Proposal to Realize Radiation Tolerant Magnetic Immune Radiation Detector Readout Using Optical Phase-modulation-based Electro-optical Coupling

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Abstract

The goal of this research is to design and demonstrate an optical phase-modulation based radiation detector readout architecture, referred to as an Electro-Optically Coupled Detector (EOCD), for a large number of readout channels, that can operate in a high-radiation background, and/or high-magnetic field environments typical in particle physics experiments. Tests of optical intensity-modulation based EOCD using an Am-Be neutron source have demonstrated EOCD radiation tolerance for neutron fluences of 10^{10} per cm^2. Tests with a 3 Tesla superconducting magnet have demonstrated that the EOCD is tolerant to a high magnetic field. However, in our initial tests, instead of using optical phase-modulation, we used optical intensity-modulation with large optical power insertion losses (> 20 dB). To minimize optical power insertion loss, we have identified optical phase-modulation based EOCD as a solution to achieve low optical power insertion loss. This proposal is to (1) request \$15K to setup optical phase-modulation and balanced detection link for EOCD, and (2) request another \$5K (for a total request of \$20K) to prototype an Indium Phosphide (InP) based phase-modulator for verification of radiation tolerance and magnetic field immunity.

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Background

The approach we propose is the use of an ***electro-optically coupled detector*** **(EOCD)** architecture based on reading out silicon-based photon sensors via analog optical data link technologies as shown in **Figure 1**.

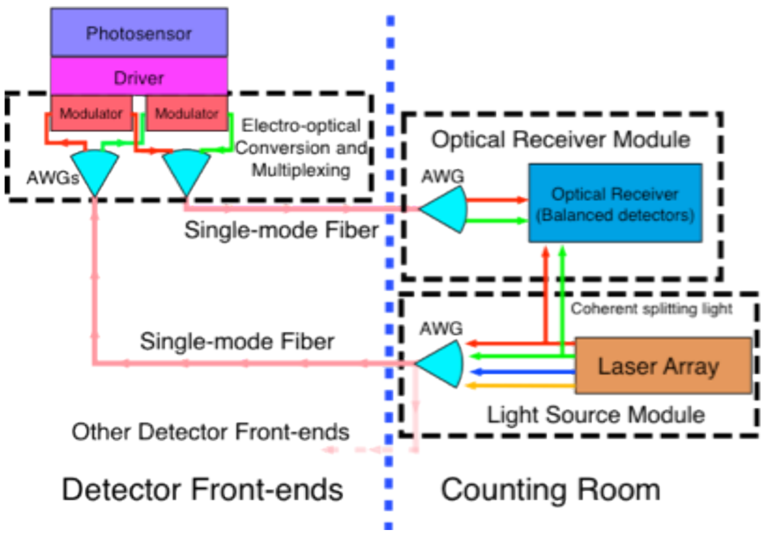

Figure 1: Proposed EOCD system diagram. In general, the EOCD detector front-end consists of three sub-modules: (I) a photosensor module, (II) a driver module, and (III) an electro-optical conversion and multiplexing module. Each modulator in sub-module (III) in a detector front-end takes only one wavelength demultiplexed from the incoming laser wavelengths (through an incoming AWG) and provides ***optical phase modulation*** (for pulses generated by the photosensor and its driver module). Optical signals produced through an array of such modulators, each with different laser wavelengths, are then multiplexed by an outgoing AWG to form an output through a single-mode fiber. Finally, the optical signals are transmitted through the output single-mode fiber to a remote counting room where conversion back to electrical signals by a *balanced detector* (with assistance of coherent splitting light from the laser array) and any necessary signal processing can occur in the receiver module far from the signal source.

Electro-optical coupling is a method of transmitting electrical charge pulse information from a photon-sensing device to a data acquisition system (DAQ) by converting the signal and sending it as a pulse of laser light through an optical fiber. In EOCD architecture shown in **Figure 1**, a laser-array light source module is based on multiplexing many different laser wavelengths through an Arrayed Waveguide (AWG) device. This light source module can be placed away from the detector front-end, inside a low radiation and low magnetic field location such as a counting room. The module provides each EOCD's detector front-end with many laser wavelengths through one single-mode fiber, and the laser power at these wavelengths can be divided and shared among many detector front-ends. In general, an EOCD detector front-end consists of three sub-modules: (I) a photosensor module, (II) a driver module, and (III) an electro-optical conversion and multiplexing module. Each modulator in sub-module (III) in a detector front-end takes only one wavelength demultiplexed from the incoming laser wavelengths (through an incoming AWG) and provides optical modulation and optical gain (for pulses generated by the photosensor and its driver module). Optical signals produced through an array of such modulators, each at a different laser wavelength, are then multiplexed by an outgoing AWG to form an output through a single-mode fiber. Finally, the optical signals are transmitted through the output single-mode fiber to a remote counting room where conversion back to electrical signals and any necessary signal processing can occur in the receiver module far from the signal source.

EOCD Characteristics

EOCD has several characteristics that are important for its use:

[1] Maintaining the fidelity of the original pulse (1% - 3% distortions)
[2] High detector readout density (> 64 channels per single-mode fiber)
[3] Radiation tolerance
[4] Immunity to magnetic fields, and
[5] Compact form factors

To understand the EOCD system, we have designed and built using commercially available components a two-wavelength demonstration system comparable to the proposed phase-modulation based EOCD system except using optical intensity-modulators as shown in **Figure 2**. The results have been published in [1].

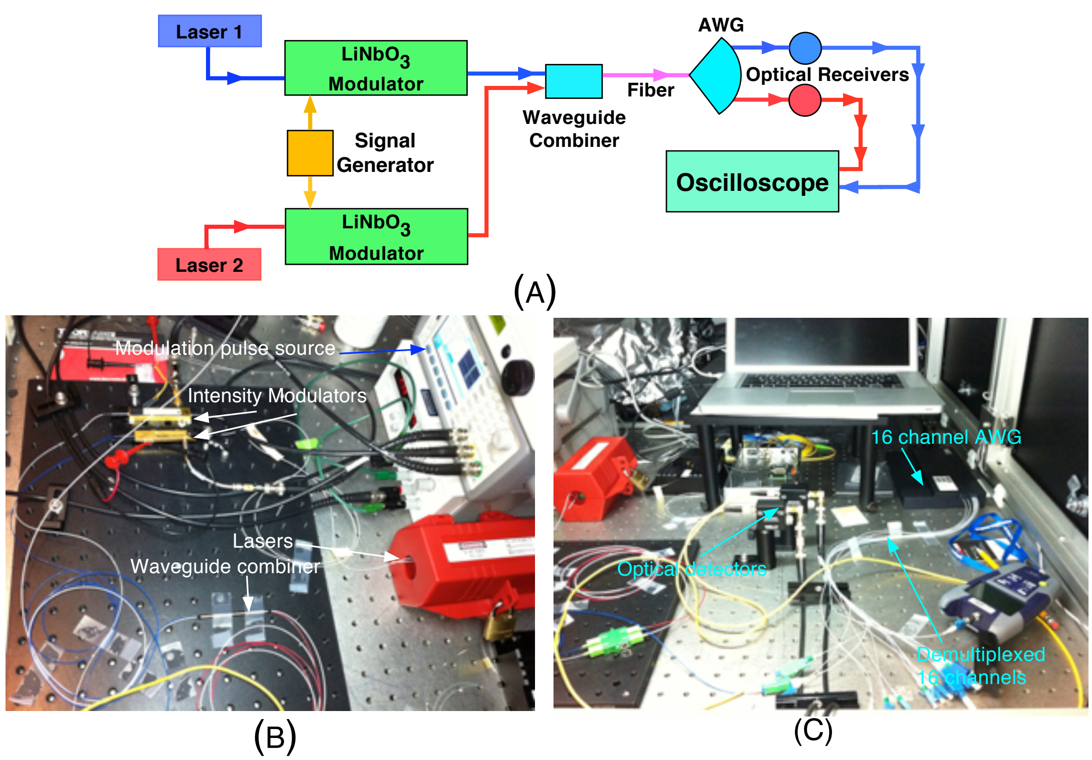

Figure 2: Top 2(A): Two-wavelength EOCD system diagram using intensity modulation. Bottom 2(B) and 2(C): Experiment setup using commercial components.

In the paper, we have successfully demonstrated two important aspects of the EOCD system (1) high signal readout fidelity, and (2) small inter-wavelength crosstalk among **W**avelength **D**ivision **M**ultiplexing (WDM) channels. By using a well-defined RF pulse source as the input of an EOCD system, we had compared the EOCD output RF pulse **rise time**, **decay time**, **full width at half maximum (FWHM)**, and **amplitude**, and demonstrated that EOCD is able to preserve analog signal features with better than 1%-3% distortion. We also demonstrated inter-wavelength crosstalk between adjacent EOCD readout channels (1.19 nm distance) after AWG demultiplexing of no more than ~ −14 dB. The inter-readout-channel crosstalk was shown to fall off even further with wider channel separation, with interference no more than −43 dB with two adjacent channels at a distance of 2.38 nm. The paper also discussed timing resolution, temperature stability and RF bandwidth issues related to the EOCD implementations

With current ~1.2 nm band-gap between each optical readout channels, up to 83 channels can be packed inside a single-mode fiber. For S-band ranging from 1460 nm to 1530 nm (total 58 channels) and for C-band ranging from 1530 nm to 1560 nm, 25 channels can be added inside a single-mode fiber. The total number of channels should be 83 in a single-mode fiber.

For the experiments described in our paper [1], a Lithium Niobate ($LiNbO_3$) modulator was used as the electro-optical coupling device with light amplitude modulation. However, it is well known that $LiNbO_3$ modulator is not radiation tolerant, nor is it immune to a strong magnetic field. Nevertheless, in this paper, we have carefully analyzed the radiation tolerance requirements of detector instrumentation for high-energy physics and nuclear physics [1]-[5], and outlined possible radiation hardness solutions in designing and implementing EOC modulators, fibers [6], AWGs, *etc*.... In a previous paper [1], it was proposed to use Indium Phosphide (InP) material for future modulators.

Following the previous publication [1], we have successfully prototyped an integrated InP-based silica chip in collaboration with University of Maryland Baltimore County (UMBC) Photonic Device and System Testing Laboratory. In this chip, three components were integrated together, *i.e.*, (1) an InP-based quantum-well laser, (2) an InP optical waveguide to guide the laser emitted light, and (3) an InP electro-absorption modulator in an area less than 0.5 mm^2 size, as shown in **Figures 3 to 6**. ***With the prototyped device, we have tested the modulator's radiation tolerance and immunity to strong magnetic fields experimentally*** **(see Figures 4 and 6)**. The results were submitted to upcoming IEEE NSS/MIC 2016 conference to be held in Strasbourg, France.

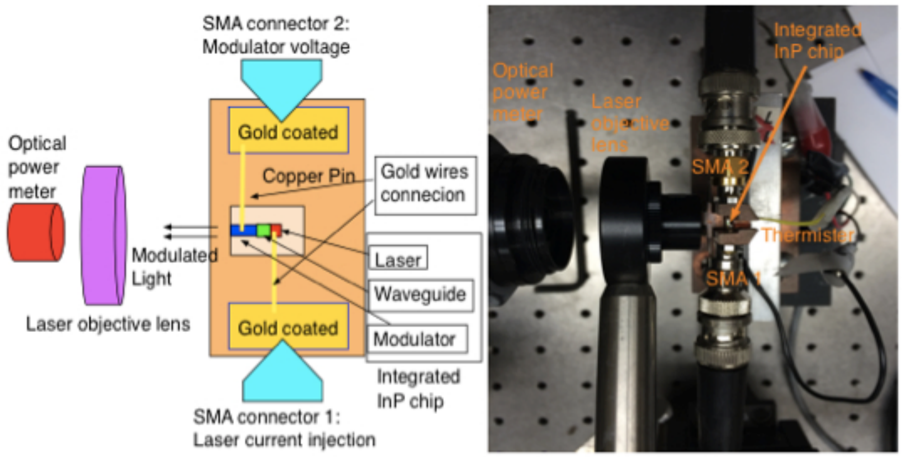

Figure 3: Radiation tolerance testing for the InP-based integrated laser, waveguide, and modulator chip mounted on a copper pin (too small to be seen in the right figure). The left figure is the system diagram of the radiation tolerance testing for the InP chip.

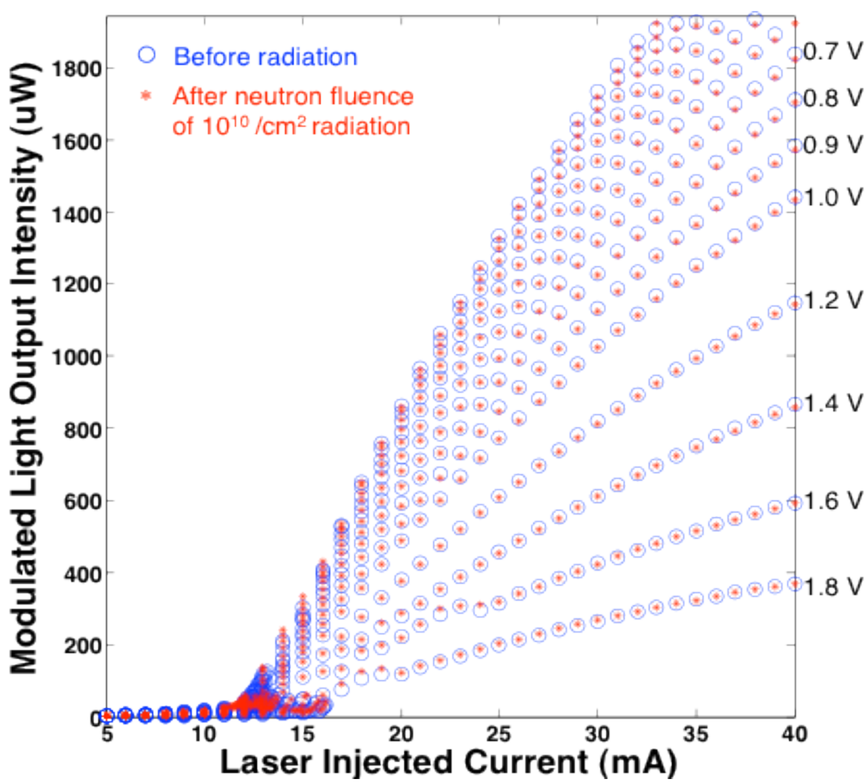

Figure 4: Radiation tolerance testing before and after radiation (with post-irradiation annealing). Left vertical axis indicates modulation voltages.

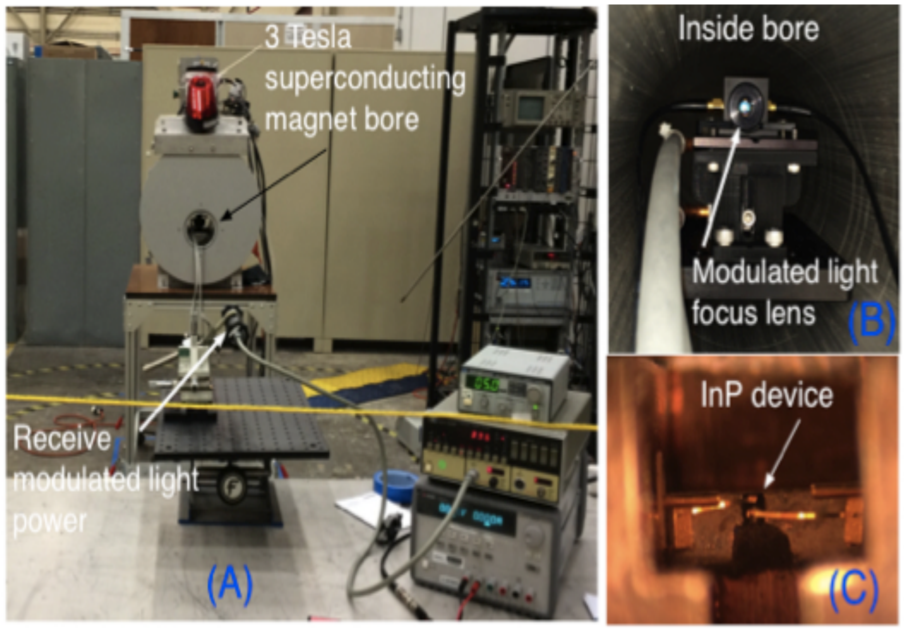

Figure 5: Strong magnetic field 3 Tesla InP device testing: (A) Setup, (B) device mount inside superconducting bore, and (C) InP device installed on the top of a copper pin.

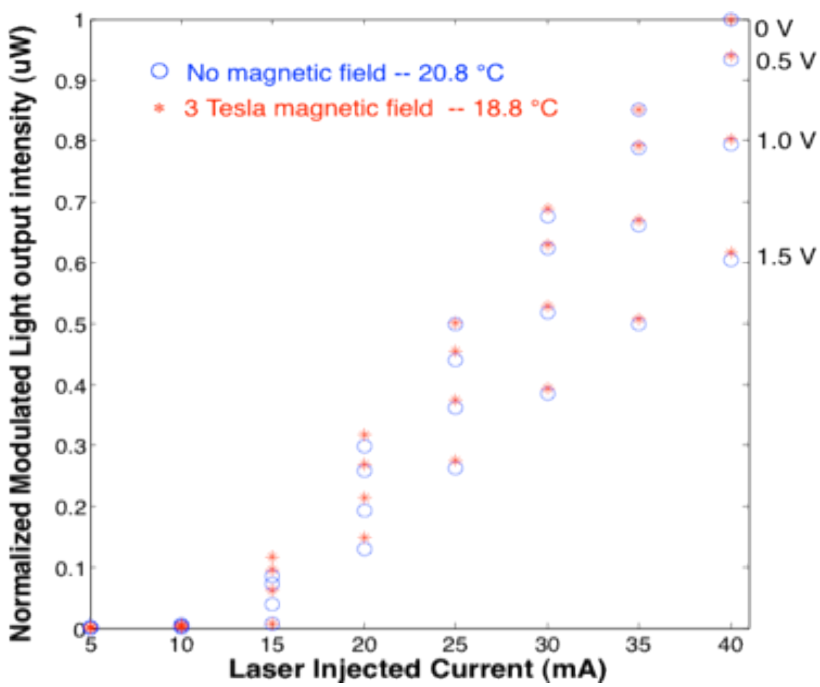

Figure 6: Normalized modulated light intensity comparison: no magnetic field and 3 Tesla magnetic field.

Optical Power Loss in EOCD

In order to launch and preserve the RF signal (from radiation sensor) into an optical transmission, an efficient modulation scheme is an important factor in minimizing RF signal insertion loss (electro-optical conversion loss). Current modulation schemes include optical intensity modulation (IM), frequency modulation (FM), and phase modulation (PM) [7], and complete description of these modulation/demodulation can be found in [8]. The three modulation schemes can be realized by either *direct modulation* or *external modulation* [8]. Direct modulation occurs when a varying current is applied directly to the *laser* controlling the light output. External modulation occurs when an *external device* modulates light, *e.g.*, an electro-absorption modulator or a Mach–Zehnder interferometer. **Table 1** shows the comparisons among three modulation schemes: IM, FM, and PM.

Table 1: Comparison Among Three Modulation Schemes and Their Realizations

Modulation	Modulation Realization	Insertion Loss/Gain (dB)	Detection	WDM Realization
IM	Internal	–10	Direct detection	No
	External	–11 to –17	Direct detection	Yes
FM	Internal	+10	Balanced detection	No
PM	External	0 to +10	Balanced detection	Yes

As one can see, IM modulations always has a large insertion loss, and this loss could easily degrade the entire optical link signal with a –20 dB loss [9][10]. However, both FM and PM provides insertion gains with a relative complex balanced detection scheme [7][11]-[13]. This valuable insertion gain is equivalent to install an optical pre-amplifier for a detector front-end. Because internal modulation realization implies laser placement within the detector front-end, it is impossible to have a precise wavelength control mechanism inside a limited space with harsh radiation/magnetic environments, and this then rules out WDM implementation. It becomes clear for us that PM-modulator is the choice for our EOCD implementation.

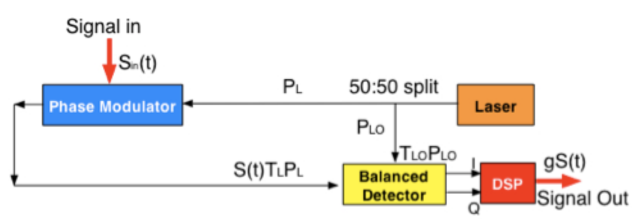

Figure 7: External phase modulation with balanced detector.

In the proposed EOCD research we employ a coherent phase modulation and balanced detection scheme. The EOCD architecture allows the lasers and detectors to be easily co-located, *i.e.*, inside a counting room far away from the EOCD detector front-end. Only the compact and simple-structured phase modulator is placed inside the radiation detector front-end, as described in EOCD architecture shown in **Figure 1**. In a realistic optical link experimental setup in **Figure 7** using the PM-modulator and balanced detector, only a fraction of power travels through the link that has an insertion loss – the local oscillator power (the coherent splitting light power from laser) is going directly to the balanced detector. Because of the relatively narrow sub-GHz bandwidth one can use a longer phase modulator to lower the half wave voltage and use the capabilities of a DSP unit to obtain the signal using a very simple algorithm of $\Phi(t)$ = arctan($I(t)$ / $Q(t)$) where I and Q are the outputs of the balanced detector [7][13]. The gain of the link can be estimated as

$$G = \frac{\pi^2 P_L P_{LO} T_L T_{LO} R_s^2 r_d^2}{V_\pi^2}$$

For example, let assume 100 mW laser, $P_L = P_{LO} = 40$ *mW* are the input powers in the signal and local oscillator channels, $T_L = 0.2$ is the transmission of the link, $T_{LO} = 0.2$ is the transmission of LO channel, R_s= 50 Ω is the impedance of the source, and $V_\pi = 1V$ s a half-voltage, and r_d=1.2 *A/W* is the detector responsivity. These numbers render a realistic optical link gain G = 9.09 (9.58 *dB*).

To implement the system with a radiation tolerant modulator, we choose to fabricate an InP/InGaAsP based phase modulator. As we demonstrated in our preliminary experiments, the InP/InGaAsP-based modulator is radiation tolerant. Outside the EOCD detector front-end area, we can use commercial coherent detection system to obtain phase detection and DSP chips to linearize it. **Appendix 1** presents several fabricated modulator devices using radiation tolerant InP process fabricated by our collaborators, such as *phase modulator for digital communications*, optical delay lines and an interferometer for an *intensity modulator*, and a FM laser integrated with interferometer (internal *FM modulator*). The proposed analog PM-modulator device can be realized based on the digital communication phase modulator structure in **Appendix 1**. However, the design revisions are needed to adapt the proposed analog PM-modulator, such as its device modulation length and efficiency, bandwidth, and phase linearity.

Specific Aims

Eliminating high optical insertion loss from optical intensity-modulation is the goal in this proposal. In this regard, we have already been seeking to optical phase-modulation to improve the entire EOCD performance. To facilitate the development of a low optical insertion loss, radiation tolerant and magnetic immune EOCD readout, we are proposing the following specific aims to be accomplished over **a period of one year**. We anticipate towards the end of this study we will be better prepared to propose further studies to continue to improve this technology for nuclear physics applications.

Specific Aim 1: Obtain 2 commercial lithium Niobate phase modulators and 2 balanced detectors, and set up standard two-wavelength EOCD prototype and compare performance characteristics to early experiment with amplitude modulation.

Specific Aim 2: Prototype two InP based phase modulators by replacing the previous silica integration from an amplitude modulator to a phase modulator.

Specific Aim 3: Repeat standard testing with radiation tolerance and magnetic field, generate reports.

Test Setups

There are three benchtop setups for characterizing the performance of the EOCD system. The first one is shown in **Figure 2**. This has been developed for characterization of EOCD system in [1] for both time domain and wavelength domain. These characteristics include pulse shape distortion, rise time, decay time, FWHM, wavelength crosstalk. With experiment modifications from **Figure 2** to **Figure 8**, similar experiments can be done for the proposed phase-modulator based EOCD system. There are also second and third test

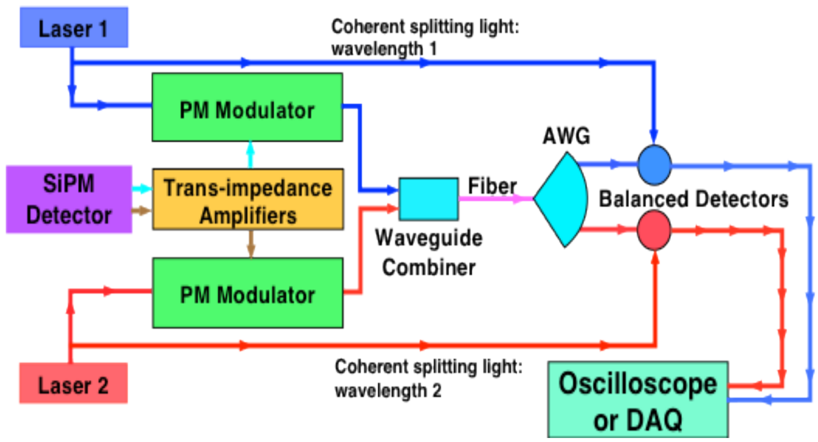

Figure 8: Two-wavelength EOCD experiment with optical phase-modulator and balanced detectors.

setups, as shown in **Figure 3 and 5** to (a) measure the radiation tolerance of EOCD InP modulator device, and (b) measure its strong magnetic field performance. Similar setups can be used for InP based optical phase modulator characterization.

Budget Justification

Because creating a fully customized EOCD is an inherently expensive process, we are proposing to use commercial phase modulator first in order to (a) testing the phase-modulation based EOCD implementation and its optical link power budget, and (b) use the funding to prototype an InP modulator based on our previous experience with IM modulator chip.

We propose a total of $20K as funds for this proposal. Of this $15K is expected to be used as costs in developing a bench-top two-wavelength EOCD. These include two sets of devices with two different wavelength lasers, phase modulators, and balanced detectors. The remaining $5K would be used for consumable materials necessary for manufacturing modifications or improvements to the present silica InP chip (to include phase modulator) incurred at UMBC' MOCVD facility and clean room. UMBC Photonic Device and System Testing Laboratory donates its facility and people for free for chip manufacturing.

Key Personnel

The Radiation Detector and Imaging Group in the Physics Division of Jefferson Lab is a team of seven researchers, comprising four Ph.D scientists, a mechanical engineer, an electrical engineer and a software developer. The Detector Group is a core capability of the Thomas Jefferson National Accelerator Facility in Newport News, Virginia.

Wenze Xi, Ph.D., Principal Investigator: (25% of FTE) is a Staff Scientist in the Radiation Detector and Imaging Group. He has over 10 years experience in the area of radiation detector research and optical transmission research. He developed a 3D sub-millimeter resolution gamma imaging system based on SiPMs and a dual PET/SPECT small animal imaging system for Cancer drug screening. He is the Jefferson Lab expert in Nuclear Medicine Physics and detector technologies. He will be dedicating 25% of his time to the effort and will oversee the complete technical aspects of the project.

Carl Zorn, Ph.D., Co-Principal Investigator: (15% of FTE) is a Staff Scientist in the Radiation Detector and Imaging Group. He has over 20 years experience in the area of scintillator implementation research and photon detection technology. He developed a beam monitoring system based on PSPMTs and is the Jefferson Lab expert in the evaluation and use of silicon photomultipliers (SiPM). He will be dedicating 15% of his time to the effort and will assist technical aspects of the project.

Andrew Weisenberger, Ph.D., Co-Investigator, (5% FTE), is Group Leader for the Radiation Detector and Imaging Group in the Department of Physics at Jefferson Lab. He has over 15 years experience in the area of detector instrumentation development and data acquisition system design. He will insure the lab resources are available to the project and coordinate between the Detector Group and University of Maryland at Baltimore County.

Jefferson Lab Resources

The JLab Physics Division has three instrumentation development groups: 1) the Radiation Detector and Imaging Group, 2) the Fast Electronics Group and 3) the Data Acquisition Group. These have scientists, engineers and technicians who possess core competencies in several technical areas useful for supporting nuclear physics research. The three groups have expertise in several areas relevant to radiation detector development and testing, including: 1) component technologies of pixellated scintillators, position-sensitive photomultiplier tubes, solid state detectors and light guides; 2) fast analog and digital detector readout electronics design and construction; 3) software development for real-time computer-controlled data acquisition.

Jefferson Lab has all the necessary facilities, tools, computer workstations and expertise to design, construct and perform laboratory evaluations of the detector systems. In addition to open laboratory areas and tools available to the general research personnel at Jefferson Lab, the Detector Group has two laboratory work areas available to it exclusively on the Jefferson Lab campus. One 1600 ft^2 lab is in the Experimental Equipment Laboratory (EEL) and the second is a 600 ft^2 lab in the Jefferson Advance Research Center (ARC). Both facilities are on the Jefferson Lab campus. Within these labs there are various pieces of equipment and tools necessary for detector development and testing. These items include radioactive calibration sources, digital and analog oscilloscopes, dark boxes for photon-detector and scintillator testing, high voltage supplies, several computer workstations interfaced to PCI, CAMAC, VME based and FPGA Jefferson Lab developed USB2 analog to digital electronics**.**

JLab has already performed a variety of radiation tests of SiPMs and has both gamma (^{137}Cs, ^{60}Co) and neutron (AmBe) sources for controlled tests. Although controlled tests are difficult in the experimental halls, high rate gamma/neutron irradiations are also possible in one or more of the three current experimental halls.

UMBC MOCVD Laboratory and Clean Room Facility
Our collaborator UMBC photonic device lab has all equipment necessary for Phase modulator manufacture, including two 2-inch wafer MOCVD reactors, gas farm, gas cabinets, scrubber, and gas and air handling facility, toxic gas monitoring systems, chemical hoods, X-ray rocking curve. Mask aligners, spinners, IR microscopes, alpha stepper, RIE systems, UV Ashers, thermal oxide system, e-beam and thermal evaporators, Chemical hoods, cabinets. Holographic Grating Fab. System: UV argon lasers, holographic exposure setup. AR Coating and measurement system: e-beam AR coating system, reflectivity measurement setup.

UMBC Photonic Device and System Testing Laboratory:
L-I, I-V testing setup, PL, EL measurement systems, Low temperature and long wavelength (up to 2500 nm) PL testing system, small and large signal modulation measurement setup, Bit error rate testing sets (622 Mb/s and 5Gb/s systems).

UMBC Clean Room Facility
Gas and air handling facility, Mask aligners, spinners, IR microscopes, alpha stepper, RIE systems, UV Ashers, thermal oxide system, e-beam and thermal evaporators, Chemical hoods, cabinets. Holographic Grating Fab. System: UV argon lasers, holographic exposure setup. AR Coating and measurement system: e-beam AR coating system, reflectivity measurement setup

Timeline

Months	1	2 3	4 5	6 7 8	9 10	11	12
Order EOCD system components	o --- x						
Setup EOCD system experiment	o ---	--- x					
Test EOCD with Phase-modulation			o --- x				
Acquire phase modulator chip and test			o ---	--- x			
Irradiate and magnet testing chip					o --- x		
Final measurements of EOCD with chip						o --- x	
Prepare technical report							o --- x

o – Task starup

x – Task complete

Reference:

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APPENDIX 1: FABRICATED MODULATORS FOR THREE TYPES OF MODUALTION

A radiation tolerant modulator can be designed and fabricated using an InP/InGaAsP process. The PM-modulator can be realized using a interferometer structure. The following devices and structures were all designed and manufactured in University of Maryland at Baltimore County (UMBC).

Figure (I) shows the fabricated digital phase modulator devices. Figure (II) shows a delay line (left) and an interferometer (right). Figure (III) shows the integrated FM laser with interferometer

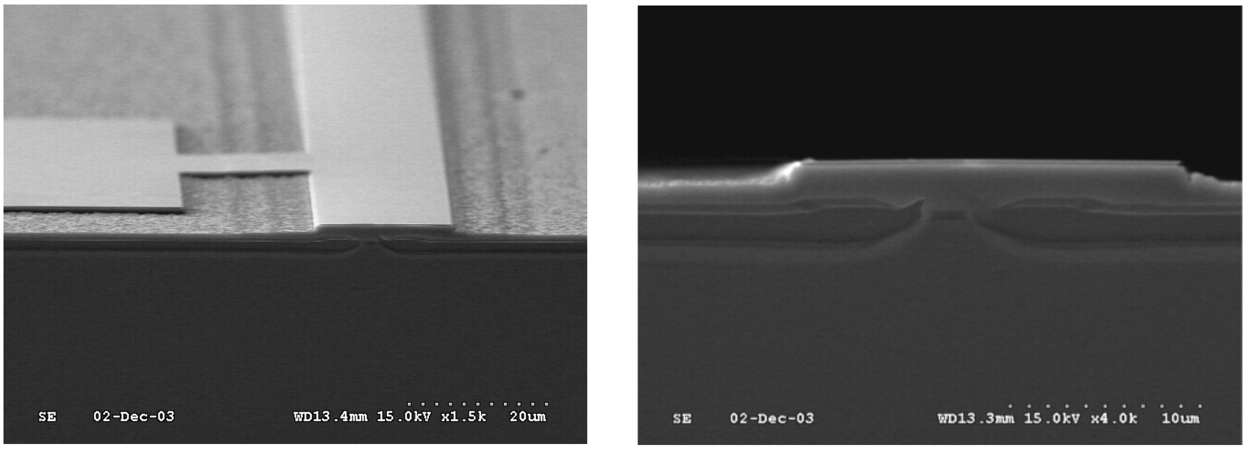

Figure (I): A fabricated phase modulator device for telecommunications. Left figure: RF contact pad, Right figure: scanning electron microscope picture of the cross section of the phase modulator device.

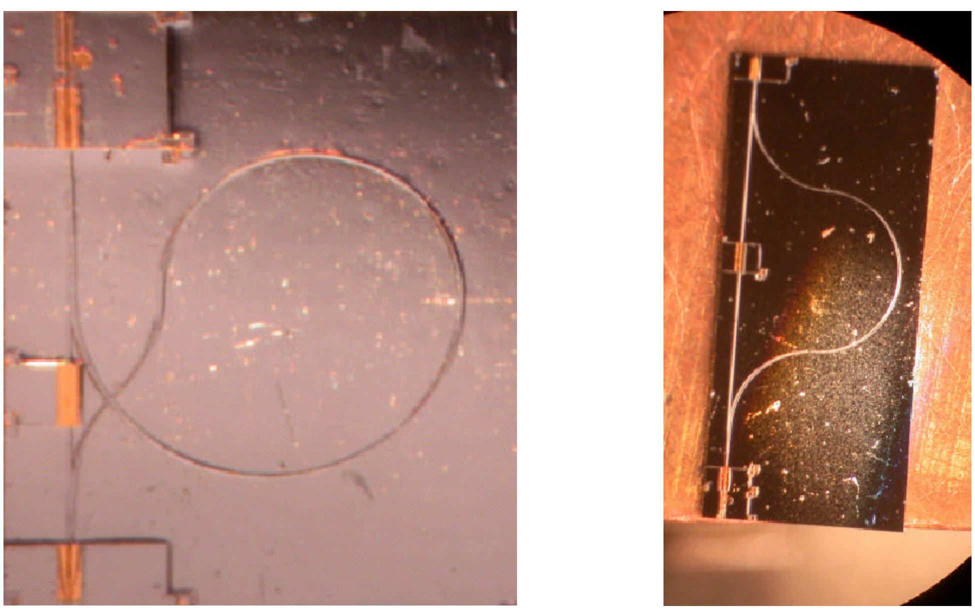

Figure (II): Left figure: a delay line. Right figure: an interferometer for intensity modulation

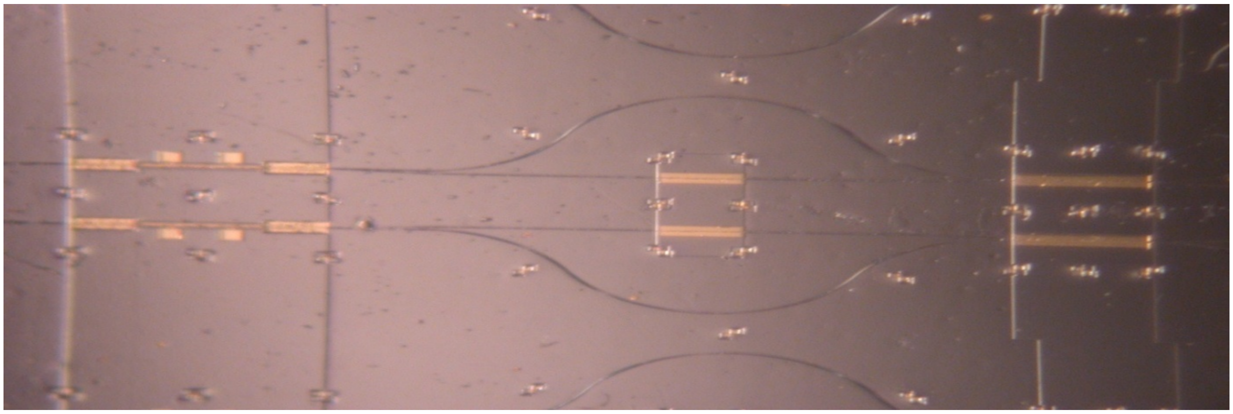

Figure (III): an integrated FM laser and interferometer