Development and Performance of a Receiver for an Analogue Optical Link

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Abstract

A receiver for an analogue optical link has been developed. The performance, with both electrical ‘calibration’ and optical signals relevant to the requirements of the liquid argon calorimeter, are discussed. The receiver consists of a newly developed silicon PIN-diode array followed by a custom-made transimpedance amplifier. The PIN-array chip has 8 elements and is passively aligned to an optical fibre-ribbon equipped with an MT-connector. The bandwidth of the receiver exceeds 100 MHz and the dynamic range exceeds 13 bits with a differential non-linearity of $\leq 1\%$. Future industrialisation of the PIN-array and the receiver as a whole is also discussed.

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1 Introduction

For many years optical links have been used to transfer digital signals in telecommunication systems. Signal transfer by optical links instead of coaxial or twisted pair cables offers several advantages:

- Immunity to electromagnetic interference and ground loops.
- Low signal attenuation, allowing long transmission distances.
- Small dimensions.
- Lower power consumption and, therefore, cooling.

Improvements in the understanding of semiconductor materials have resulted in high power light emitting diodes (> 0.5 mW) and laser diodes (> several mW) becoming available from several manufacturers. Also, the quality of fibres and connectors has improved rapidly over the years such that uniform coupling can now be obtained as standard with typical losses of ~ 0.5 dB. Both these factors make analogue optical links a viable replacement for conventional copper links.

Interest in optical read-out links for the ATLAS liquid argon (LAr) calorimeter started within the framework of preparing an optical read-out solution [1] for a high granularity preshower detector [2]. Such links were to be operated at cryogenic temperatures and had to be resistant to high levels of radiation. The preshower detector was subsequently replaced by a coarser granularity presampler [3] and there was no longer such a need to use optical links for the read-out since the number of read-out channels were reduced from 200,000 to 8,000. Nevertheless, encouraged by the operation of a cryogenic optical link used for the read-out of the presampler detector during the September 1995 test beam, the development of an analogue optical link continued with the aim of fulfilling the specification for the transfer of the signals from the front-end boards of the LAr calorimeter to the associated read-out drivers. Two main objectives for the development of such a link were low cost and the use of array components and optical fibre-ribbons to reduce space requirements.

The optical link consists of four main components. An emitter (a laser-diode, for example) turns electrical signals into light. The light is coupled into an optical fibre-ribbon which is fed into a PIN-diode receiver at the other end of the link. The PIN-diode converts the light into an electrical current. Finally, a transimpedance amplifier converts the PIN-diode current into a voltage which can be measured. In this note only the development and performance of the receiving end of the link is described. The development of emitters, fibres and the performance of a full link will be described in forthcoming notes.

This note is organised as follows. In the next section, an overview of the requirements that drove the design of the receiver system are discussed. This is followed in section 3 by a description of the PIN-array chip, including: development, geometry, performance, alignment and packaging. Section 4 presents a discussion of the design and performance of the transimpedance amplifier. A description of the complete integrated receiver unit and its performance is presented in section 5. The note concludes with a discussion of the future industrialisation of the receiver unit in section 6 and an overall summary in section 7.
2 System Requirements and Design Goals

The design was kept simple to ensure high reliability and low production costs. The use of fibre-ribbons and associated array components means that the cost per channel is reduced compared to single fibre connectors and components. The alignment of such array components was identified as a key issue for development. At the start of the development\(^c\) the only array components freely available formed a part of complete digital links\(^d\). During the prototyping stage the only option was to develop custom made emitter and receiver arrays. The link has a natural modularity which allows the use of different types and makes of components.

For the prototype it was decided to use commercially available MT-connectors [5]. The maximum number of channels that can fit into a ribbon cable and MT-connector is 12, but our design is based on the more common ribbon with 8 fibres. The pitch between the fibres in the ribbon is 250 \(\mu\)m. The use of MT-connectors ensures compatibility with array components as they become commercially available. Packaging and future industrialisation of the receiver end of the link is discussed in section 6.

The operational wavelength of the link is 850 nm which means that inexpensive silicon PIN-diodes can be used as receivers. This choice of wavelength also means that newly developed GaAs vertical cavity surface emitting lasers (VCSEL) can be used. Such devices are thought to be very attractive for future applications due to their low threshold current and power consumption. In order to accommodate both light emitting diodes (LED) and VCSEL's as emitters, the maximum power the receiver should except is of order of 2-3 mW.

Analogue signal transfer requires that the link has a large linear dynamic range. For the LAr calorimeter, the signals to be transmitted are bi-polar shaped with a shaping time of 20 ns\(^e\). The design for the optical link was started at a time when the read-out architecture resulted in the calorimeter's intrinsic dynamic range of 16 bits being reduced by the use of shapers with four different gains. The use of such shapers would limit all electronics following the shaper to a dynamic range of 12 bits. In this read-out scheme the shaped signals would be sampled at 40 MHz and this analogue signal would be followed by two digital bits, describing which shaper gain was used. This data transfer scheme has not been pursued in detail however. We concentrate on the less demanding transfer of purely analogue signals, with the following target requirements:

- Dynamic range \(\geq 12\) bits.
- Differential non-linearity \(\leq 4\%\) (with polynomial fit or look-up-table \(\leq 2\%\)).
- Rise/fall time \(\leq 4\) ns.
- Bandwidth \(\geq 100\) MHz.
- Crosstalk \(\leq 1\%\).
- Swing of output voltage = 2.5 V.

Also, as the optical link would be used to replace conventional copper cables, there are two further considerations:

\(^c\)Autumn 1995.
\(^d\)For example the Motorola Optobus [4].
\(^e\)In this note a \(\text{CR} (R\text{C})^2\) filter is considered and the shaping time is defined for a \(\delta\)-pulse.
• The gain should be close to one.
• Channel-to-channel variation of the gain should be $< 1$ dB.

The second point is particularly important since, if the gain variation between links (including all connector losses and insertion losses) is small then different gains can be handled with normal calibration procedures.

In order to achieve the required dynamic range the optical power budget is fairly strict and insertion losses, attenuation in connectors (at least one fibre-fibre connector is foreseen) and transmission losses over roughly 100 m should be less than 3 dB. Insertion losses are minimised by the use of large core multimode fibres which also relax the emitter/detector to fibre alignment requirements. For this application core diameters between 50 to 200 μm were considered. A core of 200 μm would maximise the coupling of light into the fibre, which is particularly important if conventional LED’s would be used as emitters.

To handle signals of either polarity, the emitter must be biased with a constant current to also allow negative signals. For a bi-polar shaped triangular LAr calorimeter signal the opposite compensating amplitude is roughly 10% of the signal amplitude.

If the link would be used in ATLAS to transfer signals from the detector to remote electronics there will be radiation hardness requirements for the detector-based emitter side. For the off-detector receiving end, which is discussed in this note, no radiation hardness is required.

3 The PIN-array Chip

Two semiconductor materials, InGaAs and Si, were considered for the PIN-array chip. The former was rejected because at the selected wavelength of 850 nm the sensitivity is lower and the cost higher. Several companies were contacted for quotations for the production of a PIN-array. A Norwegian based company, AME [6], tendered the best price-performance combination and was selected to realise the design and production of the PIN-array in silicon.

3.1 PIN-array Geometry

The eight-way fibre-ribbon from the emitter stage is connected to the PIN-array via a proprietary MT-connector. In a novel approach, the MT-connector is coupled to the PIN-diode array head-on, as shown in figure 6. This approach is simple and cheap since it includes no ‘V’-grooves, pig-tailing mirrors or light guides.

In order to facilitate this. head-on approach, a chip layout was developed where bonding takes place approximately 2 mm away from the centre of the active PIN elements. Coupling uniformity, connector robustness and the possibility of using fibres with a core diameter up to 200 μm called for large PIN elements. The final PIN element size is $175 \times 330 \, \mu m^2$. The PIN elements are surrounded by a grounded guard-ring to reduce inter-element cross-talk. The chip geometry is displayed in figure 1 and more details of the layout and bonding are presented in appendix A.

In order to protect the PIN-array when coupling to the MT-connector and to provide a reference surface, a cover-glass is used. The MT-connector is pressed firmly to the

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5 This device is manufactured by AME as AE9708.
cover-glass. The cover-glass is coated to reduce reflections, which may cause cross-talk or possible optical feedback noise in a laser emitter. The glass is borosilicate-based\textsuperscript{g} and was originally designed for solar panels. It is mounted on the chip with optically transparent epoxy resin\textsuperscript{h}.

### 3.2 The Performance of the PIN-array

In this section the performance of the PIN-array is discussed. The main optical and electrical characteristics are summarised in table 1.

#### 3.2.1 Response

The response, $\mathcal{R}$, of a photodiode can be expressed in units of $\text{AW}^{-1}$ as:

$$
\mathcal{R} = \varepsilon(\lambda) \frac{e}{hc} = \frac{\varepsilon(\lambda) \lambda}{1.24},
$$

\textsuperscript{g}CMX, manufactured by Pilkington Space Technology.

\textsuperscript{h}EPO-TEK 301-2, manufactured by Epoxy Technology Inc, MA, USA.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Test condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response</td>
<td>0.58 AW⁻¹</td>
<td>no cover glass</td>
</tr>
<tr>
<td>Response</td>
<td>0.50 AW⁻¹</td>
<td>with cover glass</td>
</tr>
<tr>
<td>Capacitance</td>
<td>0.8-1.0 pF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_R=30$ V</td>
</tr>
<tr>
<td>Rise/fall time</td>
<td>0.7 ns</td>
<td>reverse voltage, $V_R=100$ V</td>
</tr>
<tr>
<td>Dark current</td>
<td>0.09 nA</td>
<td>20°C</td>
</tr>
<tr>
<td>Cross-talk</td>
<td>≤ 0.05%</td>
<td>no cover glass</td>
</tr>
<tr>
<td>Reverse Breakdown Voltage</td>
<td>-344 V</td>
<td>for $I_{reverse}=-10.0$ µA</td>
</tr>
</tbody>
</table>

Table 1: Optical and electrical characteristics of the KTH-AME silicon PIN-array.

where, $e$ is the elementary charge, $h$ is Planck’s constant, $c$ is the speed of light, $\epsilon$ is the quantum efficiency and $\lambda$ is the wavelength of the incident light in µm.

The response of the PIN-array was measured with a narrow beam of laser light shone onto the center of an element. The laser only illuminated one element of the array at a time and the response was compared to a calibrated reference detector. The response was determined to be 0.58 AW⁻¹ for a bare chip and 0.50 AW⁻¹ after a cover-glass was glued onto the chip. These results correspond to quantum efficiencies of 0.85 and 0.72, respectively.

The response is expected to exhibit a small temperature dependence since the absorption spectrum of semiconductors varies with temperature due to the effective band-gap changing. A rise in temperature shifts the absorption spectrum to longer wavelengths. In silicon at wavelengths around 850 nm this effect is small. At a peak wavelength of 850 nm the change in response can be parameterised in units of $\%^\circ$C⁻¹, as [7]:

$$\Delta R = 6.85 \times 10^{-3} \Delta T k_T,$$

(2)

where, $\Delta T$ is the temperature change and $k_T$ is the temperature coefficient of the quantum efficiency. Thus, a temperature increase of $10^\circ$C increases the response by approximately 0.7 %.

3.2.2 Dark Current

The PIN-diode dark current depends on the number of free electrons in the semiconductor bulk, and has an exponential temperature dependence. A rule of thumb [7] states that the dark current approximately doubles for every $8^\circ$C increase in temperature.

The dark current was measured to be 0.09 nA at 20°C. This current is a minor source of noise, as discussed in section 3.2.5.

3.2.3 Capacitance and Speed

The capacitance of the PIN-diode arises from the active detector area, the guard ring, the leads to the bond pads and the bonding wires. Even-though the active elements are unusually large they only contribute to roughly a quarter of the observed capacitance.

The capacitance was measured with a 1 MHz LCR-meter. The capacitance is reduced when the reverse bias voltage is increased, as shown in figure 2. A reverse bias voltage of 30 V is sufficient to reduce the capacitance below 1 pF. Several detector elements within an
array were measured at this voltage. Edge elements were observed to have a capacitance of 1 pF and middle elements 0.8 pF.

![Graph](image)

**Figure 2:** The capacitance of a central PIN-array element plotted as a function of the reverse bias voltage, measured at 1 MHz.

The expected carrier drift time for the PIN-array is 0.57 ns, however this value is subject to large uncertainties since the electric field in the diode is not uniform. The rise and fall time for the PIN-array chip, with a reverse bias voltage of 100 V, was measured with a pulsed laser. The rise and fall times were both found to be 0.7 ns. This corresponds to the expected design value after taking capacitive effects into account.

### 3.2.4 Cross-talk

There are three sources of cross-talk between PIN-array elements:

- Scattering of light onto neighbouring PIN-array elements from reflections between the connector and PIN-array surface.
- Light scattered within the PIN-array chip.
- Electrical cross-talk due to capacitive coupling.

The latter two are minimised by placing a grounded guard ring around the PIN-elements on the chip. Reflections are minimised by the coating on the cover-glass.

To measure the cross-talk within the PIN-array without a cover-glass, a small laser beam was shone onto the middle of a single PIN-element and the signal in adjacent elements were measured. This procedure enabled a limit of $<0.05\%$ to be assigned to cross-talk. The cross-talk with the cover-glass in place was measured with a MT-connector coupled to the PIN-array and results are presented in section 5.2.1.
3.2.5 Dynamic Range of the PIN-array

The maximum dynamic range of a PIN-diode is governed by the maximum light power that the PIN-diode can detect without reduced response. The response decreases when the number of photo-generated carriers are so large that the space-charge screens the bulk of the PIN-diode. The optical power when these effects become important is above \( \sim 4 \text{ mW} \), which is well away from the expected maximum peak power of 2 mW, as shown in figure 3. This measurement was performed using a high power laser with a constant output and an optical attenuator.

![Figure 3: The PIN-diode output current as a function of the input optical power. The crossed points were used in the linear fit.](image)

The minimum light power the PIN-diode can detect is related to the intrinsic noise of the PIN-diode. The noise equivalent power (NEP) can be defined as:

\[
\text{NEP} = \frac{\sqrt{2eI_dBW}}{R},
\]

where, \( e \) is the elementary charge, \( I_d \) is the dark current (0.09 nA), \( BW \) is the bandwidth of the electronics following the PIN-array and \( R \) is the response. For this PIN-diode, the NEP is 110 (190) pW for a bandwidth of 100 (300) MHz. Taking the worst case NEP, the PIN-diode has a dynamic range exceeding 20 bits.

3.3 Alignment of the PIN-array

The PIN-array chip is precision-cut using a diamond edge and glued onto a ceramic carrier substrate. The substrate has reference holes for alignment of the PIN-array chip and the MT-connector. Two sets of three (single-shot) laser cut holes in the substrate act as a reference when aligning the chip corners through a microscope. Two larger (multi-shot) laser cut holes locate the MT-connector alignment pins, as shown in figure 4. Once aligned in the plane of the chip, the chip is covered by an 50 \( \mu \text{m} \) thick glass cover-plate (see section...
Figure 4: Details of the PIN-array ceramic. Note the pair of three one-shot laser holes used to align the PIN-array.

3.1) which provides a reference surface for the MT-connector. Table 2 gives a breakdown of the precision (in the plane of the chip) with which the alignment can be performed.

<table>
<thead>
<tr>
<th>Process</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser drilling</td>
<td>±15μm</td>
</tr>
<tr>
<td>MT pin alignment</td>
<td>±30μm</td>
</tr>
<tr>
<td>Chip cutting</td>
<td>±5μm</td>
</tr>
<tr>
<td>Total</td>
<td>±35μm</td>
</tr>
</tbody>
</table>

Table 2: PIN-array alignment precision (in the plane of the chip).

In figure 5 scans across the face of a single element in the PIN-array are shown in three orthogonal directions. An optical fibre of diameter 62.5 μm was used. The extent of the plateau of maximum coupling indicates that the ±35μm alignment precision is not a limiting factor.

Finally, in order to test the reliability of the MT-connector/PIN-array coupling, a connecting/disconnecting operation was performed approximately 100 times by several different people. The variation in the coupling for a single channel was observed to be
Figure 5: Scans across the face of a single element of the PIN-array in three orthogonal directions.

< 0.09 dB for this test.

3.4 Packaging the PIN-array

After an investigation of commercially available packages, it became clear that the best compromise in terms of price, availability and size was a custom-made solution. This package consists of a standard DIL-sized ceramic substrate covered with a thick-film onto which a printed conduction pattern is glued. The ceramic carrier substrate with the PIN-array and the MT alignment pins is mounted on the DIL-package. The MT-connector is held in position with a support consisting of two hinged arms which are fixed with a screw. The size of the package is about 10 × 20 mm and has 12 legs, with a pitch of 2.54 mm. A photograph of the package is shown in figure 6.
Figure 6: A photograph of a prototype packaged PIN-array component. Note the two pins for locating the MT-connector. The prototype connector support is made of brass.

4 The Transimpedance Amplifier

The purpose of the transimpedance amplifier is to convert the optical power, $P_{\text{in}}$, incident on the PIN-diode into a voltage, $V_{\text{out}}$:

$$V_{\text{out}} = P_{\text{in}} Z R. \quad (4)$$

The transimpedance is denoted by $Z$ and response of the PIN-diode by $R$. The amplifier was designed under the criteria that the optical link should transmit signals with a one-to-one correspondence between the input and output. Preliminary estimations indicated that the likely received power would be 2 mW which led to a design based around a transimpedance of 2.7 k$\Omega$ for a maximum output of 2.5 V. No commercially available transimpedance amplifier complied with the linearity and dynamic range requirements. An in-house custom-made transimpedance amplifier was designed and realised with discrete components.

The amplifier requires a split supply voltage of ±12 V and the current consumption of a single amplifier is 25 mA per supply rail. This relatively high power consumption, necessary to achieve the linearity and dynamic range, requires that the amplifiers are effectively cooled. The output swing of an amplifier is between ± 2.5 V and the signal is inverted.

The amplifier was designed to have a differential non-linearity better than 2%. In principle, the amplifier could work at 350 MHz but to reduce overshoot and settling time the bandwidth is somewhat reduced, as discussed in the next section.

4.1 Design

The complete circuit diagram of the transimpedance amplifier is shown in appendix B along with some design notes and circuit board layout details.
The maximum available bandwidth, \( BW \), of the amplifier can be derived in units of Hz as:

\[
BW = \frac{1}{2\pi} \sqrt{\frac{\omega_{ol}}{R C_t}},
\]

where, the transimpedance resistor, \( R \), is 2.7 k\( \Omega \), \( C_t \) is the sum of the photodiode capacitance, \( C_d \) (1.0 pF), and the feedback capacitance, \( C_f \) (0.6 pF), is formed by the collector-base capacitance of the input transistor. The value of \( \omega_{ol} \) is given, in units of rad s\(^{-1} \) by:

\[
\omega_{ol} = \frac{g_m}{C_l},
\]

where, \( C_l \) is the load capacitance at the collector of the input transistor (2 pF) due the junction capacitances of the transistors and the circuit layout and the transconductance of the input transistor, \( g_m \), is 100 m\( \Omega \)\(^{-1} \). The gain-bandwidth product, GBW, of the open-loop amplifier is given, in units of Hz, by \( GBW = \frac{\omega_{ol}}{2\pi} \). These values give \( \omega_{ol} = 50\times10^9 \) rad s\(^{-1} \) and, therefore, GBW = 8 GHz. The resultant bandwidth is in excess of 100 MHz. With transistors with smaller base capacitances a bandwidth of 350 MHz is possible.

A quality factor, \( Q \), can be defined as:

\[
Q = \frac{\sqrt{\omega_{ol} RC_t}}{1 + \omega_{ol} R C_f}
\]

The value of \( Q \) must be less than unity for a good compromise between overshoot and settling time. A value of \( Q=0.18 \) is achieved for this design.

### 4.2 Calibration

The amplifier is equipped with a calibration input, so that it can be tested with electrical signals. The main purpose of the calibration input is to allow function-testing. In practice, even channels are connected to one calibration input and odd channels to another. The calibration input resistances are large (27 k\( \Omega \)), so that amplifiers connected to a common input are well isolated. To cover the full dynamic range a calibration input swing of 25 V is needed. The capacitance of the 27 k\( \Omega \) resistance gives the amplifier a different frequency transfer function, which makes it impractical to use the calibration inputs for absolute calibration or for making look-up tables of shaped signals.

### 4.3 Performance

The transimpedance amplifier has been thoroughly tested and the characteristics are shown in table 3.

As previously stated, the amplifier is designed to have a fast rise-time with a small overshoot. In figure 7 the output resulting from a 200 mV square pulse applied to a calibration input is shown. The response to a shaped (20 ns) signal is shown in figure 8.

#### 4.3.1 Speed and Bandwidth

The rise- and fall-time of the transimpedance amplifier for a square input pulse was determined to be 3.6 ns, taking into account the profile of the square input pulse.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transimpedance</td>
<td>2.7 kΩ</td>
</tr>
<tr>
<td>Noise</td>
<td>45 μV, for 20 ns shaping time</td>
</tr>
<tr>
<td>Rise time, $t_{\text{rise}}$</td>
<td>3.6 ns</td>
</tr>
<tr>
<td>Fall time, $t_{\text{fall}}$</td>
<td>3.6 ns</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>&gt;100 MHz</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>&gt;13 bits</td>
</tr>
<tr>
<td>Differential Non-linearity</td>
<td>≤ 1 %</td>
</tr>
</tbody>
</table>

**Table 3:** Characteristics of the transimpedance amplifier.

**Figure 7:** The output response of the transimpedance amplifier to a square input pulse. The upper trace is the calibration input signal and the lower trace is the amplifier output. The rise-time is limited by the capacitance of the large calibration input resistor.

The transfer function of the transimpedance amplifier was measured using a 200 MHz spectrum analyser. The frequency response is shown in figure 9 and indicates a bandwidth (3 dB point) in excess of 100 MHz. Figure 7 shows that the overshoot and settling time for the transimpedance amplifier are small. No attempt was therefore made to further estimate these quantities.

**4.3.2 Noise**

The noise of the transimpedance amplifier was measured with the PIN-array connected. The RMS noise levels for different channels of a prototype receiver unit are shown in figure 10 as a function of the shaping time of the output pulse. At a shaping time of 20 ns the noise level is ~ 45 μV.
4.3.3 Dynamic Range

The dynamic range of the receiver is limited by the noise of the transimpedance amplifier. For signals with a 20 ns shaping time a dynamic range of 13.4 (14.2) bits is achieved for a signal-to-noise ratio (SNR) of 5 (3). For faster signals, with a shaping time of 10 ns, the dynamic range is 13.0 bits for a SNR of 5.

4.3.4 Linearity

Linearity is of prime importance in an analogue optical link system if one is to ensure the faithful reproduction of signals as they traverse the link. In order to cover the full dynamic range with the calibration input, the calibration input resistor (27 kΩ) was replaced with a 2.7 kΩ resistor. The output signals were filtered with a 20 ns shaping time before they were fed to an ADC with a 12 bit dynamic range. A high-precision programmable attenuator in conjunction with a pulse generator was used to generate the input calibration signals.

The linearity measurement over the full dynamic range had to be divided into two parts, due to the limited dynamic range and resolution of the ADC used for the measurement. The first measurement covered the upper part of the transimpedance amplifiers’ dynamic range (from 10 mV up to the maximum of 2.5 V). A linear fit of the response to these ‘large’ signals is shown in figure 11. The differential deviation from the linear fit is shown as an insert in the same figure. The scatter at the low end is due to the limited resolution of the ADC. The lower part of the transimpedance amplifiers’ dynamic range (from 100 µV to 30 mV) was measured by increasing the gain of the shaper preceding the ADC, so as not to be limited by the resolution of the ADC. The linear response and differential non-linearity are shown in figure 12. A differential non-linearity of $\lesssim 1\%$ over the full dynamic range was observed for both the measurements.

**Figure 8**: The output response of the transimpedance amplifier to a 20 ns shaped input pulse. The upper trace is the calibration input signal and the lower trace is the amplifier output.
Figure 9: The transfer function of the transimpedance amplifier. The horizontal scale runs between 1 MHz and 200 MHz. The vertical scale is divided into 1 dB divisions.

4.3.5 Uniformity

To compare channel-to-channel differences, the calibration inputs were pulsed with 5 V signal. This covers the lower fifth of the full dynamic range, as shown for 8 channels in figure 13. The gain and linearity is uniform across all channels. The variation across channels is only 0.2 dB.

5 The Prototype Receiver Unit

5.1 Description

A prototype receiver unit is shown in figure 14. The unit is designed to be self-contained and rugged to allow for easy testing by different users. The PIN-array and transimpedance amplifier are mounted on a 4-layer circuit board. Note that while the layout of the board was a serious design concern, it was not fully optimised. For example, the distance between the PIN-array elements and the inputs of the transimpedance amplifier was not rigorously minimised.

All inputs (power, PIN bias and calibration) are provided by standard LEMO OOType connectors. The high power consumption of the electronics (see section 4) means that effective cooling is essential. For the prototype this was achieved with a small brushless fan\(^1\).

\(^1\)Matsukyu Co. Ltd. MDF-4020-12.
Figure 10: The noise measured at the output of four channels in a receiver unit as function of shaping time.

5.2 Performance

Tests of the prototype receiver unit over the full dynamic range were limited by the availability of suitably linear emitters. For the results on rise-time and cross-talk presented here a Honeywell HFE4080 VCSEL [9] laser-diode has been used.

Figure 15 shows the transfer of a square pulse from the HFE4080 through 70 m of fibre to a prototype receiver unit. The overall form of the pulse is maintained during transmission.

Since the non-linearity of the HFE4080 dominates, measurements of the linearity of the prototype unit are not very useful. However, the linearity of the PIN-array and transimpedance amplifier have already been reported in this note and gave a clear indication that the linearity of the unit will fall within the required specifications. For completeness, the response of the whole link over the linear range of the HFE4080 (0.2 to 2 mW) is illustrated in figure 16.

5.2.1 Cross-talk

The cross-talk was measured by pulsing a single HFE4080 emitter coupled to one fibre in the 8 fibre-ribbon equipped with a ST-connector. The other end of the ribbon was connected to the receiver with a MT-connector and the signal in neighbouring channels to the pulsed one was measured. The origin of the cross-talk between output channels of the receiver unit is predominantly capacitive, as shown in figure 17.

This implies that the optical cross-talk is small compared to electrical sources. Since the shaped signal will be sampled at the maximum, the effective cross-talk is reduced. The magnitude of the cross-talk (measured on the signal peak) for a 20 ns shaped signal is 0.08% for adjacent channels and 0.04% for next-to-adjacent channels, where both the signal and the cross-talk is measured at the peak of the pulses.
Figure 11: The linearity of the transimpedance amplifier for the upper part of the dynamic range (10 mV to 2.5 V). The insert shows the differential deviation from a linear fit to the data-points.

5.2.2 Temperature Stability

The high power consumption of the transimpedance amplifiers could cause heating of the PIN-array and give rise to fluctuations in the response. However, these effects are expected to be small since the fan keeps the receiver unit at a constant temperature. Variations in temperature of $<1\,^\circ$C were measured during an hour-long trial.

5.2.3 Mechanical Stability

The overall mechanical stability of all eight receiver units, including PIN-arrays and transimpedance amplifiers, has proven to be excellent. The units continue to function reliably after many months\(^1\), with no malfunctions having been observed to date.

\(^1\)and students . . .
Small signals
(100 µV → 30 mV)

Figure 12: The linearity of the transimpedance amplifier for the lower part of the dynamic range (100 µV to 30 mV). The insert shows the differential deviation from a linear fit to the data-points.

6 Future Industrialisation and Packaging

Large scale series production of PIN-arrays has been discussed with AME. Further development will be concentrated on the packaging of the PIN-array and the integration of the transimpedance amplifier into the packaging. Both these concepts are discussed below.

A final component could, for example, be some type of plastic mould with the ceramic carrier substrate, with the PIN-array chip and connector alignment pins, integrated together with pins for electrical connections and support for an optical connector. The precision alignment of the array and optical connector is done passively with the precision laser cut holes on the ceramic carrier substrate.

Key points to be addressed for the design of the plastic packaging include:

- Accurate mechanical assembly suitable for mass production.
- Long term mechanical stability of the packaging.
- Stable and accurate behaviour of the electrical components.
AME has past experience of producing injection moulded plastic packaged optical components, similar to that envisaged for the PIN-array. Other companies also have experience of producing precision plastic moulded optical components [10].

The packaging could be designed in any shape that fits onto a PCB or a front panel. Easy connection and disconnection of the optical connector is crucial. Other optical connectors than the MT type can be used if they have alignment pins that can be mounted on the ceramic carrier substrate. The connector also needs to be sufficiently small so that it does not interfere with the PIN-array bond wires.

If larger bandwidths are considered, the speed of the PIN-array can be improved by using thinner silicon and smaller detector elements. This aside, no major design changes are introduced if one wants to produce a very fast (> 1 GHz) detector for digital applications.

The plastic housing would also include the transimpedance amplifier. For large scale production the transimpedance amplifier would be realised as an ASIC. The amplifier is better realised on a separate chip to the PIN-array since the process technology needed for ASIC designs are unnecessarily sophisticated and thus more expensive than that needed for the manufacture of PIN-arrays. Amplifier chips would be mounted and bonded on the same carrier substrate as the PIN-array chip and incorporated into the plastic housing.

**Figure 13:** The linearity of the transimpedance amplifier across all 8 channels. Note that only the lower fifth of the dynamic range is covered due to the input resistance of the calibration input.
7 Conclusion

In this note a receiver for an analogue optical link has been described and tests of the individual components (PIN-array and transimpedance amplifier) and a full prototype receiver are presented.

A PIN-array chip with 8 elements has been developed. A novel and economic technique, where the PIN-array is passively aligned with a MT-connector, has been successfully demonstrated by the tests described in this note. The PIN-detector fulfills all required specifications. A custom-made transimpedance amplifier was developed to satisfy the requirements.

For the complete prototype receiver both electrical calibration and optical signal characteristics, relevant to the requirements of the liquid argon calorimeter are presented. The bandwidth of the complete receiver exceeds 100 MHz and has a dynamic range in excess of 13 bits (for a signal-to-noise ratio of 5) with a differential non-linearity of \( \lesssim 1 \% \).

It is shown that is possible to realise the optical transfer of analogue signals. The optical tests in this note are limited by the linearity of emitters available to us at this time. Development and tests of new emitters are progressing and will be presented in forthcoming notes.

Future industrialisation of the PIN-array is also discussed. With an eye on the future it is pertinent to note that the design of the PIN-array was based around optical fibres of up to 200 \( \mu \text{m} \) in diameter. However a fibre diameter of 62.5 \( \mu \text{m} \) is more realistic today and so the active area of the PIN-array can be reduced. This reduces the PIN-array capacitance and therefore increases its speed. Together with faster transimpedance amplifiers (which are readily available), the transmission of digital signals with array...
Figure 15: The transfer of a square input pulse through a complete optical link. The emitter is a Honeywell HFE4080 VCSEL [9]. The signal is sent through 70 m of fibre-ribbon to the prototype receiver unit. The rise-time of the input signal is preserved.

components and optical fibre-ribbons becomes an attractive proposition.

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Figure 16: The linearity for the complete optical link. The plot is constrained to the linear range of the Honeywell HFE4080 VCSEL.

Figure 17: The upper trace shows the signal on an active output channel of the prototype receiver unit. The lower trace illustrates the capacitive nature of the cross-talk on an adjacent channel.
References


Appendix A

A Layout and Bonding of the PIN-diode Array

Figure 18 shows details of the layout of the chip carrying the PIN-array. The electrical pin-out is indicated and the relative positions of the PIN-array, MT-connector and MT support are shown.

The soldering pads on the substrate are made from a AgPd thick film. The wiring on the substrate is also AgPd and the bond pads are thick film Au. The legs are soldered to the substrate with a high temperature soldering tin.

Figure 18: Details of the chip layout and bonding pattern for the PIN-array. See also figures 4 and 6.
Appendix B

B The Transimpedance Amplifier

B.1 Layout of the Transimpedance Amplifier

The printed circuit board housing the components of the transimpedance amplifier is shown in figure 19. The board has dimensions of (54 × 15.2) mm and the spacing between the connector pins (P1–9) is 2.54 mm.

Figure 19: The layout of the transimpedance amplifier circuit board.
Figure 20: The complete circuit diagram of the transimpedance amplifier.
B.3 Technical Design Notes

The emitter of the input transistor, NE856, is not grounded, but is included in a differential pair. This provides a DC output level close to 0 V.

The collector of NE856 is fed back through an emitter follower, Q3, and a voltage shifter, R6/C4, which increases the collector-base voltage of Q1. This makes it possible to accommodate negative pulses of several volts.

The output buffer was not included in the closed loop, because the associated delay would have caused some undesirable overshoot. However, the price of this is that nonlinearities are not compensated for by the loop. This makes it necessary to operate with a rather high bias current (approximately 6 mA), in order to decrease the effect of the transconductance of the transistors.

The resistors, R17, R20 and R21 enable robust setting of the bias current for Q7 and Q6.