strip contact opposing a planar contact, and a device with a dot contact opposing a planar contact. The CdZnTe cell in the planar configuration was mounted such that the 10×10 mm Au coated faces were perpendicular to a 3 in. diameter neutron beam emanating from a radial port at the Kansas State University (KSU) TRIGA Mark II nuclear reactor. A 1064 nm Orbits Ethernal ETH-26 laser was used to direct a beam through a collimating lens approximately 30 cm from the CdZnTe crystal, into the first polarizer (oriented 45°), and on through the crystal, as indicated in Fig. 1. The laser beam diameter was approximately 0.5–1 mm as it entered the crystal. The light exiting the CdZnTe crystal was focused onto a Newport 818-BB-30 InGaAs PIN photodiode after passing through the second polarizer (oriented 90° to the first polarizer). The photodiode was placed approximately 10 cm from the CdZnTe crystal. The entire assembly was laid out on a large optical table with a light-tight metal enclosure to prevent interference from ambient light and background electronic noise. The current produced at the photodiode was measured directly by a Keithley 617 electrometer with a current range of 2 pA–20 mA.

Fig. 2. Planar, strip, and dot electrodes fabricated onto the CdZnTe Pockels cell crystal.

A Pockels cell characteristic curve for CdZnTe sample was obtained by recording the current on the electrometer in 50 V increments, ranging from 0 to 1550 V. This measurement verified the behavior of the Pockels cell experimental arrangement, and also identified 1/4-wave voltage. The CdZnTe crystal was then exposed to neutrons in a radial beam port at the KSU TRIGA Mark II nuclear reactor at power levels of 100, 200, 300, 400, and 500 kW. At each power level, the differences in photodiode current with the shutter open and closed were recorded. A slab of borated high-density polyethylene (HDPE) and Pb provided an effective shutter for the neutron beam. After either opening and closing the shutter, the current measurements were delayed 5–10 s before recording a measurement to ensure a steady state reading. Afterwards, the same experimental arrangement and procedure were reproduced using a $2\times4\times25$ mm $LiNbO_3$ Pockels cell.

The Au electrodes on the CdZnTe sample were removed, the crystal was repolished, and new electrodes were placed on the same crystal faces. The cathode dimensions were kept the same, but the anode was changed to a 2×10 mm strip. During the experiment, the strip was oriented parallel to the laser light. A Pockels cell characteristic curve was obtained again over the same voltage range and the sample was exposed to neutrons at the same reactor powers, with the exception that the maximum reactor power used was 480 kW (limited due to the production of the reactor poison Xe during the procedure). The difference in photodiode current was again recorded with the shutter open and closed. The procedure was repeated a third time for the same crystal, but the anode dimensions were changed to a 1.5 mm diameter dot and the cathode was kept at 10×10 mm. When exposed to neutrons, the maximum reactor power was 460 kW (again, due to Xe production). The planar, strip and dot electrodes are shown in Fig. 2.

Because the best results were obtained from the dot electrode Pockels cell, the procedure was repeated once again for the dot electrode sample with higher stability electronics, including a new photodiode, laser, and power supply. The photodiode was a Pacific Silicon Sensor Q-series PS100-Q-BNC photodiode with a 100 mm^2 active region with a high QE for 1064 nm. The laser was a single longitudinal mode 1064 nm laser from CrystaLaser with and output stability of 0.25% over 2 h, a noise of $<0.5\%$, and a power range of 0–101 mW. The power supply was an AE-3R20 from Matsusada with a ± 3 kV range with a 0.001%rms ripple and a stability of 0.005%/Hr. Additionally, the change in photodiode current was observed as a function of laser power when the Pockels cell was neutron irradiated at a reactor power of 500 kW.

4. Experimental results

From the Pockels cell curves generated in Figs. 3 and 4, the 1/4-wave voltages for the CdZnTe device were determined to be 610 and 1500 V. Similarly for $LiNbO_3$ the first 1/4-wave voltage was 550 V, while the second was not considered for experimentation. The change in photodiode current using CdZnTe at different reactor powers for both applied biases is shown in Fig. 5. With the applied bias at the 1/4-wave voltage, the base photodiode current was approximately 700 nA with the neutron beam shutter closed. The deviation from the base current observed with the shutter open was recorded. The current from the photodiode *increased* steadily with *increasing* neutron flux at the first 1/4-wave voltage of 610 V. At the second 1/4-wave operating voltage of 1500 V (on the other side of the Pockels curve maxima), the current *decreased* from the base photodiode current of 700 nA with *increasing* neutron flux. The observed results are predictable from Fig. 3, where it is shown that an increase in the internal electric field at the lower inflection point (610 V) should cause an increase in current, and an increase in internal electric field at the higher inflection point (1500 V) should cause a decrease in current.

To ensure that the response was due to neutron interactions and not the gamma-ray component associated with reactor beams, a thin sheet of Cd was placed in the beam with the shutter open. The system responded as in the case for a closed beam, indicating that stimulus for the response was indeed neutron dependent. The experiment was repeated with the laser turned off as a test to ensure that the InGaAs photodiode was not responding to some other stimulus during the experiment. Identical experimental arrangements and procedures were executed with $LiNbO_3$ Pockels cell. However, no change in photodiode current was observed with incident radiation for the $LiNbO_3$ Pockels cell, even with reactor power increased to 640 kW.

A comparison of the Pockels cell characteristic curves for the planar, strip and dot electrode devices is shown in Fig. 6. Note that the magnitude of the characteristic curve is smallest for the planar device and largest with the dot sample. The maxima for the curves shift to different voltages because the internal electric field changes with the electrode design. However, the operating voltage was kept the same for all three Pockel cell variations when under test. The change in photodiode current as a function of reactor power, when using the CdZnTe Pockel cell biased at 700 V, is shown in Fig. 7. The change in transmitted light, and consequently the diode current, is largest for the Pockel cell with a

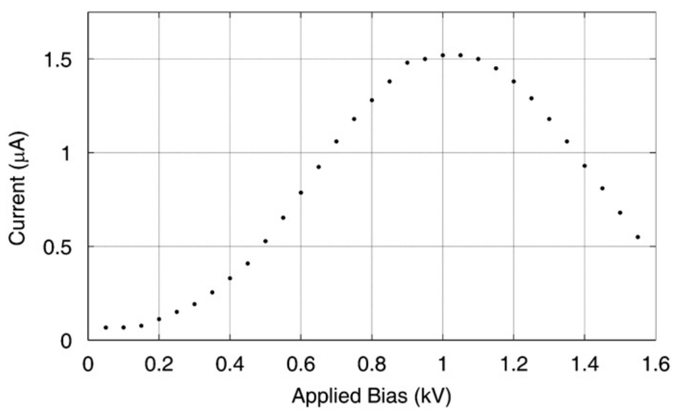

Fig. 3. The Pockels cell response curve obtained from the CdZnTe detector sample.

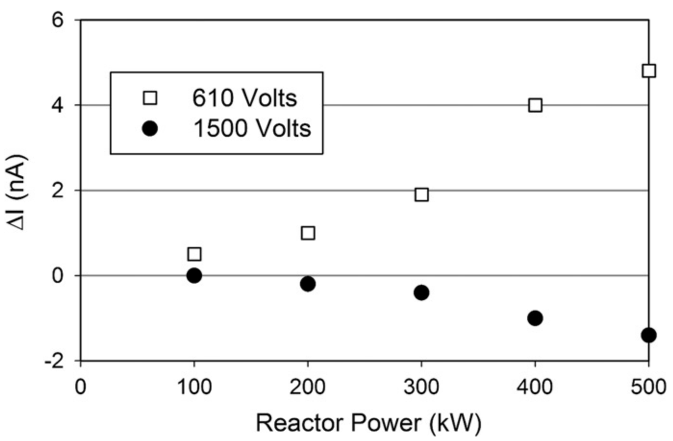

Fig. 5. Photodiode current response as a function of increasing reactor power for the CdZnTe Pockels cell. Shown are responses for CdZnTe Pockels cell bias voltages of 610 and 1500 V.

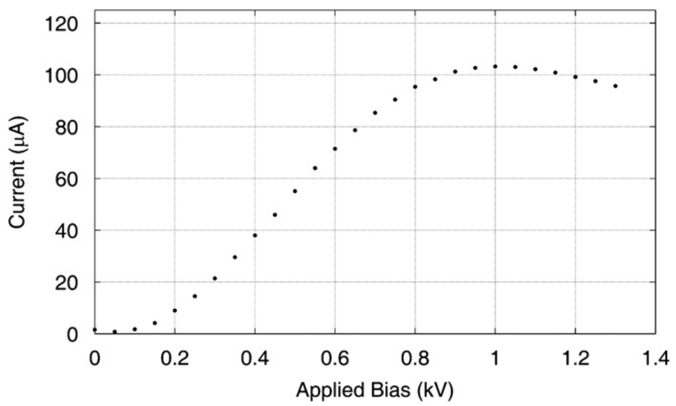

Fig. 4. The Pockels cell response curve obtained from the $LiNbO_3$ sample.

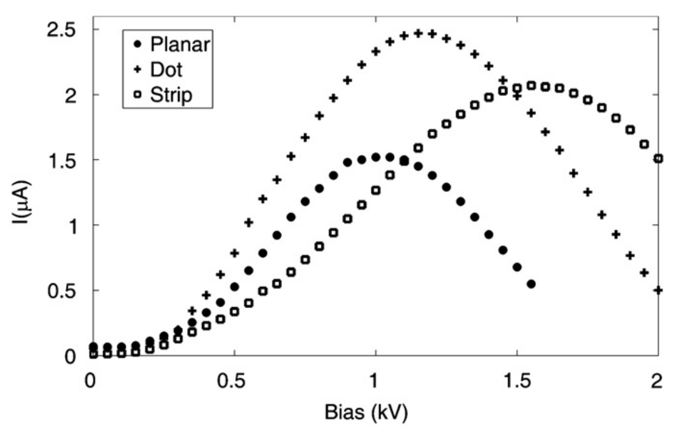

Fig. 6. The Pockels cell response curves obtained from the planar, strip, and dot electrode samples.

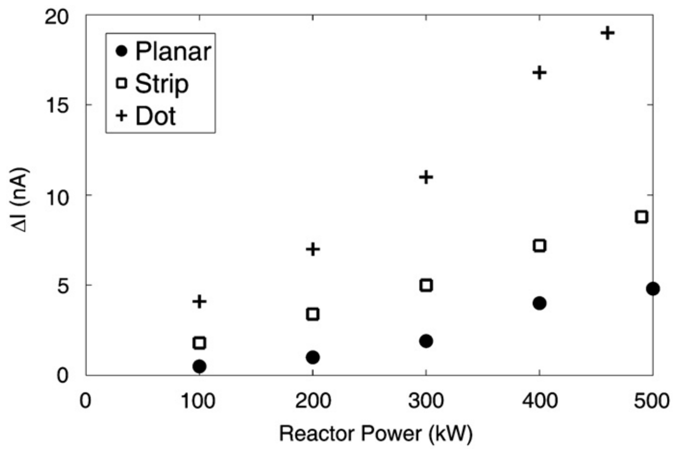

Fig. 7. Photodiode current response as a function of increasing reactor power for the CdZnTe Pockels cell for the planar, strip, and dot electrode samples. Shown are the responses for bias at approximately 700 V for all samples.

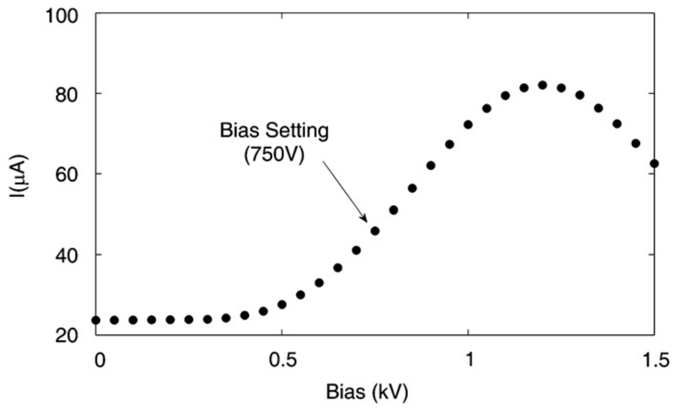

Fig. 8. The Pockels cell response curve obtained using the Pacific Silicon Sensor silicon photodiode, ultra stable power supply, and variable power laser set to 100 mW of power.

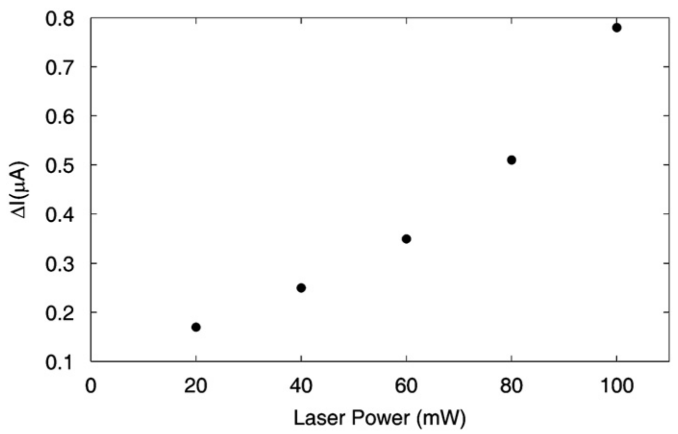

Fig. 9. The Pacific Silicon Sensor silicon photodiode current response as a function of increasing laser power for the CdZnTe Pockels cell with the dot electrode at a bias of 750 V.

dot electrode and smallest for the planar device. The strip electrode approximately doubles the sensitivity of the device to neutrons over the planar device, and the dot electrode approximately quadruples the sensitivity over the planar device.

The Pockels cell with the dot configuration was further investigated with a variable power laser with an ultra stable power supply. The dot configuration Pockels cell characteristic curve had a larger amplitude, as shown in Fig. 8. The 1/4-wave voltage was set to 750 V and the change in photodiode current, when exposed to 500 kW of reactor power, at different laser powers is shown in Fig. 9. Because the laser was variable power, the characteristic Pockels curve was obtained for a range of powers. It was found that the amplitude of the Pockels curve increased with increasing laser power.

5. Discussion

An increase in current in the positive slope of the Pockels curve at 610 V as well as a decrease in current at the negative slope of the curve at 1500 V for the first Pockels cell setup is clear indication that the Pockels effect is responsible for the change in light intensity, concurrent with an increase in the electric field within the device for both cases. Note that absorption by free electrons could account for diminishing light intensity, yet not for increasing light intensity. Hence, if the phenomenon was due to light scattering off free electrons, the observed current should diminish for all Pockels cell bias voltages. From the described observations, it is indeed the alteration of the internal electric field by charges liberated through radiation interactions, and the consequent change in polarization, that produces the change in light output and photodiode current.

The multiple electrode dimensions investigated show a larger response to neutrons as the anode area decreases (with respect to the cathode). Electrons liberated by radiation interactions are drifted apart by the voltage (and electric field) applied to the Pockels cell. For small anodes (strip and dot), the internal electric field is not constant and must be highest in the vicinity of the anode. The free electrons are forced to converge into a smaller volume defined by the anode, resulting in a denser electron cloud and a larger change in local electric field. As a result, the change in polarization is larger for laser light transmitted through the crystal sample, thereby leading to larger changes in current sensed on the photodiode. Subsequent experiments with the variable power laser showed that the amplitude of the characteristic curve increases, as does the response to neutrons. The magnitude of change in photodiode current is proportional to the amplitude of the characteristic curve and the strength of the radiation field. The ratio of the change in photodiode current to the amplitude of the characteristic curve stays relatively constant at equal reactor powers.

Two major differences in properties between the CdZnTe cell and the $LiNbO_3$ cell are the charge carrier mobilities and lifetimes. From Au foil activation analysis, the neutron flux at the exit plane of the radial beam port at 500 kW of power was $8 \times 10^6\,n\,cm^{-2}\,s^{-1}$, yielding an approximate average time between interactions of 125 ns. The charge carrier lifetimes in $LiNbO_3$, are considered to be of the order of 0.1 ns [7], whereas charge carrier lifetimes in CdZnTe are typically on the order of 0.2 μs. The electron mobility in $LiNbO_3$ is extremely small, yielding material resistivities on the order of 10^{15} Ω-cm. With the charge carrier lifetimes in $LiNbO_3$ being 4 orders of magnitude shorter than the average time between neutron interactions, coupled with low electron mobilities, the charge carriers are not sufficiently separated to create an electric field of strength necessary to produce an observable change in birefringence or rotation of the polarized light. Therefore, no change in photodiode current was observed for the $LiNbO_3$ Pockels cell when exposed to neutrons.

6. Conclusions

The Pockels effect has been successfully implemented to detect neutrons. CdZnTe, a birefringent semiconductor crystal with relatively long charge carrier lifetimes, demonstrated a change in electric field due to ionization within the crystal that is observable through the Pockels effect. This is the first recorded attempt to utilize the Pockels effect in a neutron detection system. On the other hand, $LiNbO_3$ did not produce such a response even though its composition is much better suited to capture neutrons and their reaction products, a consequence attributed to the very short carrier lifetimes associated with the material.

This optical form of signal formation demonstrates unique characteristics for a detection system, which include non-contact read-out and no pulse processing equipment. Other than the bias supply connected to the Pockels cell crystal, signal was extracted from the device with a sampling laser and a photodiode, both many centimeters away from the sensor crystal and well clear of the neutron irradiation beam during the experiment.

Acknowledgments

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