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OPTOELECTRONIC DATA TRANSFER FOR EAGLE

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Introduction.

The operations of first level triggering, data readout after a first level trigger and general control signal transfer associated with data acquisition for any LHC detector will all require high rate capability, freedom from electromagnetic interference (EMI), and massive parallellism. Any associated electronic and optoelectronic components located on the tracking chambers or embedded in the electromagnetic calorimeters will be subject to high integrated radiation doses and high neutron fluences; of order 300KGy and 3 10**14 neutrons/cm**2 respectively over the first ten years of LHC operation at a luminosity of 10**34 /cm**2/sec. In the case of the tracking chambers the large number of channels involved (up to 10**7 or more) means that heating from active electronic components mounted on the detector elements has to be restricted to under one mW per channel. In the circumstance of having to service large numbers of channels an equally significant restriction is the cost per channel. All these considerations point to the need to make extensive use of optoelectronic systems at the front-end.

The components of this document are the following:

1) A summary of recent experience in optoelectronics, seen from the viewpoint of the Birmingham group;

2) An overview of the possibilities for using optoelectronic readout at LHC;

3) An outline of some features of the R and D programme of the proposal DRDC 91-41/P31;

4) Conclusions about future developments.

Recent Experience.

At Birmingham we have been working on optoelectronics for LHC readout and triggering for the last two and a half years. The aim has been to acquire expertise, develop industrial (primarily Datacom and Telecom) contacts, attract and fund post-graduate students, and go forward with like-minded HEP groups in an R and D programme. A first step was to build and test an FDDI digital data link in 1989. Then in 1990 CERN (Robert Maclaren), Hewlett-Packard Research Laboratories and Birmingham undertook to construct an optoelectronic based link between the L3 DEC and CERN IBM to run at 1.5Gbits/sec [1]. This link will use the protocol, HiPPI, which is becoming an industry standard for Datacoms. A CASE studentship was obtained for this work by Birmingham and HP and the student has now spent 14 months on the project. It is anticipated that the link will be installed during this coming winter.

During 1989 Birmingham made a first contact with GEC-Marconi to investigate optical modulators. More recently we became aware of interest in the TRD collaboration[2] (through Chris Fabjan) for analogue readout using optical modulators. Discussions with GEC and with British Telecom followed during the winter of 1990/91, with a view to collaborating on R and D for analogue optoelectronic readout from LHC detectors. These early contacts were encouraged and expanded by CERN and RAL participation. There is currently a DRDC proposal on Optoelectronic Analogue Signal Transfer for LHC detectors being submitted by Birmingham, CERN, Ecole Polytechnique Federale de Lausanne, GEC-Marconi, Imperial College (London), Lund, Oxford and RAL [3] with Giorgio Stefanini as Spokesman. The EPFL group headed by Prof Reinhart has considerable expertise in the design and fabrication of multiquantum well and other related III/V devices. Both CERN and Birmingham have been loaned single channel Lithium Niobate optical modulators by GEC and have results from working optoelectronic testbenches. The testbench at Birmingham has been partly paid for using pump-priming funds made available in June by the UK PPESP. GEC-Marconi and Birmingham have obtained a CASE studentship for this project and the student started work at Birmingham in October.

General Advantages of Optoelectronic Systems.

The common denominator of relevant optoelectronic systems is the use of optical fibre for the transfer of data. This immediately eliminates all electromagnetic interference (EMI) arising from cross-talk and ground loop pick-up. The complex circuitry needed to drive twisted pair connections at high rates is also avoided. As to cost, the Telecom price per metre for monomode fibre is as low as that for unshielded twisted pair cable; the reason being that monomode fibre production for the Telecom market is now Mkm/yr. Signal attenuation over monomode fibre is only 0.3dB/Km, well below that for any copper-based connection.

Optical fibre data transfer offers bandwidths of several hundred Gbits/sec per fibre; but as yet it is not possible to make full use of this bandwidth because of the lack of techniques for signal multiplexing. In any case it would not make sense to run wires from all parts of an LHC detector, just so they could feed one fibre. What is on offer is data transfer on single fibres at rates (roughly) up to 2 Gbit/sec using relatively standard laser diodes, up to 100 Mbits/sec using fast LEDs (that are not very different in structure or price from laser diodes), and up to 10 Gbits/sec with passive optical modulators. Passive modulators are not themselves the source of the photons and so they can be switched more rapidly. Lasers on the other hand 'chirp' when turned on or off rapidly. Converting more of the potential bandwidth into available bandwidth is a matter that needs to be investigated.

Fibres, LEDs, laser diode and modulators are all potentially radiation hard at the level needed at LHC. A report by Leskovar at the 1989 Toronto Conference [4] and subsequent papers to the Aachen Conference especially from the Fraunhofer Institute [5] document the situation.

At the Birmingham Dynamitron we have exposed a lithium niobate modulator to a neutron fluence equivalent to two week's exposure on a tracking chamber at LHC: the behaviour of the modulator response was monitored continuously during the two hour exposure and showed no degradation.

The volume of the fibre and the cross-section of the fibre needed to transfer the data from an LHC detector are many times smaller than the equivalent volume and cross-section for the copper-based connections. Standard monomode fibre complete with protective cover ('buffering') ranges from 0.2 to 0.9mm in diameter; the choice depending on the environment. Consequently the active region of the detector will approach an ideal hermetic shell more closely if optical fibre readout is used.

Another general advantage of the optoelectronic approach is that fibres can be used as part of any analogue pipeline.

Possible Optoelectronic Systems.

The optoelectronic systems discussed here all employ fibre connections, but beyond that there is a wide choice of devices and strategies in using the devices.

1) Analogue data transfer can be implemented as well as digital data transfer. The latter is technically simpler as regards the optoelectronics design. Furthermore, whenever there is multiplexing plus data-compression before readout, then some digital information is needed in order to identify the detector element associated with each signal transmitted. In such cases (as for the SiTP[6]) digital readout of both the data as well as its identifier makes for a less complicated system. The availability, relative cost and power budget of the

radiation hard ADCs required for the digitization of the data have also to be taken into consideration before the choice between pure digital and mixed analogue-digital readout can be made. The same can be said for the data-compression circuitry. It is important to address the question as to whether analogue readout with no data-compression is more or less expensive and/or more or less technically reliable as a complete system compared to the all digital readout with data-compression. The considerable R and D effort now being made on the latter needs balancing if a sound conclusion is to be reached. More is said about the analogue solution in the section on passive modulators.

2) In data readout the devices that convert the electronic signals to optical signals can be either active or passive. Active devices are themselves the source of the photons and would be either LEDs or laser diodes; the amplified electronic signals from the detector elements can control the light intensity they emit. Alternatively the convertors can be passive modulators. Then by contrast the source of photons is a remote LED or laser diode and the light from this source is piped by fibre to one or more passive modulators on the detector. The modulators can be of various types: the applied electronic signal from a detector element may alter the phase, polarization or (the simplest) the amplitude of the light traversing the modulator. From the the modulator the modulated light is piped by fibre to the electronics barrack/rucksack, where a photodiode is used to recover the original electronic signal.

3) There is also a choice of the technology to implement the type of modulator. One species of amplitude modulator is a Mach Zehnder interferometer where the arms are optical waveguides formed of Titanium doped channels on a Lithium Niobate substrate. Another species of amplitude modulator is a multiquantum well reflective device based on GaAs and other III/V compounds.

4) For the sake of completeness it is necessary to point out that there are three favoured wavebands where fibre has low absorption: 800nm, 1300nm and 1550nm. While in the LHC situation the length of fibre is only of order 100m and so absorption along a fibre is in any case small, the requirement of low absorption is a crucial ingredient to the Telecom firms who are the major customers for optoelectronic systems. This choice of wavebands increases the number of combinations of device and fibre type. To complicate the matter, the CD market uses 800nm lasers while the Telecom market prefers the 1300nm and 1550nm windows.

The R and D programme on optoelectronic systems for EAGLE and LHC detectors in general needs to take account of these alternatives. The separate applications of optoelectronics to readout for triggering, to readout after triggering and to control signal transfer impose different criteria. In the following sections some conclusions are drawn about the readout alternatives.

Analogue Data Transfer using Passive Modulators.

Readout from the tracking detectors requires a data-channel of only limited dynamic range [2,6,7]. In the case of the TRD[2] the basic requirement is to distinguish electrons with their accompanying TR photon conversions from hadrons or multiple hadrons. The dynamic range required is 8 bits, with 5 bits precision on the largest signals. (The use of the word 'bits' to define the range and precision is not meant to imply use of digital transfer, but is made to conform with common parlance.) In the case of the SiTP one need is to distinguish single electrons from pairs. The studies made at BNL[8], CERN[9] and recently at Birmingham [see below] indicate that passive optical modulators can readily transfer signals with this dynamic range while maintaining linearity between the input and output signals.

A recent report [10] from BNL extends the possibilities: it is shown there that if the requirement of linearity is dropped then the dynamic range can be extended to the 14 bits necessary in the case of calorimeter readout.

The advantages of passive readout over active readout are quite clear:

1) The heating at the detector is drastically reduced. Laser diodes generating one mW of optical power actually consume around of order one hundred mW of electrical power. Multiquantum well lasers, which are not as yet widely available, have a better electrical power to optical power ratio. On the other hand a passive lithium niobate modulator dissipates little power, because the light it modulates is pumped in from outside the detector. There is a 6dB reduction in the optical power throughput when an optical modulator is coupled into a fibre circuit (which we have verified in our tests). Thus for one mW of optical power emerging from a modulator there will be 3mW of heating coming from the light lost. To be strictly accurate the 'light' is likely to be 1300nm infrared radiation.

2) The laser diodes require very stable current sources, with protection against a rapid increase in current. Otherwise their power level fluctuates and in the event of a current surge they fail. This requirement augments the electronics required at the detector, which necessarily must be made radiation hard.

Note that typical LEDs, although being more robust than laser diodes are even more power hungry. The faster, less typical, LEDs with rise times of 3ns are in fact structurally very similar to laser diodes, and share some of their weaknesses.

3) With passive readout the number of components to be mounted on the detector, that are not vital to detector functionality, is minimized. Electrically the lithium niobate modulator behaves like a 10pF capacitance. The signals from the tracking detectors are of order a 10**3 to 10**5 electrons and will require at most limited preamplification in order to drive any of the passive modulators under discussion here.

The other comparison that is worth making in this context is the comparison between the use of passive modulators for analogue readout and for digital readout. What passive modulators there are on the market, are sold for use as digital devices, but from the studies noted above it appears they are adequate for analogue data transfer. This is well established now for the lithium niobate devices at the level of 8 bit dynamic range.

One important advantage that can be gained by analogue readout is that the data can be directly used in the trigger processors at level 1. Not much consideration has been paid to the accessibility of tracking chamber data that optoelectronic analogue signal transfer confers. This situation will hopefully improve as this accessibility becomes more generally appreciated. One possibility is suggested for study. This would involve looking for isolated stiff tracks in the outer region of the tracking chamber where tracks are becoming sparse; the information could prove valuable in enhancing electron, jet or muon triggers. In the case of the TRD the pulse size is of relevance too. More generally it seems wise to retain as much information as possible which can be used for trigger requirements that are as yet unsuspected: during the years of LHC construction the LEP and HERA experiments could produce all sorts of surprises.

The requirement for electronic processing at the detector is reduced with analogue readout. This leads to significant improvement in reliability, accessibility of the electronics for repair or upgrading, and also reduces the requirement for low power, radiation hard electronic components. The financial savings which accrue from moving electronics from the detector may prove substantial.

For the various reasons indicated above the real and potential advantages offered by analogue optolectronic data transfer using passive modulators make this approach, amongst those considered here, the most appropriate for a substantial R and D effort. In the next sections the operation of lithium niobate and the multiquantum well (MQW) devices will be outlined. Something will also be said about the plans to build and test multichannel devices. A complete discussion can be found in the DRDC proposal DRDC 91-41/P31[3].

Lithium Niobate Amplitude Modulator.

Figure 1 shows a single channel lithium niobate modulator. The few micron wide linear channels shown are formed by diffusing or implanting titanium on the surface; these channels act as waveguides for light. Light can be pumped into such a waveguide from a laser diode using an optical fibre connection. The waveguide structure has two arms which share the light equally, after which the beams reunite and the light emerges at the far side of the modulator. It can then be transferred to a detector photodiode by a second optical fibre with one end butted to the far end of the waveguide. The two arm structure of the waveguide can be recognized as a Mach-Zehnder interferometer. In the diagram electrodes are shown located between the two arms. When an electrical signal is applied between the electrodes (coming from an LHC detector element) the electric field across the waveguides changes the refractive index of the arms through the electro-optic effect. By having the field in opposite senses across the two arms the changes of refractive index are opposite in sign in the two arms. The interference between the light emerging from the two arms changes from destructive to constructive for a change in potential of typically 5-10 Volts. The device behaves electrically as a 10pF capacitance.

Figure 2 shows the test setup at Birmingham used for studying a GEC modulator on loan since early October. The response as a function of the DC bias applied to the device is shown in figure 3. The expected cosine form of the response is clearly seen. At a bias of around 2.0 volts the response for small signals will be nearly linear and this is the mode of operation forseen for readout at LHC. Figure 4 shows an applied 50ns pulse and the photodiode response with a DC bias of 1.9 volts. We have made studies of the response of the system to pulses of varying amplitude around this bias point. The results are shown in figure 5. The straight line has unit slope (linear response) and it can be seen that the dynamic range over which linearity is maintained is already 2-300:1. At high pulse values the departure of the cosine response from linearity is evident. In order to explore the response at lower pulse levels we need to use an amplifier with lower noise. The studies at CERN and BNL are more mature and reveal that for comparable devices the linear region has a dynamic range of more than 8 bits. Figure 6 shows the optoelectronic test bench set up at CERN by Giorgio Stefanini in July this year. Figure 7 shows the transfer characteristics for the lithium niobate modulator at CERN. Figure 8 shows the linearity plot for the same modulator.

MQW Amplitude Modulator.

The MQW modulator is designed to reflect light incident from a fibre back along the same fibre. When a voltage is applied to the electrodes of the modulator its reflection coefficient changes. These devices are extremely compact, being a few hundred microns square in the plane at right angles to the fibre and their active thickness is a few microns. They are one example of a plethora of possible modulators that can be designed in GaAs/GaAlAs and other III/V compounds. All possess the established inherent radiation resistance of these materials. They are related also to the MQW lasers that are currently coming to the market place.

In a heterostructure in which the GaAs layer is 10nm to 100nm in thickness the electrons and holes within this active layer find themselves in a quantum well with discrete levels, rather than the energy bands typical of bulk semiconductor material. The important effect for lasing is that the density of states jumps from zero at energies below threshold to a finite value above threshold and there are equal steps at each succeeding energy level. The density of states is determined by the lateral motion of the holes and electrons in the plane of the GaAs layer. As a result the population inversion is large exactly at threshold unlike a standard laser diode, so that an output of one mW of optical power only requires an input of order ten mW of electrical power. Typical devices have many quantum wells built up layer by layer. The industrial requirement is for arrays of MQW lasers to generate power to pump other devices. Fabrication of arrays of reflective modulators must clearly involve very similar manufacturing processes to those needed for MQW laser arrays.

Figure 9 shows a section through a MQW reflective modulator reported by Moseley et al [11]. The alternate layers of InGaAs/InP form the MQW structure. This is enclosed between two mirrors formed by the p+ InP at the top and the 7 period InP/GaAlInAs quarter wave layers at the bottom. The former mirror is nearly 100% reflecting and the latter only 30% reflecting. These two mirrors form a Fabry-Perot cavity so that the light incident from below passes to a fro many times across the MQW structure before re-emerging at the same face. Absorption of light has a threshold at the energy required for creating an electron and hole in the lowest quantum states. There is a peak at the threshold arising from the formation of excitons: these are bound states of a hole and an electron - each in the lowest quantum level. At threshold the absorption coefficient changes rapidly with the incident photon energy. When an electric potential of a few volts is applied across the MQW structure the band structure tilts so that the electron and hole wavefunctions overlap less and their energy separation changes. This is the quantum confined Stark effect. As a result the absorption edge shifts and this shift will be marked by a reduction/increase in the amount of light reflected at wavelengths near the absorption edge. There has to be a threefold match for any useful effect to be acheived. The wavelength of the absorption edge, the wavelength of the incident laser light and the wavelength for the Fabry-Perot resonance must all match up. Then a reflectance change of 30%/volt is acheivable. Temperature affects the refractive index of the material so that compensation for temperature variation has to be forseen. As mentioned earlier there are alternative devices also using III/V materials, such as GaAs Ridge Waveguides, Barrier Reservoir and Quantum Well Electron Transfer Structures. An R and D programme will involve an initial assessment of an appropriate III/V technology from among the range on offer.

The III/V devices are ideally suited for hybrid integration with drive electronics using the flip-chip technique, the drive circuits being III/V HBT circuits for radiation hardness. GEC-Marconi have also demonstrated that the drive and modulator may be integrated directly.

Multi-channel Modulators.

The attractions of passive optoelectronic modulators for readout at LHC will be considerably enhanced if multi-channel devices can be constructed. The DRDC proposal from Birmingham, CERN, EPFL, GEC-Marconi, Lund, Oxford and RAL looks forward to a collaborative programme to build and extensively test such devices. There is a parallel programme in the US involving BNL, Boston and Columbia, and aimed at SSC detectors. The CERN based R and D programme is aiming to design and construct a complete system with laser source, ribbon fibre cables and suitable connectors, multi-channel modulator, receiver photodiodes and the necessary control and compensation circuitry. The whole is called an Integrated Optoelectronic Circuit (IOC). IOCs will be built for two passive modulator technologies: using lithium niobate and also using MQW (or other appropriate III/V) modulators. The designs are shown in figures 10 and 11.

Conclusions.

There is little doubt that optoelectronic data transfer will be required at EAGLE or any other LHC detector. Read out from tracking detectors is where the technique is most obviously needed. It is also clear that passive modulators are superior to active devices (laser diodes or LEDs) for transfering data from a detector. Beyond that it is as yet unclear which strategies and technologies are the most appropriate. The strategies for the readout range all the way from reading out all tracking detector analogue signals directly with passive modulators to reading out digital data after multiplexing and data compression, also with passive modulators. In each case a choice can only be made if the technical feasibility and cost of all components of the readout are considered together, not just of the optoelectronic components in isolation. There is also the question of how much, if any, data should be read out from a tracking chambers for use in the first level trigger. Here in addition the Physics interest needs investigation through Monte-Carlo studies. Hopefully this document will stimulate a dialogue between interested parties in the detector R and D groups and those involved in optoelectronics R and D. As to assessing and selecting from the range of technologies available for the modulator construction, a programme of R and D with industrial involvement like that proposed in DRDC 91-41/P31 seems essential.

Figure Captions.

Figure 1: Single Channel Lithium Niobate Modulator.

Figure 2: Optoelectronic Test Bench at Birmingham University.

Figure 3: Response of Lithium Niobate Modulator as a function of DC bias voltage. Measurements made with the setup shown in figure 2.

Figure 4: Input pulse to Lithium Niobate Modulator and the amplified output pulse from the photodiode receiver. Measurements made with the setup shown in figure 2.

Figure 5: Response of the Lithium Niobate Modulator to pulses as a function of the pulse amplitude. The DC bias is 1.9 volts. The amplified output from the photodiode receiver is plotted against input pulse amplitude in volts. Measurements made with the setup shown in figure 2.

Figure 6: Optoelectronic Test Bench at CERN.

Figure 7: Transfer characteristic of a Lithium Niobate Modulator. Measurements performed at CERN with receiver photocurrent of approximately 0.5 mA maximum. The extinction ratio is close to 18dB. The setup for these measurements is shown in figure 6.

Figure 8: Linearity of Lithium Niobate Modulator measured at CERN. Modulator biassed at quadrature , 0.7 Volts. Input is a rectangular voltage pulse. Photodetector output into a charge sensitive preamp, with amplifier shaping time constant 20ns. Overall equivalent input noise is about 1mV(baseline fluctuations from laser excess noise). Dynamic Range is about 500:1 for an integral non-linearity of less than 1%. The setup for these measurements is shown in figure 6.

Figure 9: Section through a Reflective Multiquantum Well Modulator.

Figure 10: Proposed Integrated Optical Circuit for a Multi-Channel Lithium Niobate Modulator.

Figure 11: Proposed Integrated Optical Circuit for a Multi-Channel MQW Reflective Modulator.

References:

1] 'HiPPI Developments for CERN experiments', T. Anguelov et al. (to be presented at the Santa Fe Meeting of the IEEE in November 1991).

2] 'Integrated High-Rate Transition Radiation Detector and Tracking Chamber for the LHC'. Brookhaven, CERN, JINR(Dubna), Lund, Moscow Collaboration - CERN/DRDC/90-38; DRDC/P8, 29th August 1990.

3] 'Optoelectronic Analogue Signal Transfer for LHC Detectors'. Birmingham, CERN, EPFL, GEC-Marconi, Imperial College (London), Lund, Oxford, RAL Collaboration - CERN/DRDC/91-41; DRDC/P31, October 9th, 1991.

4] 'Radiation Effects on Optical Data Transmission Systems'. B. Leskovar , Proceedings of the Toronto Conference, IEEE trans Nucl. Sci. 36, 543-551, 1989.

5] Proceedings of the ECFA Workshop on LHC Detectors, Aachen 1990, CERN 90-10.

6] 'A proposal to study a Tracking/Preshower Detector for the LHC'. - Cambridge, CERN, Dortmund, Universite de Geneve, Hamburg, Melbourne, Oslo, Oxford, Perugia, RAL, Sydney Collaboration - CERN/DRDC/90-27; DRDC/P3, 2nd August 1990.

7] 'Development of High resolution Si Strip Detectors for experiments at high luminosity at LHC'. - CERN, Cracow, Helsinki, Imperial College (London), Oslo, S.I. (Oslo), RAL, LESPI Strasbourg, INFN Turin, Yale Collaboration. - CERN/DRDC/91-10; DRDC/P26, 7th March 1991.

'Proposal to Develop GaAs Detectors for Physics at the LHC'. - Bologna, CERN, Florence, Glasgow, RAL, Sheffield Collaboration, - CERN/DRDC/90-58; DRDC/P13, 8th October 1990.

Other tracking detectors such as Gas Avalanche Microstrip Detectors and the Gaseous Pixel Chamber are described in Proceedings of the LHC Workshop, Aachen 1990, CERN 90-10, Vol III, p207 et seq.

8] 'A Study of Electro-Optical Modulators for Transfer of Detector Signals by Optical Fibers'. T. Tsang, V. Radeka, T. Srinavasan-Rao and W.J. Willis, BNL-45393, October 1990.

9] 'Measurements on a GEC-Marconi Electro-optic Modulator'. C. Da Via, I. Kenyon and G. Stefanini, in preparation.

10] BNL preprint, September 1991, V. Radeka, W.J. Willis et al.

11] 'Low Voltage InGaAs/InP Multiple Quantum Well Reflective Fabry-Perot Modulator'. A.J. Moseley et al., Elec. Lett. 26(13), 913-915, 1990.

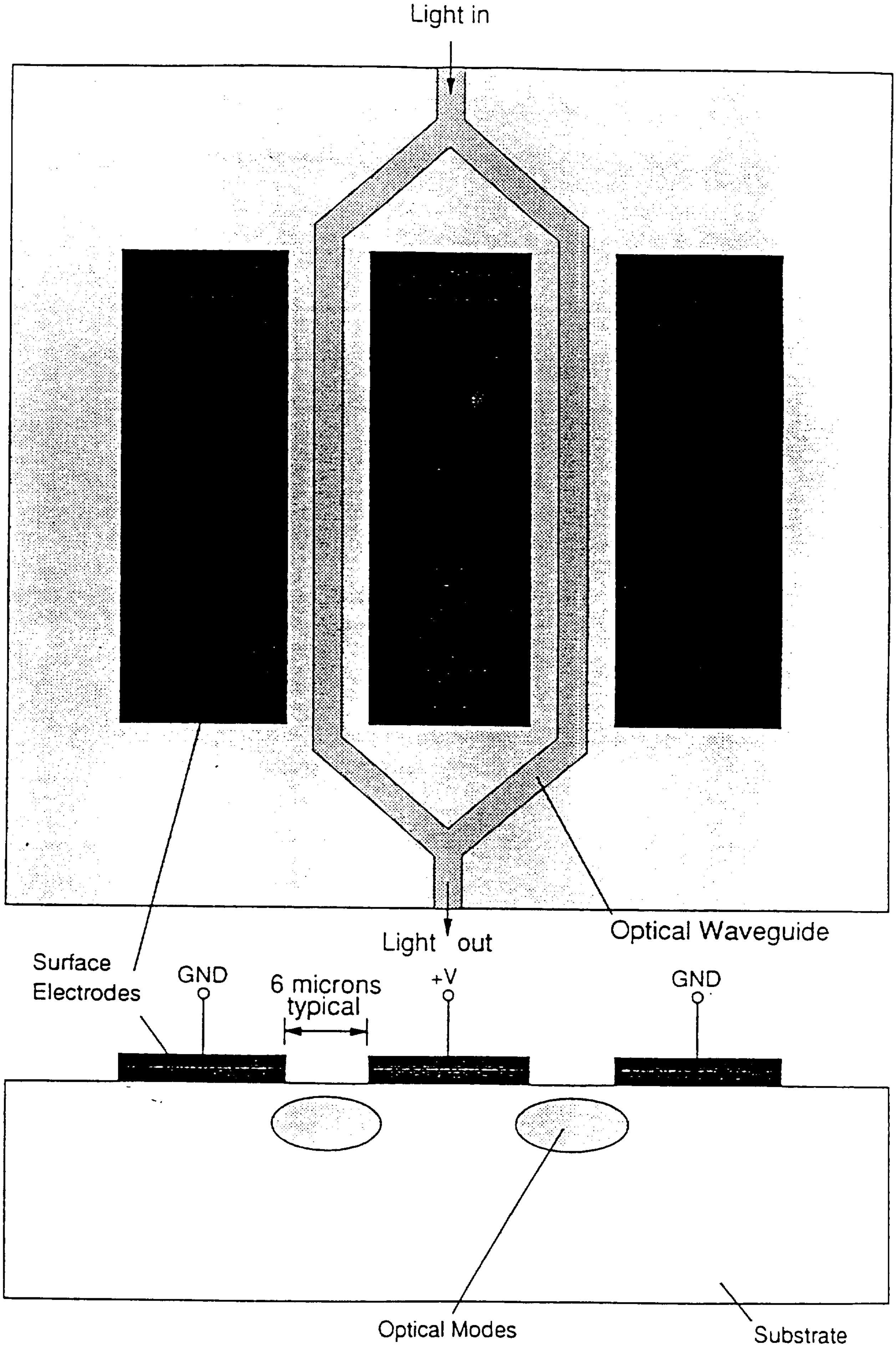
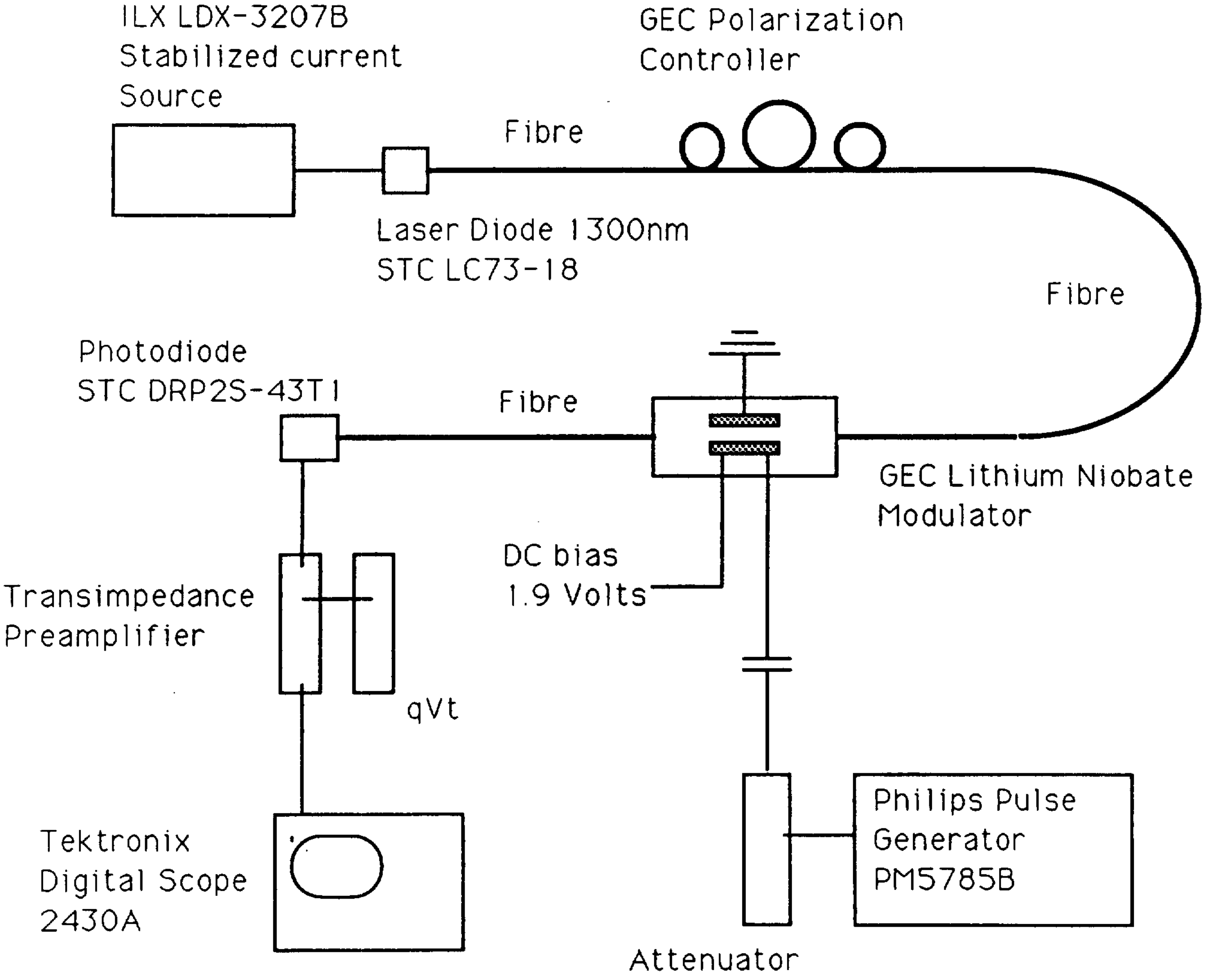
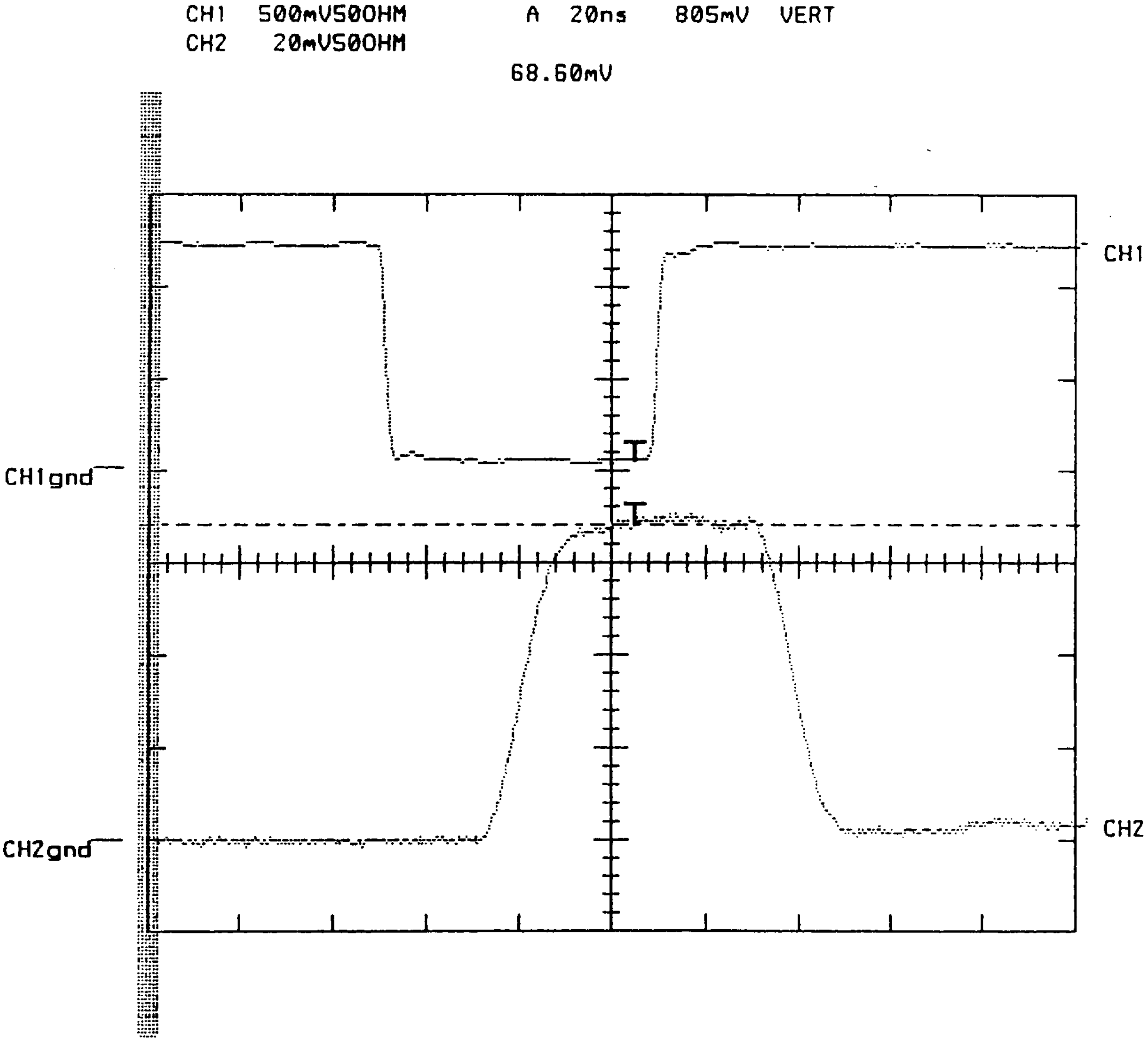
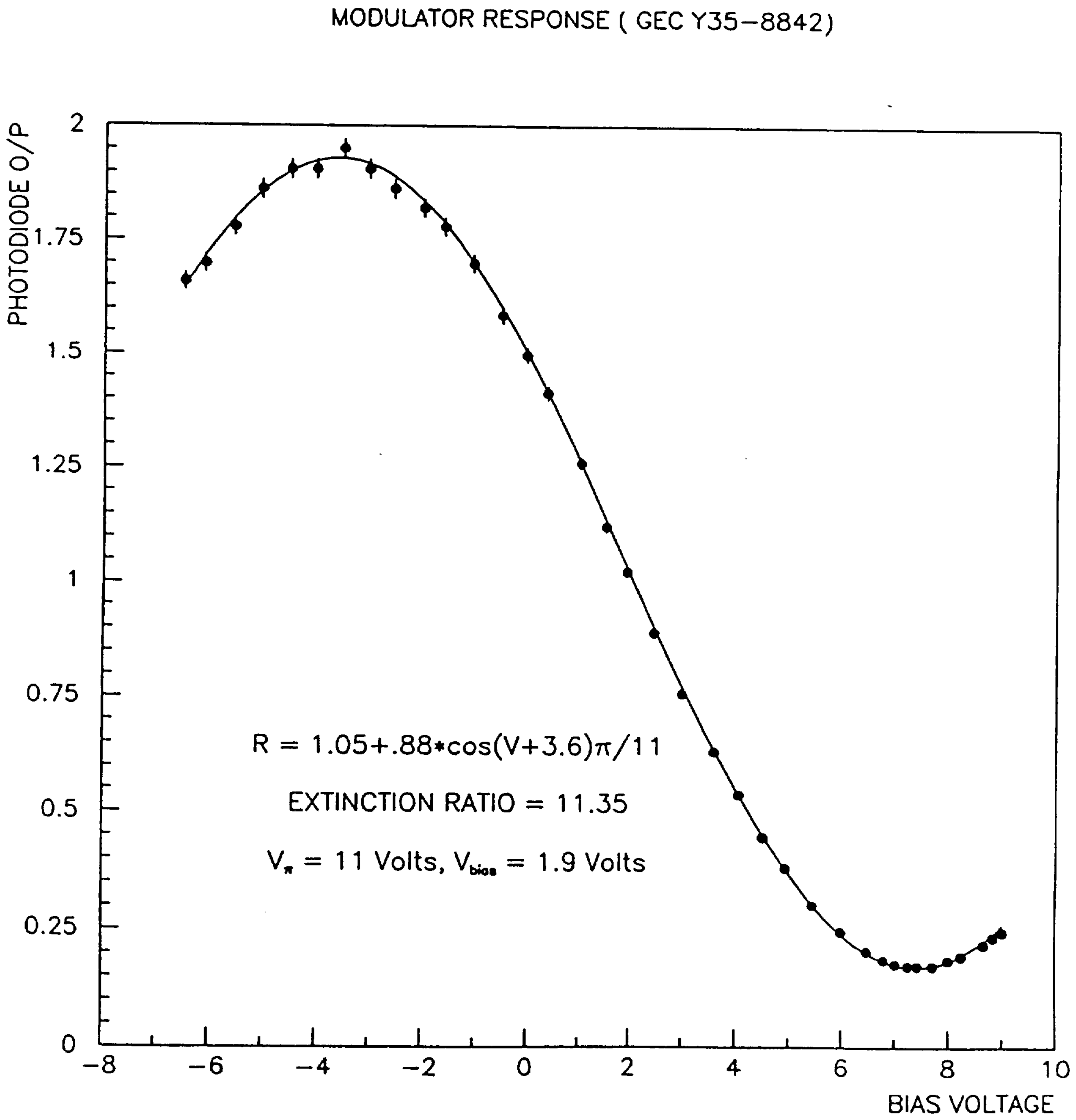


Fig. 1 : Plan and Cross-Section of Electro-Optic Modulator

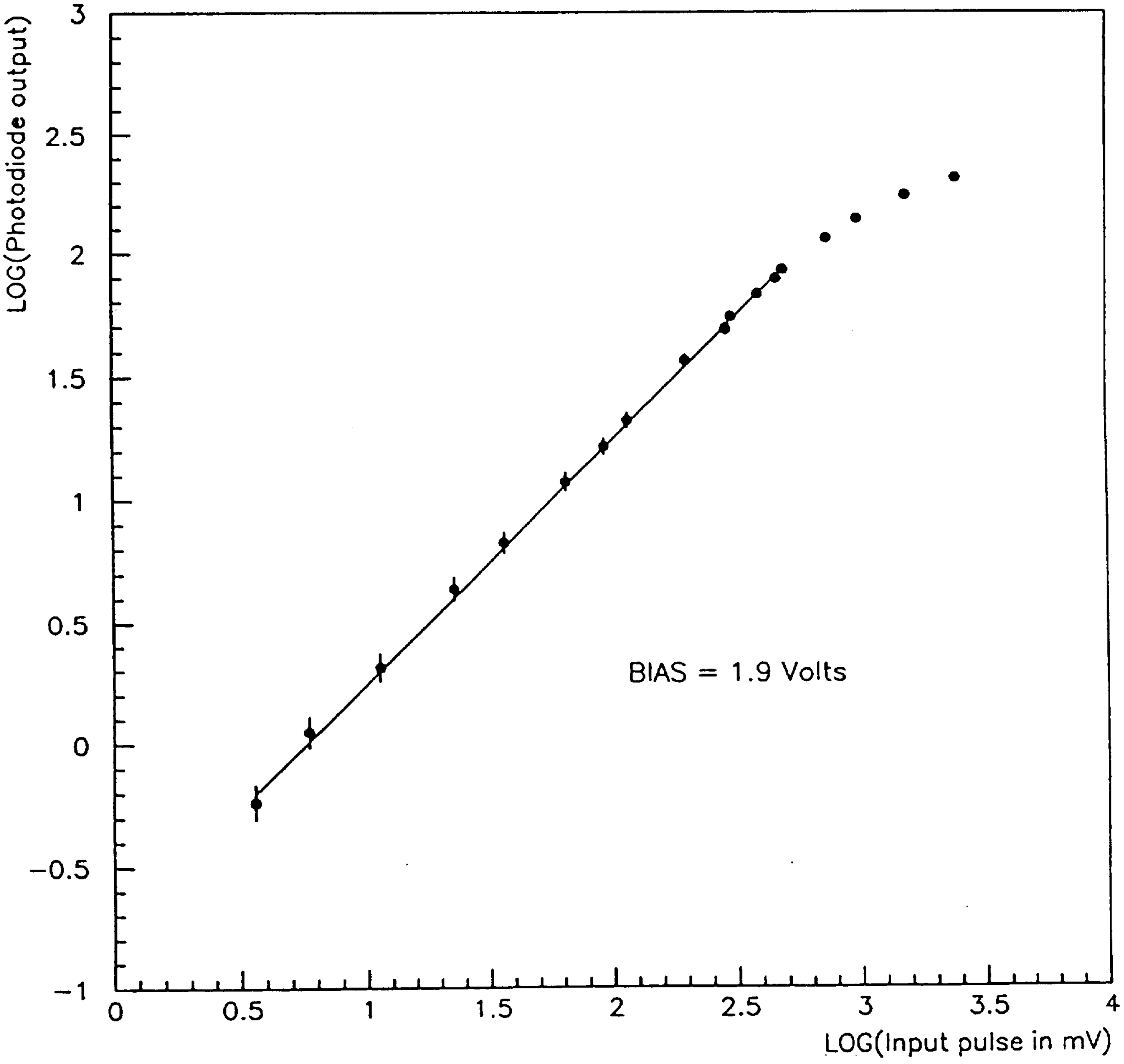


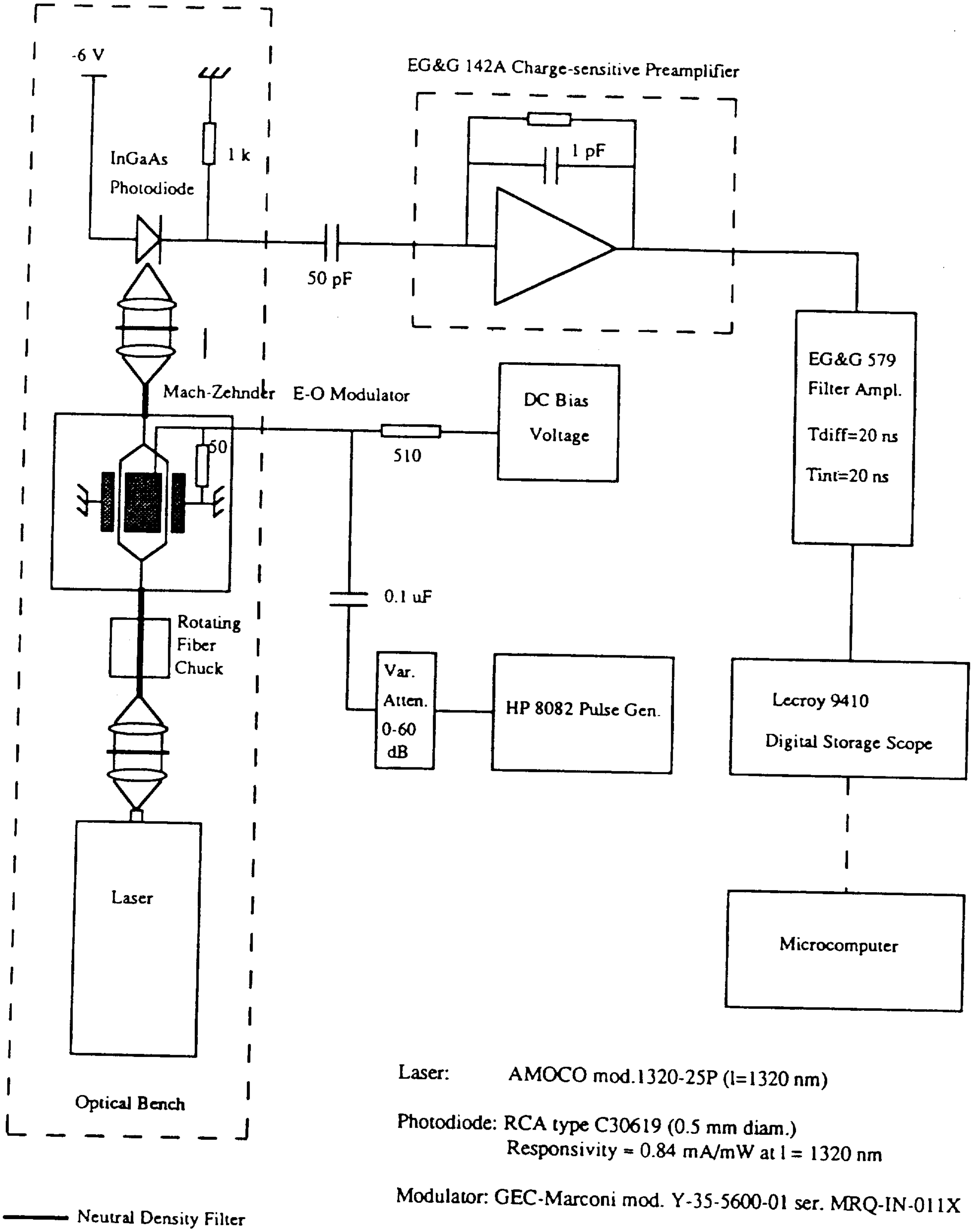
Modulator Testbench at Birmingham, Oct 91


CH1 500mV50OHM
A 20ns 805mV VERT
CH2 20mV50OHM
68.60mV
CH1
CH1gnd
CH2
CH2gnd


MODULATOR RESPONSE (GEC Y35−8842)
PHOTODIODE O/P
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
−8
−6
−4
−2
0
2
4
6
8
10
BIAS VOLTAGE
R = 1.05+.88*cos(V+3.6)π/11
EXTINCTION RATIO = 11.35
V_π = 11 Volts, V_{bias} = 1.9 Volts

MODULATOR PULSE RESPONSE (GEC Y35−8842)





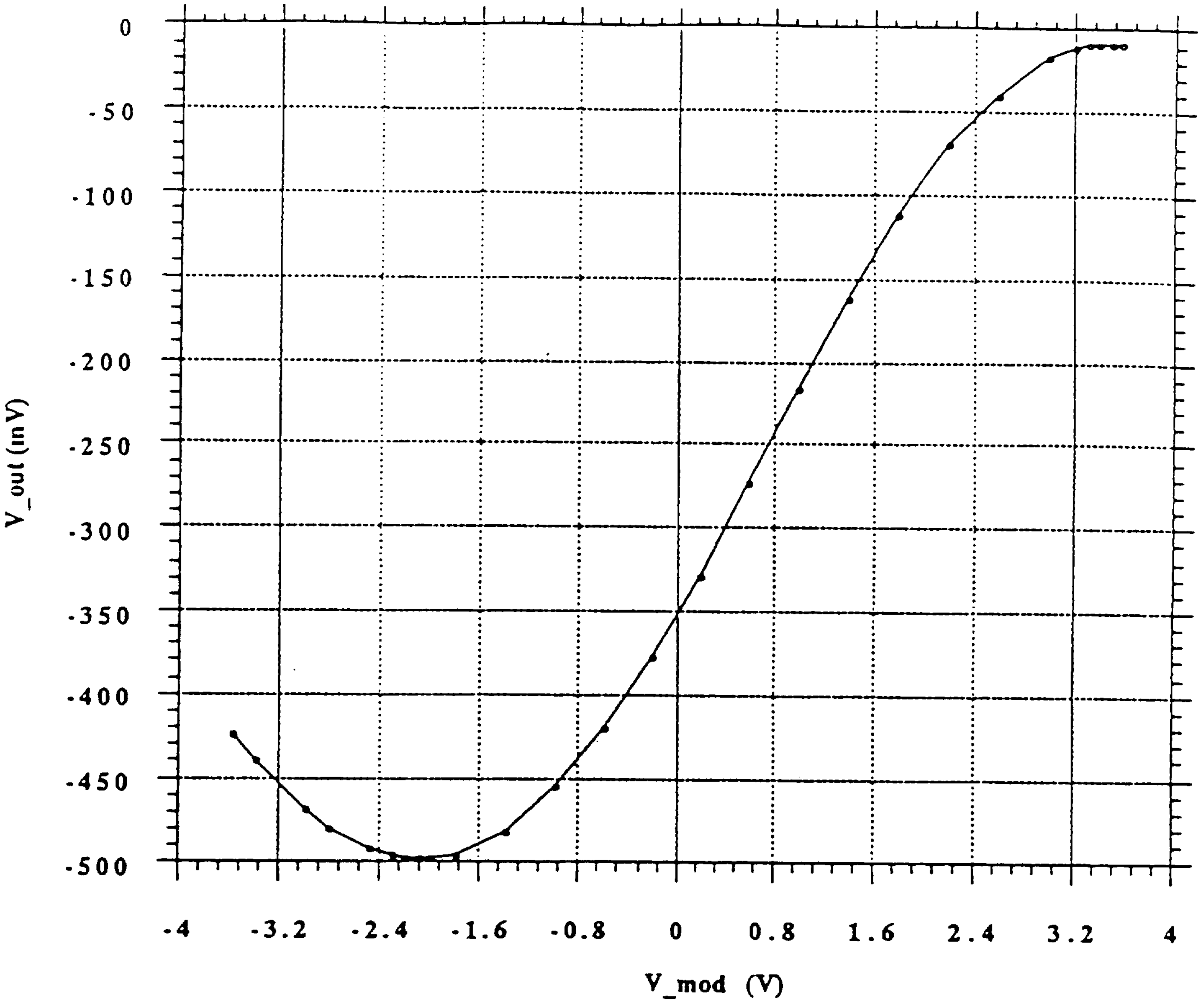
Laser: AMOCO mod.1320-25P (l=1320 nm)

Photodiode: RCA type C30619 (0.5 mm diam.)
Responsivity = 0.84 mA/mW at l = 1320 nm

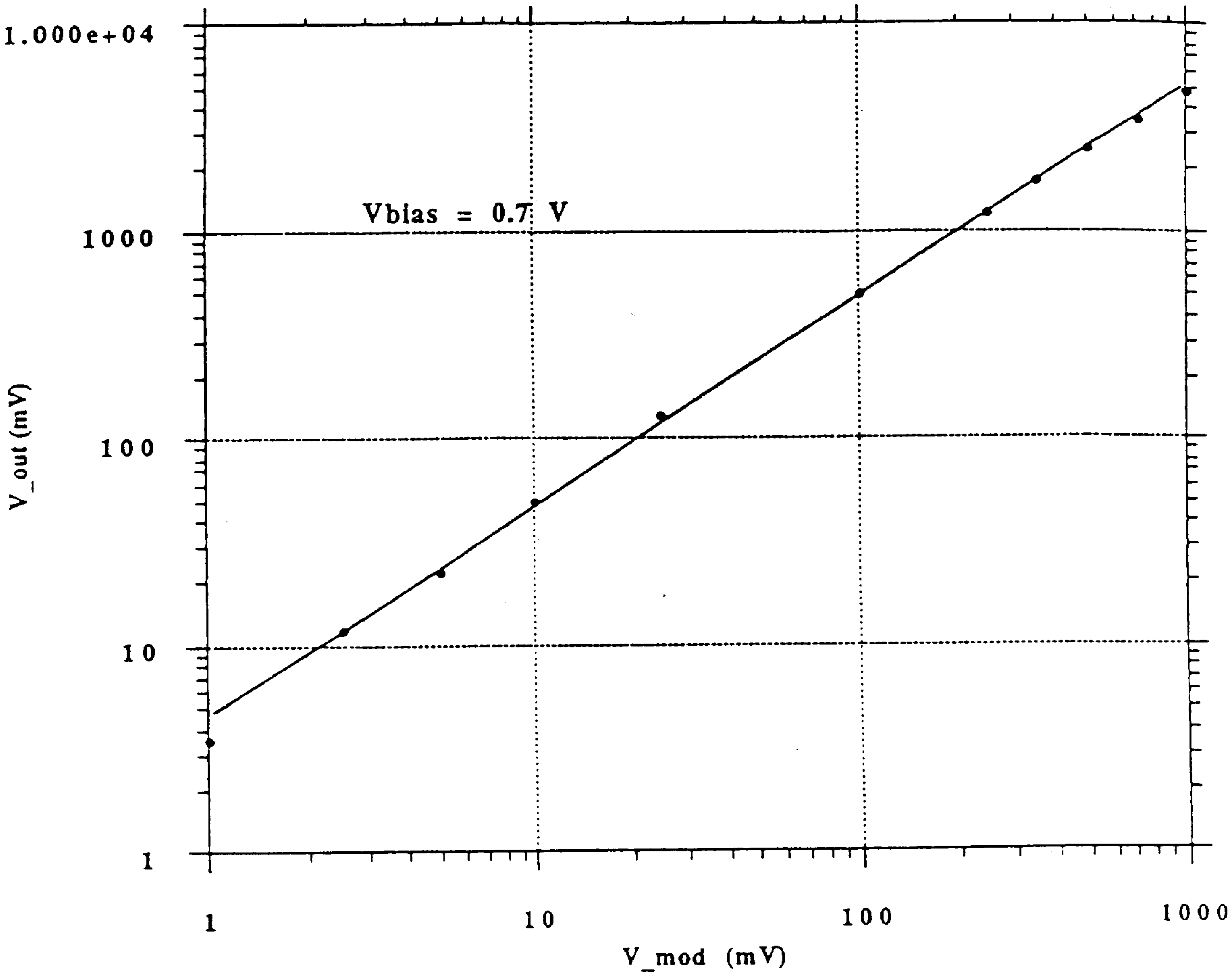
Modulator: GEC-Marconi mod. Y-35-5600-01 ser. MRQ-IN-011X

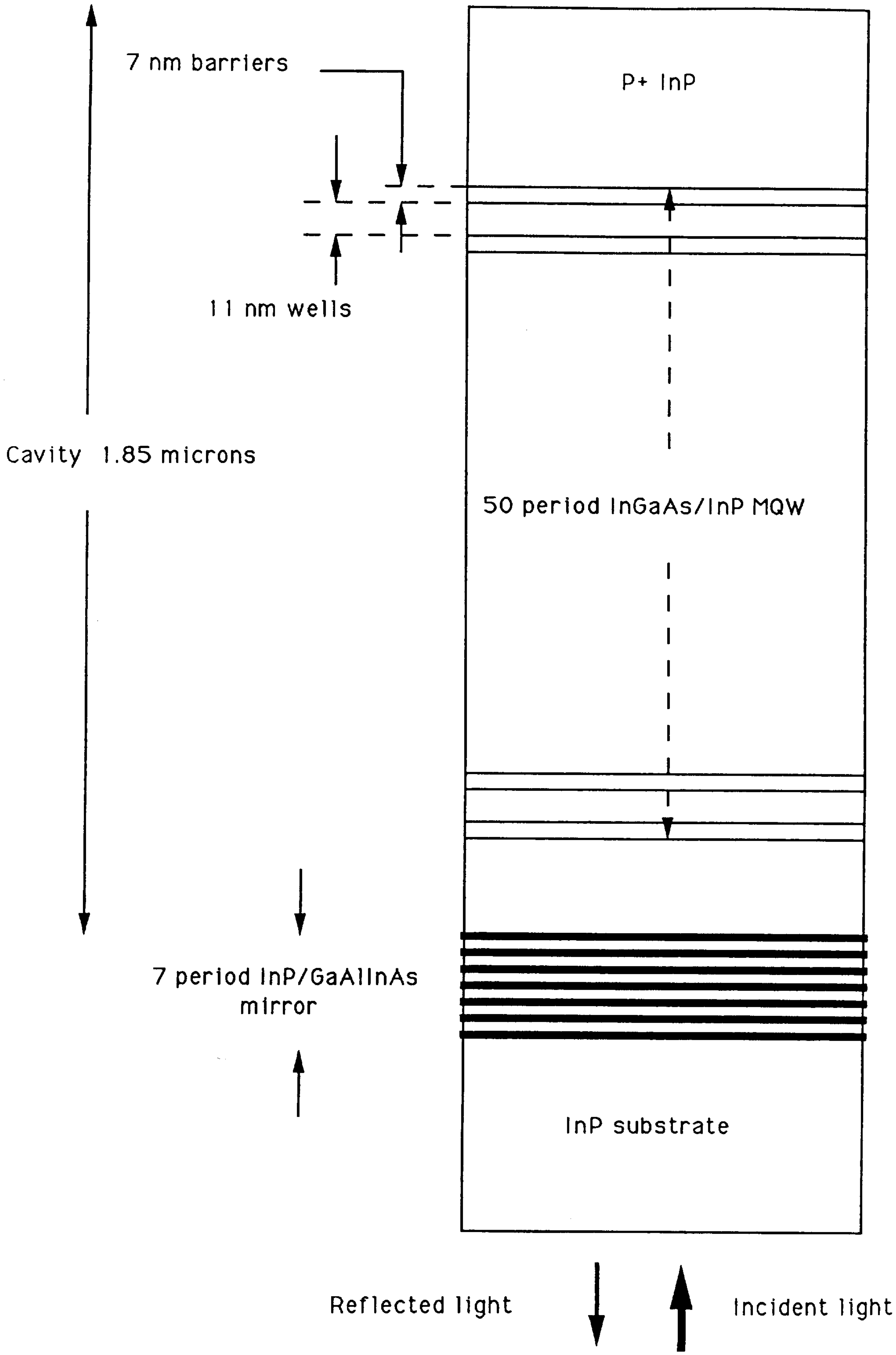
Experimental Setup for Linearity and Noise Measurements

Modulator Transfer Characteristics

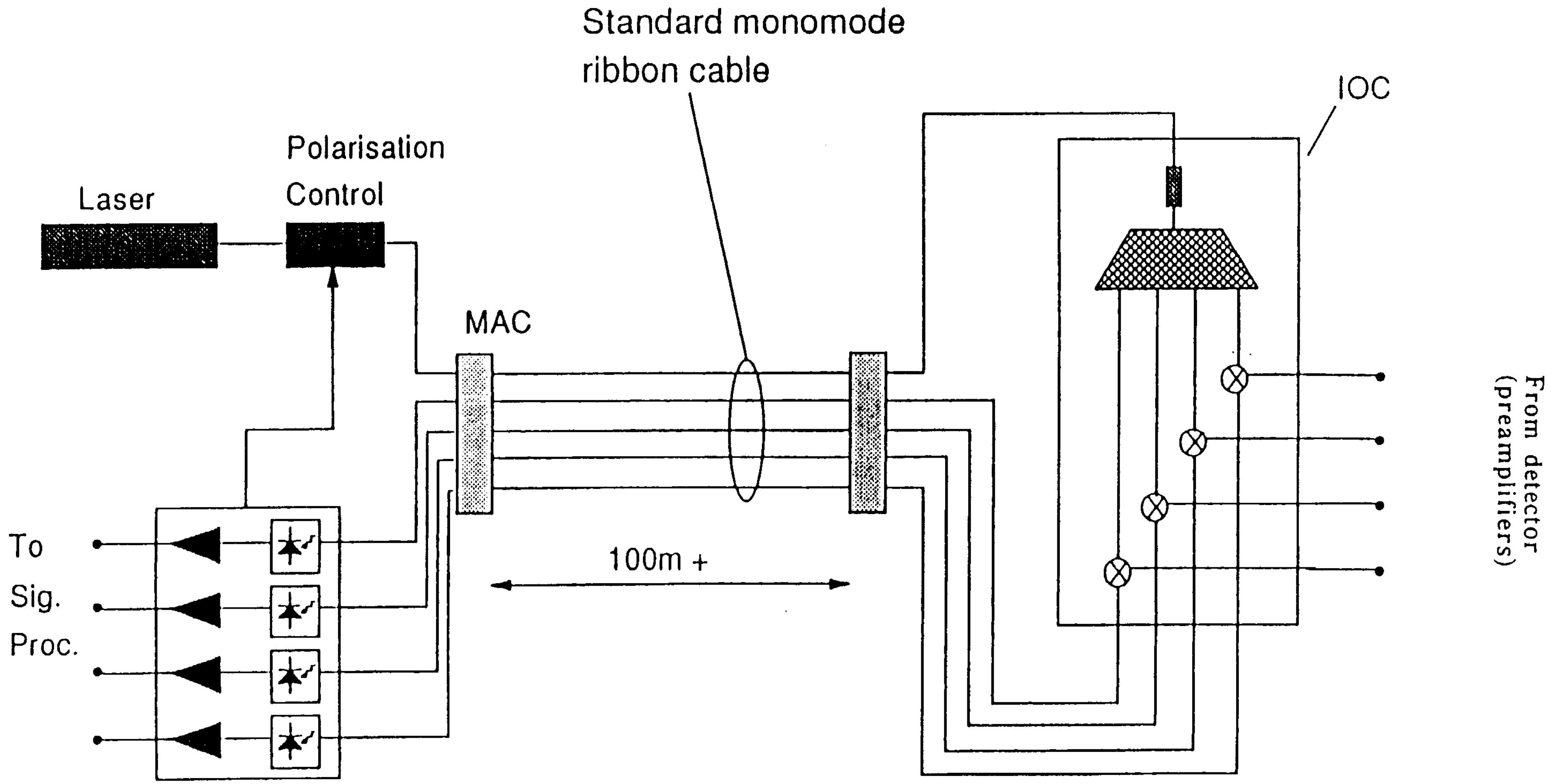


Modulator Linearity Curve

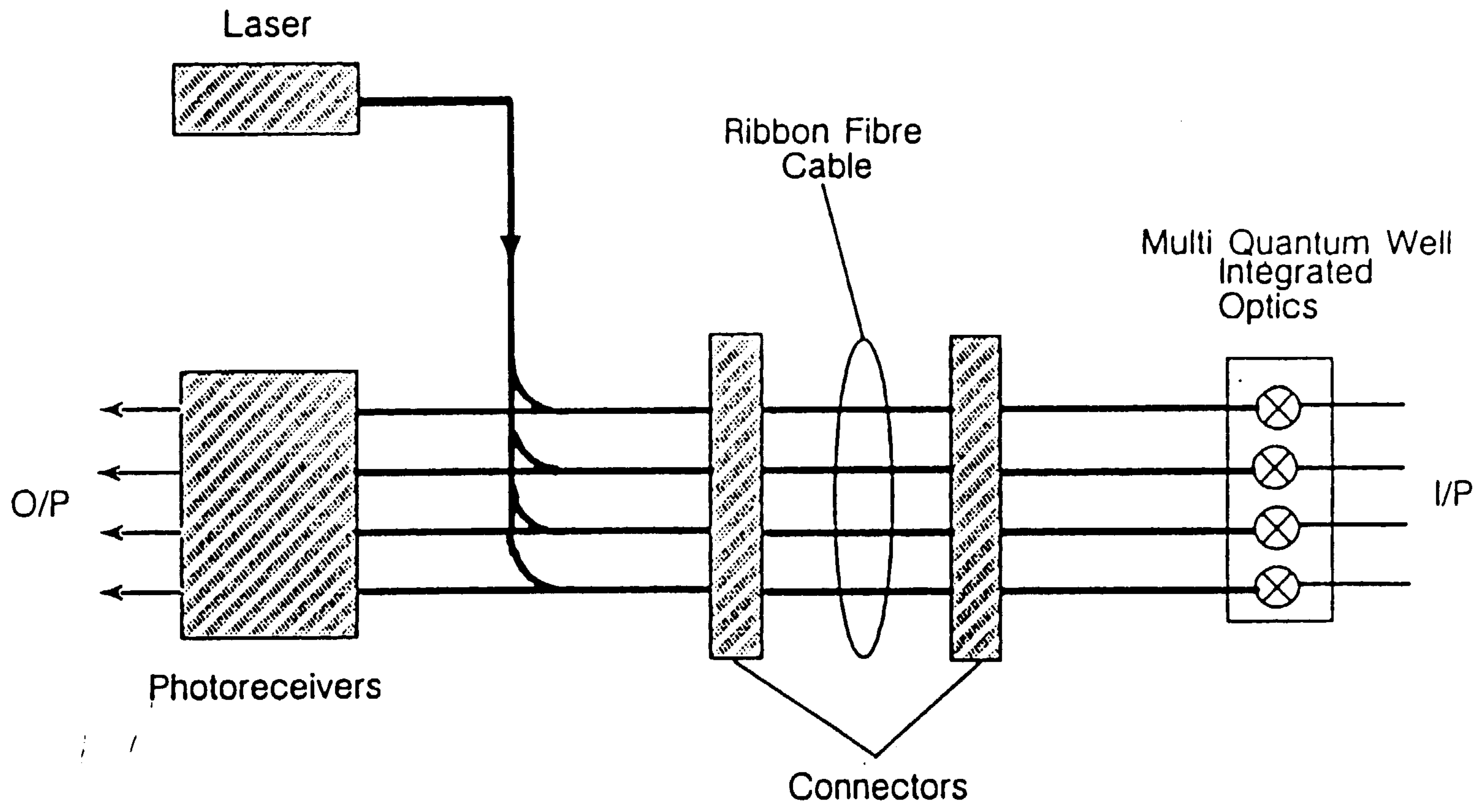



7 nm barriers
P+ InP
11 nm wells
Cavity 1.85 microns
50 period InGaAs/InP MQW
7 period InP/GaAlInAs mirror
InP substrate
Reflected light
Incident light

Schematic of LiNbO$_3$ Modulator Integrated Optical Circuit



GEC - Marconi
Research Centre


Laser
Ribbon Fibre Cable
Multi Quantum Well Integrated Optics
O/P
I/P
Photoreceivers
Connectors