Analog optical signal transmission for high-energy physics experiments

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SLAC
Introduction

Digital Optical Links
Digitization on front-end, transmission of digital signal (bits), decoding at DAQ side.

+ Much industry experience and many components (mostly for room temperature operation in vacuum and air)
+ Noise margin advantages
+ Flexibility in coding (error detection/correction)
+ Time Division Multiplexing may be employed
  - Signal-to-quantization noise is unavoidable

Analog Optical Links
Accurate conversion of the electrical pulse into optical on front-end preserving pulse shape and current-modulation of a laser (modulating optical power or optical signal amplitude), transmission in analog form.

+ Lower cost and complexity in typical installations, less components prone to failure
+ Possible to design with low power consumption and heat dissipation

→ Can find good application in extreme environments as well as remotely deployed and inaccessible experiments: cryogenic temperatures, noble liquids, high electric and magnetic fields, explosive media, high radio-frequency noise environments, large distance from the detector to DAQ, low-power requirement applications

Imposed challenges:
Little industry experience
Unknown functionality in extreme temperatures and in highly-refractive media
Higher signal-to-noise ratio requirements typically imply higher optical power
Transfer function must be well characterized to insure extraction of original signal
Light source choices

Analog optical signal can be transmitted using an incoherent light source (LED) or coherent (Laser)

After initial tests, an edge-emitting Fabry-Perot (FP) laser diode was selected for further R&D

Output beam of the laser has an elliptical shape with the “fast” end “slow” axes

Multi-mode laser diode was selected for higher available power (~1-2mW)

[Diagram of Fabry-Perot laser diode]


FC connector was chosen among all available for robustness, materials with low thermal expansion coefficient, self-alignment, potential for customization and application in low-radioactive background experiments

[Diagram of FC connector]
Optical fiber choices

One of the main parameters for optical fiber is the diameter of the core.

R&D started with 9μm single-mode fibers for the reasons of possible modal noise appearance (later in slides).

Progressively studied various multi-mode fibers with 50μm, 62.5μm, 125μm diameter core.

Each has advantages depending on specific application (i.e. smallest and largest signal that needs to be transmitted and required signal/noise ratio).

Outer jacket that was found the best is black PTFE (teflon), due to suitability for application in cryogenic liquids and protection against light leakage in higher-power applications and light-sensitive environments.

- **single-mode 9μm**
- **multi-mode 50μm**
- **multi-mode 62.5μm**
- **multi-mode 125μm**
Spectral characteristics of Fabry-Perot laser diode

The selected laser diode operates at near-infrared (NIR/SWIR) wavelength of 1310 nm, common in data communication, and is based on indium gallium arsenide phosphide (InGaAsP) semiconductor.

The emission spectrum is very sensitive to temperature. Spectral shift can be predicted with Varshni equation (1967)

Parameters for InGaAsP: $\alpha = 4.9 \times 10^{-4} \text{ eV/K}^2$, $\beta = 327 \text{ K}$

“Temperature Dependence of Photoluminescence of n-InGaAsP”


Compute the 0 K band gap, using $E_g(300 \text{ K}) = 0.949 \text{ eV}$, solve for $E_g(0 \text{ K})$ using Varshni’s equation:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}$$

$$E_g(0) = 1.019 \text{ eV}$$

Plot photoluminescence wavelength:

```
\begin{align*}
\text{Wavelength (nm)} & \quad 1.20 \times 10^3 \quad 1.25 \times 10^3 \quad 1.30 \times 10^3 \quad 1.35 \times 10^3 \quad 1.40 \times 10^3 \\
\text{Temperature (K)} & \quad 0 \quad 100 \quad 200 \quad 300 \quad 400
\end{align*}
```

Shift 0.4 nm/K in the central spectral peak
Theoretical and experimental spectra

Predicted wavelength at room temperature and in liquid nitrogen:

**Calculated:**
- 1301 nm at 295 K  
- 1222 nm at 75 K

Measurements with an optical spectrum analyzer (spectroscopy with a diffraction grating):

- **Room temperature**
  - Center WL 1312 nm

- **Liquid argon**
  - Center WL 1232 nm

**Mode spacing 1nm:** cavity L=0.75nm
Signal source - silicon photomultipliers

Single photon detection signals are known to be difficult to extract from the detector, prone to pick-up of EM noise in the signal path.

One of the applications that can greatly benefit from optical signal transmission is silicon photomultipliers. The system was adapted and tuned for use with various samples from various suppliers. Including connected photo arrays with multiple sensors, and a NIR-sensitive NFAD.

Requirements:
– high amplification gain (sensitivity to single photoelectron)
– high signal-to-noise ratio
– adequate bandwidth
– high dynamic range (thousand photoelectrons), constrained by the capability of the commercial optical receivers and available ADCs ($V_{\text{max}} = 1.5–2\text{V}$)
– preservation of the original pulse shape
Cold electronics and laser diode driving circuit

The cold electronics is based on commercially available components, tested for suitability in cryogenic environment. The circuit design provides signal amplification and laser diode current drive through a 3 stage amplifier circuit.

1. The first stage (full-differential THS4131 OpAmp) provides a fully balanced differential interface to the SiPM devices and produces a balanced, amplified differential output to...

2. The second stage which provides the capability for additional amplification and differential to single ended conversion as well as independent control over the bias current setting of the laser diode.

3. The third stage performs voltage to current conversion plus an edge enhanced gain (R17 and C37, C16, and C17) circuit to drive the laser diode.
Temperature effect on lasing threshold current

The threshold current at which the FP diode starts lasing is significantly reduced with lowering the temperature.

Lower power consumption and heat dissipation

Lower power to operate is good, but how to check the system after integration of the full detector, and before deployment into an inaccessible location for many years of operation?

Design a passive warm/cold switch based on resistors with negative temperature coefficient (NTC thermistor)

\[ R_{NTC} @ 77K >30\text{MOhm} = \text{open circuit} \]
Effect of transmission media with high refractive index

Everything was working fine when testing in liquid nitrogen and argon, but almost complete loss of optical power was observed under >12-16 inches of cryogenic liquid.

**Investigation:**

Anatomy of a typical commercial laser diode assembly / optical signal transceiver (pigtail-coupled version):

Main components:

First hypothesis: Fresnel reflection. Effect of high refractive index (above 1.2 for LN\textsubscript{2} and LAr), loss of coupling at the FC connector due to air being replaced with cryogenic liquid.

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Loss of light at (FC) coupling interface

Fresnel reflection due to step changes in refractive index at the jointed interface (glass –argon– glass) –air– –nitrogen–

For light of normal incidence in perfectly aligned system:

\[ r = \left( \frac{n_1 - n}{n_1 + n} \right)^2 \]

– fraction of reflected light \((n_1 – \text{fiber}, n – \text{medium between two jointed fibers})\)

\[ \text{Loss}_{\text{Fres}} = -10 \log_{10}(1 - r) \]

– loss in [dB] due to Fresnel reflection at the single interface

<table>
<thead>
<tr>
<th>Medium</th>
<th>Refractive index @ λ</th>
<th>fraction (r)</th>
<th>Loss [dB]**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass***</td>
<td>1.4676 @1310nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>1</td>
<td>3.6e–2</td>
<td>0.16</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.2242 @546.1nm</td>
<td>8.2e–3</td>
<td>0.036</td>
</tr>
<tr>
<td><strong>Argon_1</strong></td>
<td><strong>1.2279 @1300nm</strong></td>
<td>7.9e–3</td>
<td>0.035</td>
</tr>
<tr>
<td>Argon_2</td>
<td>1.38 @128nm</td>
<td>9.5e–4</td>
<td>0.004</td>
</tr>
<tr>
<td>Argon_3</td>
<td>1.23 @587.6nm</td>
<td>7.8e–3</td>
<td>0.034</td>
</tr>
</tbody>
</table>

Conclusions:

Air coupling is the worst

Loss in liquid nitrogen or argon is negligible
Solution to high refractive index media problem

Evidence that the loss of light is happening before the FC fiber coupling:

Component 1: Emitter with a lens
Component 2: Receiver with a fiber stub

Focal length and angular distribution in air/vacuum
Difference in high refractive index media

Change in the refractive index of the medium results in changes to the focal length of the length and the angle at which the rays enter the receiving fiber stub.

Engineered solutions:
Customization of the laser diode assembly:

1. Implementation of venting holes for the cryogenic liquid to easily fill the interior
2. Adjust lens-to-fiber stub distance for the change in rays path (focal length and angular distribution)
SiPM signal transmission

Experimental development for SiPM signal transmission and optical signal acquisition was performed with a commercial Koheron PD100 optical receiver coupled to an oscilloscope or ADC (CAEN v1720)

Voltage (current through R) sent to the laser diode ("–" terminal of the 3rd OpAmp)

Electrical representation of the transmitted optical signal (Over 40m fiber, received with Koheron PD-100)

Example of SiPM signal (circuit tuned for dynamic range of ~800 PE within 1.5V scale)
Noise dominated by RF-pickup by ~1m cabling between two open-neck dewars with LAr (4×5 SiPM array stimulated with blue light) and LN₂ (cold electronics development board)

\[ P_{\text{IN,max}} = 600 \mu \text{W} \]
\[ V_{\text{max}} = 1.5 \text{V} \]
Is this technology absolutely noise-free? (1)

While analog method of optical signal transmission is absolutely immune to the RF sources of noise on the signal path, there are at least two sources of optical noise to be taken into account when designing for specific project and requirements.

**Modal noise:**
Transmission of multi-mode optical signal through an optical fiber results in a formation of a “speckle pattern” at the exit end of the fiber. If this pattern changes, e.g. due to misalignment of the optical components, or due to the fiber dynamically changing its shape, this results in ‘modal noise’, which appears in the converted electrical signal waveform as noise with many overlapping frequencies.
Is this technology absolutely noise-free? (2)

While this method of signal transmission is absolutely immune to the RF sources of noise on the signal path, there are at least two sources of optical noise to be taken into account when designing for specific project and requirements.

Reflections
Light propagates in the optical fiber with the speed of 2.14e8 m/s. In case of misalignment of the optical components or defects this may result in noise with characteristic period (~50ns for 10m fiber).

Attention is given to the type of the optical connectors beyond FC-type specification.

Observation of optical reflections noise with 4m long 62.5μm multi-mode optical fiber

https://www.thefoa.org/tech/ref/testing/test/reflectance.html


J. Dawson, S. Sacerdotti, APC (Paris), Private communication
What could be next?

**Optimization of the optics and full customization of the laser diode assembly**

Commercially available laser diode assemblies are designed to have “cavities” filled with either air or vacuum with the unity refractive index.

Optical coupling of optical fiber is not well studied for transmission media with high refractive index of e.g. liquid nitrogen, or noble liquids argon and xenon.

Higher transmission efficiency may be achieved with accurate measurements of the beam profile from a Fabry-Perot laser diode, and custom design of the optical coupling with an appropriate selection of the elements (e.g. lenses with higher refractive index or metalenses).

Ball lenses for collimating the light beam

Example of a beam profile (far-field) measurement of a commercial laser diode with an integrated lens

Imaging with a 22μm diameter NFAD mounted on automated XY scanning stages with 50nm microstep and 4um pixel resolution (100×100 pixels imaging)
Low-power digital links with silicon photonics and digital silicon photomultipliers (DSiPM). Free-space optical communication could eliminate the need for optical fibers: less components in the detector, less dead volume, lower radioactivity, etc. Demonstration of a gigabit digital link with 1310nm laser diodes through ~2mm of doped silicon over a free-space optical path of 60cm.

Measurements with a manual 4-axis instrument equipped with a 22μm single-photon NIR-sensitive negative-feedback avalanche diode (NFAD). Dark noise 0.3nA, DC signal at 27cm free space 8nA (SNR=27).
Conclusions

Analog optical signal transmission was designed and validated with signals from silicon photomultipliers.

The main advantages and features of interest for HEP experiments:

– simplicity in design, small number of components, lower probability of failure in long-term operation

– relatively easy adaptation for specific application (e.g. with SPICE simulation): gain, dynamic range, S/N ratio, voltage and current sources of electric signal, AC- and DC- coupling

– low power requirement (~100mW) and heat dissipation in cryogenic liquids

This technology has been tuned for the DUNE FD2 PDS requirements and successfully deployed and tested in several prototype detectors at CERN (talk of Ajib Paudel)

Stable operation demonstrated without change of several FP laser diodes in liquid argon at an absolute pressure varying from 1.5 to ~2bara (equivalent to ~6m depth) over two weeks period of time

Higher statistics sample experiment is prepared.

Hot-carrier effect studies in CMOS circuits are being carried out

Alternative op amp choices (providing the necessary current drive and dynamic range) are being studied