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Power over fiber development for HEP detectors

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ABSTRACT

Power-over-Fiber (PoF) technology has been used extensively in settings where high voltages require isolation from ground and electromagnetic isolation is critical. In cryogenic environments, PoF offers a reliable power transmission technology, leveraging optical fibers to transfer power with minimal system degradation. PoF technology excels in maintaining low noise levels and isolation when delivering power to sensitive electronic systems operating in extreme temperature ranges and high voltage environments. In a novel application of PoF for a HEP detector, power is provided to photon detector modules located on a surface at ~300 kV with respect to ground in the planned DUNE experiment. This summary paper of the PoF talk at the 16th PISA Meeting on Advanced Detectors highlights the R&D effort of PoF in extreme conditions and underscores its capacity to revolutionize power delivery and management in critical applications offering a dependable solution with low noise, optimal efficiency, and superior isolation. The DUNE (Abi et al., 2020) experiment will soon deploy large liquid argon (LAr) time projection chambers (TPC) to detect neutrino interactions and other particle physics phenomena. In addition to the particle tracking provided by the TPC, photon detectors, powered by a first ever PoF system, in the cryostat will leverage the high scintillation light yield of LAr to provide crucial timing and additional calorimetric information.

1. PoF overview

Optical fibers have broad applications in underwater power transmission, telecommunications, rotor blade monitoring systems, current and voltage sensors in high-voltage environments, and many other areas discussed in literature. Optical fibers are used in cryogenic applications for tasks like detecting quenches in high-temperature superconductors, infrared instruments for space and in quantum computing experiments conducted at very low temperatures. However, their use for carrying high intensity photon power in a cryogenic application is novel. Additionally, due to single photon sensitivity of the HEP DUNE far detectors [1], development of a light tight system was a critical design constraint. Finally, the system development was treated as 'launch' technology. The system, once deployed in a large detector, is expected to be operational for the entirety of the detector's lifetime; like a space launch, repairs are not feasible. Components and testing procedures were developed and performed to ensure 30-year viability with minimal impact to the HEP physics performance. A more comprehensive description of the PoF development can be found in DUNE vertical drift document [2] and JINST Preprint [3] Paper.

Each of the PoF components, lasers, fiber and optical photovoltaic converters (OPC) existed but as a system had never been used in a cryogenic power system. The development largely focused on the cryogenic side of the HEP application system which included the fiber and OPC hardware. A variety of fiber jackets were tested before choosing a FC terminated black polyvinylidene fluoride (PVDF) jacketed fiber. Sheathing opacity prevents light from leaking out of the fiber and minimizes background light noise to the photon detector system (PDS) [2]. The power for the electronics is obtained by paralleling two gallium arsenide (GaAs) OPCs connected on a cold readout board. The semiconductor GaAs OPCs convert the optical power to electrical

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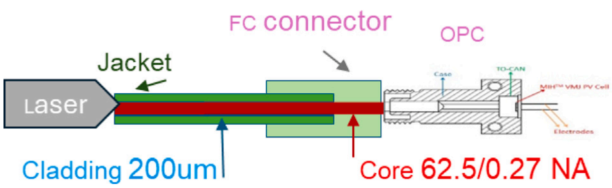

Fig. 1. PoF basic components.

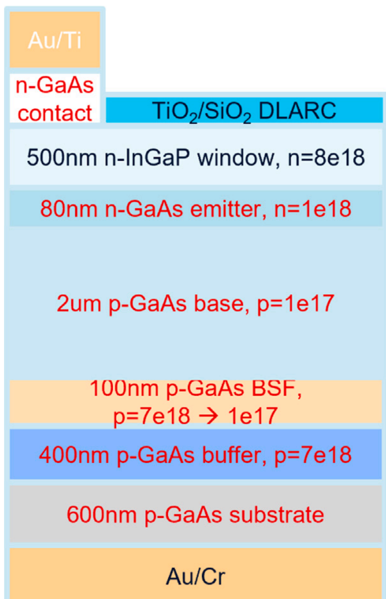

Fig. 2. GaAs OPC.

power at an efficiency that depends upon the load matching to laser power and to a lesser extent upon the temperature [4]. This innovative PoF solution provides three major benefits:(1) voltage isolation, (2) noise immunity, and (3) spark-free operation. The two components extensively explored and developed were OPCs and fiber hardware (see Fig. 1).

2. OPC overview

OPCs are semiconductor devices used to convert optical power into electrical power. OPCs are typically categorized as either single junction or multijunction devices, with the majority of modern OPCs falling into the multijunction category, Fig. 2. These multijunction designs, such as the vertical epitaxial heterostructure architecture (VEHSA) design from Broadcom [5], are composed of many semiconductor sub cell layers.

Modifications to the GaAS OPC semiconductor layering and materials to support electron carrier motion and packaging to handle the higher laser power improved the cryogenic efficiency by 100% with a slight negative impact to the warm efficiency. The GaAs OPC maximum efficiency can reach approximately 55% in ideal conditions, which is significantly higher than the silicon OPC option that reaches approximately 20% at desired power levels.

3. DUNE PoF use case

The development of the DUNE vertical drift (VD) TPC [2] configuration with its largely unobstructed geometry presents an opportunity to

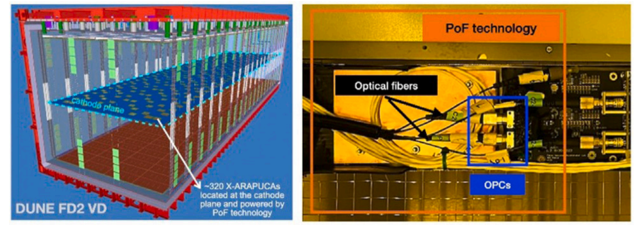

Fig. 3. DUNE overview and electronics board with two OPCs.

provide excellent photo-detection coverage using 320 photo-detectors known as X-ARAPUCAs [6] placed in the cathode plane provided that the X-ARAPUCAs can be electrically isolated for safe operation on high-voltage surfaces of the cathode. This requirement is met for the Photon Detector System (PDS) of the DUNE VD detector using PoF in a novel application both in particle detectors for high energy physics and in cryogenic environments. PoF transmits laser power over lightweight, non-conductive optical fiber to a remote photovoltaic receiver called an optical power converter, OPC, allowing the operation of remote sensors or electronics. Existing PoF technologies are commonly employed for voltage isolation between source and receiver and embedded electronics in high voltage or high noise environments. However, none of the commercially available PoF system technologies are rated to operate in cryogenic environments such as liquid argon (LAr) or liquid nitrogen (LN2).

In the PoF HEP DUNE application shown in Fig. 3, multimode fibers with a core radius of 62.5 um are utilized to transmit the laser diode power to the OPCs located on each X-ARAPUCAs electronics board. The DUNE PD cathode power requirement and PoF capability resulted in the use of two OPCs per X-ARAPUCA. The individual PoF units, using 800 mW Laser power and 20 meters of cold fiber, can deliver to the cold electronics approximately 370 mW. With two OPC units in parallel, the power delivered can reach about 700 mW, which is 150 mW over the requirement. The PoF has been designed with two OPCs per X-ARAPUCA but can operate with a single unit at twice the laser power if necessary. This is less desirable due to higher fiber risks and OPC efficiency degradation.

4. Conclusions

This novel application and technology development effort has resulted in PoF becoming an accepted tool for use as a cryogenic HEP detector power delivery system. Detailed studies of optical power loss at cryogenic temperatures for multiple optical fiber lengths submerged in LN2 showed a linear dependence on the input power and the amount of fiber submerged. At the planned laser power of 800 mW, the 3.2mW/m jacketed fiber is achieved and acceptable. The physical properties and selection process of the entire PoF delivery system were analyzed, resulting in a successful final design. One example of property analysis is Jacket compression losses, such as PVDF jackets, which were shown to have three times greater power loss than fibers without jackets when submerged in LN2. A tensile strength test made it possible to estimate an approximate breaking point of $\sim$ 5.5 kg for the studied PVDF optical fiber at room temperature and $\sim$ 6 kg in LN2 including buoyancy. Breaking weight is 10 to 20 percent beyond damage weight and not quoted in literature but is critical for POF use case. A long-term test of the OPC operating in LN2 showed that during $\sim$ 6.1 months of operation, the efficiency variation from conversion of optical-to-electrical power is less than 2.6%. Laser fluctuations have been studied under different input powers, and it was observed that the laser transmitter's power stabilizes after $\sim$ 25 min of operation. This result was expected, based upon industrial partner conversations and experiences, and satisfies DUNE testing requirements. During ∼ 6.1 months of the long term test operation, the laser temperature and laser current variations remained below 2.5 °C and 225 mA, respectively. The results presented in this paper serve as a foundation for future endeavors towards the use of PoF technology in other systems operating in HV environments and cryogenic conditions, such as HEP dark matter experiments, space exploration technologies, and other applications where low noise, superior isolation, and optimal efficiency are needed. Further investigations are underway to continue improving the PoF technology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: William Pellico reports financial support was provided by Fermilab. William Pellico reports a relationship with Fermi National Accelerator Laboratory that includes: employment and travel reimbursement. None If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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