A PROTOTYPE INVESTIGATION OF A MULTI-GHz MULTI-CHANNEL ANALOG TRANSIENT RECORDER

by

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ABSTRACT

The feasibility of a new concept in high speed digital recording is investigated in this thesis as an alternative solution for ultra fast transient recording. The resulting cost and performance improvements could present a fundamentally new direction in high speed data recording principles, and a much needed tool for rapidly advancing nuclear research

The investigation is directed into four parts The first step analyzes the operating performance of the system in harsh environments. This is followed by a study of the limitations of conventional A/D conversion techniques and the reason for a completely new approach. The third part introduces the new principle of indirect digitizing methods and finally the last part explains the details of the new recording instrument based on such principles

RESUME

Cette thèse présente une enquête sur la réalisation d'un nouveau concept d'enrégistrement numérique a haute vitesse comme solution alternative aux problèmes de conversion analogique/numérique d'impulsions ultrarapides. Les améliorations de coût et de rendement qui en résultent pourraient présenter une direction complètement nouvelle au niveau des principes d'enrégistrement de transientes de hautes fréquences De plus, ceci fournirait un instrument très recherché pour les nouvelles avances de la recherche nucléaire.

L'enquête est dirigée en quatre parties. La première partie analyse le rendement du système dans des environnements rudes. Le tout est suivi d'une étude des limitations des techniques de conversion analogique/numérique conventionnelles, et les raisons pour le besoin d'une nouvelle approche. En troisième lieu le nouveau principe d'enrégistrement est introduit, et finalement la dernière partie explique les détails de l'instrument basé sur ces principes.

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INTRODUCTION

The feasibility of a new concept in high speed transient recording is investigated in this thesis The new instrument records data signals directly in optical form to permit very high recording speeds and full exploitation of the advantages in optical signal transmission The resulting performance improvements could present a fundamentally new direction in high speed data recording principles

High Energy Experiments

Very fast transient recorders find applications in situations where very short life times or very short periods of interest are involved Such short life time phenomena can happen in nature but are generally found in highly sophisticated experiments such as in nuclear physics research

Pulsed power is one such field which is ever increasing its scope of research and the recording equipment requirements are becoming significantly more difficult to meet New energy and power levels of the experiments have reached the point where conventional data recording methods can no longer satisfactorily handle the speed of incoming data and the growing deterioration of the environmental conditions Consequently there is a need for new equipment which can resolve two problems concurrently; high speed data recording and a high noise immunity capability. Both specifications bear the same importance in the success of the new system. Therefore the same design efforts should be attributed to the data communication link as to the recording instrument itself

Most environmental conditions will affect the system performance through the deterioration of signal transmission This, together with the high bandwidth requirement of the transmission line have always been serious obstacles in the achievement of high performance levels Any form of noise immunity is generally gained by a proportional loss of bandwidth due to the introduction of complex circuitry Innovations in optical signal transmission, however, allow the design of high bandwidth channels, with a very high level of noise immunity as an inherent characteristic Optical signals are indeed the ideal solution, but optical transmission is faced with a major speed limitation which arises from the need to convert electrical sensor signals into analog optical signals Any electronic circuitry responsible for such medium conversion will directly affect overall performance levels Hence, conversion circuit complexity should be kept to a minimum or ideally be completely eliminated The new data recorder presented in this thesis is capable of recording optical signals directly This eliminates one level of medium conversion, ie. there is no need to convert from optical back to electrical, but still requires electrical to optical conversion of the high frequency transient signals. Electrical to optical conversion can be achieved using laser diode technology but response times are still far less than the bandwidth potential of the data recorder.

Digital Recording of Data Signals

The usefulness of a data acquisition system relies as much on the amount of data it can extract from an experiment as on the resources available to process the data. Large amounts of data can only be properly interpreted by computer analysis. Hence any system aimed at providing high performance data recording should produce the results in digital form.

There are various methods to achieve analog to digital (A/D) conversion, each technique having a specific advantage under various circumstances. Some methods offer high resolution with good linearity while others are aimed at high speed conversion. Since high speed data acquisition, and digitization, is the basis of short transient recording, it is important to understand the limitations of A/D conversion. Conventional signal digitization is based on direct A/D conversion, incoming data signals are sampled and converted in real time. This implies that the sampling and conversion speeds of these circuits directly limit the channel bandwidth. It is therefore necessary to find the limitations of such circuits to estimate the bandwidth potentials of future conventional digital transient recorders.

Direct A/D conversion is a complex process, always limited by a speed barrier set by transistor switching times. The recognition of the sources of such limitations and the belief that order of magnitude improvements are improbable, has lead to the development of indirect digital recording methods. Indirect A/D conversion is based on the principle of temporarily storing the input data signals at very high rates and retrieving them later at a rate which would suit a fast, high resolution conventional A/D converter circuit. The innovation of indirect digitization systems lies mostly in the conception of a temporary storage medium with a fast writing capability.

The new data recorder described in this thesis is based on such indirect conversion methods. The system involves a streak camera which is an instrument used to obtain time resolved pictures of X-ray formations. Such a system can be modified to produce time resolved pictures of a large number of optical input signals simultaneously. The camera records the intensity variations of the input signals on a fluorescent screen. This screen acts as the temporary storage medium, saving the image until it is digitized using a TV camera and a conventional digitizing circuit. The high bandwidth potential of such a system is based on the fast recording ability of the fluorescent screen. Furthermore, the resolution of the output is directly related to the TV camera which is independent of the basic recording process, a phenomenon which is impossible to obtain using direct digitization methods

The performance improvements and economic feasibility of this design are treated in this thesis to determine the possibility of this instrument becoming the standard transient recorder of future high speed data acquisition systems

CHAPTER 1

SHORT DURATION EXPERIMENT ENVIRONMENTS

1.

Short duration experiments are characterized by large energy banks, high power discharges and large EM noise levels. The resulting environ mental conditions and the precise control requirements play an important role in the design specifications of a high speed data recording system Hence, the direct effects of the working environment should be clarified prior to further investigation of a new recording system

1.1. Introduction

The time scale of short duration experiments, as considered in this thesis, typically ranges from microseconds to sub nanoseconds A large part of scientific development today is aimed directly at the production of very short experiments Experiments which only last a few nanoseconds are intrinsically high power events which can become extremely complex procedures when it is attempted to reproduce them under controlled conditions Nuclear physics is a major area where such experiments are currently conceived.

One of the major branches of nuclear physics involved with short duration experiments is pulsed power research. Most of the work described in this thesis will be directly applicable to this field.

The principle of pulsed power is the concentration of energy within a very small amount of time and space. Consequently pulsed power experiments involve the production of high power levels The demand for increased power levels for research areas such as nuclear fusion has lead to a general tendency to build larger experimental facilities, which would allow more energy storage and faster discharge times

The production of such high power levels create extremely adverse noise conditions for any electronic equipment responsible for experimental control or data acquisition. These noise levels cannot be avoided but have to be treated to minimize the chances of damage to experimental equipment or data signals

The short duration of such experiments also creates many timing and switching problems as well as necessitating the use of expensive high speed data recorders. Switching speeds are directly responsible for the production of the high power pulse. An equivalent amount of energy discharged in a shorter time period would result in the production of higher power levels. The short time span of an experiment makes the equipment triggering and synchronization much more difficult, as well as necessitating high bandwidth communication channels. Any transmission delays and delay variations can result in the loss of important data, or the damage of expensive equipment.

Both problems are highly inter-related but have to be solved independently. However, they both create a working environment which has to be taken into account during the design of new control equipment or diagnostic instrumentation.

1.2. Elimination of Noise

Pulsed power experiments are aimed at producing short, high power discharges. Since it is electrical energy which is stored and released under high power conditions, an inevitable side effect is an enormous noise level - in the form of an electromagnetic pulse This cannot be avoided as it is based on the fundamental principle that a varying current through a conductor will create a magnetic field and will emit EM radiations Consequently, this factor has to be dealt with, especially since the intensity of the EM radiations is directly proportional to the power of the source signal

The most dangerous effect of the EM power impulse is not the high magnetic field but its rate of change. Equation 1 shows that the induced electric potential is directly proportional to the rate of change of the magnetic flux. Very rapid changes in flux, as would occur in a pulsed power discharge, could induce large voltage potentials in a small loop of wire. Therefore any integrated circuit exposed to such conditions would burn up due to large potential differences induced across small junctions in the circuit. Hence it is necessary to protect any electronic equipment from such radiations.

Equation 1. $$e = N\, d\Phi / dt$$

where e : Induced potential

N : Number of turns in the loop

Φ : Magnetic flux

It is impossible to avoid such EM radiations so it is necessary to find a protection measure to deal with it This is why any experimental facility will require a shielded room, usually referred to as a Faraday cage[22,13], to contain all diagnostic equipment. The shielding thickness of the Faraday cage will depend on its distance from the source and the power of the radiation. This method is the most effective way to protect the equipment. However there remains the problem of EM interference (EMI) with the diagnostic signals, and pick up in ground loops. The effects of the EMI on diagnostics signals will be treated in detail in chapter 2.

Ground loop problems originate from the fact that currents are induced through field variations inside a loop of wire. Such loops can be formed by interconnecting cables or by common ground connections between equipment. The resulting loops can be very large and not always obvious. In the case of pulsed power experiments, the power levels can induce considerable ground loop currents which can cause severe equipment damage and data loss.

Equation 1 presents the potential problem of ground loops with respect to increased power levels. Large amounts of energy discharged within a small time period would produce a very large $d\Phi/dt$. Consequently, higher power levels would induce larger potentials in the system ground lines. Fighting ground loops can become very complex when having to consider an entire pulsed power experimental set up as shown in figure 1.2.1[12].

The most efficient way to fight such loops is to separate the experiment into modules and isolate them from each other. The basic techniques available are either isolation transformers or optical fibers, the latter being the best solution.

Within each module ground loops can be avoided by using a STAR type inter-connection layout between equipment grounds[14]. This method consists of defining a central ground point from which all equipment grounds branch out radially, thus eliminating loop connections. For many instruments it is best to use small STAR based models which are themselves connected in a bigger STAR model as shown in figure 1.2.2.

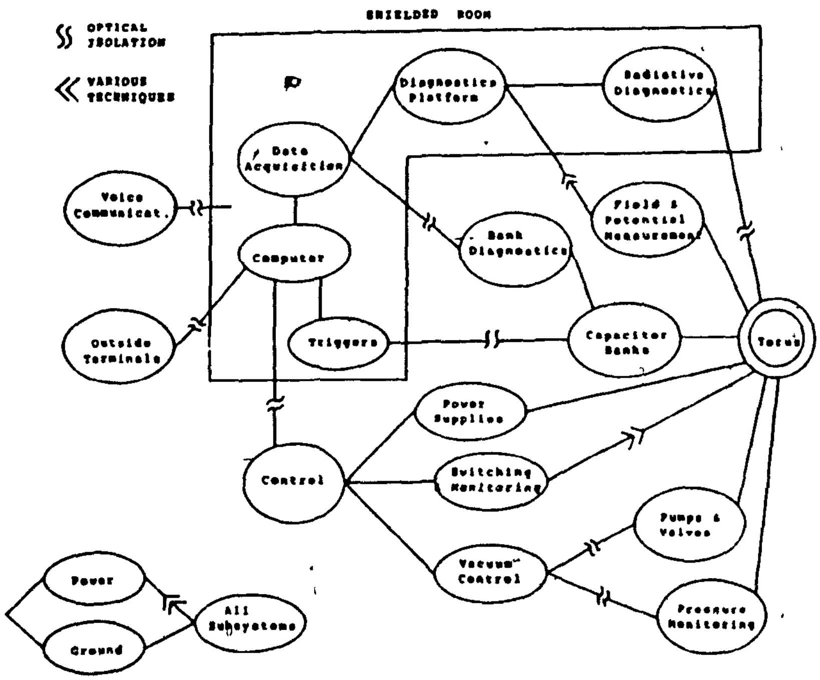


Figure 1.2.1 Ground plane layout and module isolation scheme

Developments in fiber optics in the last years have made it a feasible option for ground loop protection, and the elimination of EM interference in diagnostic signal transmission. Very expensive and complex shielding procedures can now be avoided through the performance improvement of commercial fiber optics. However, wire cables will always be used to some degree, so ground loop problems are not completely alleviated

1.3. Short Duration Effects

Short duration experiments, such as in pulsed power, involve large amounts of energy which have to be released as fast as possible under full control. It is not only a task of high power switching but also one of precise

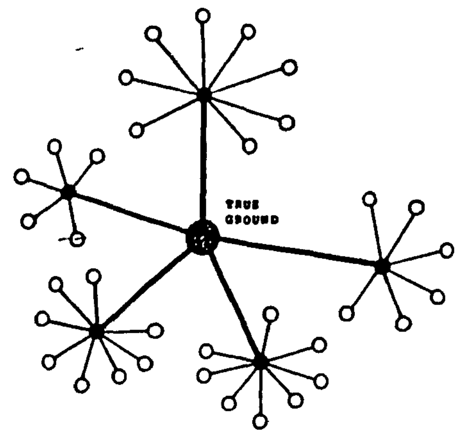


Figure 1.2.2 STAR model ground line layout

timing so that everything switches in the right pattern at the right time. Any switching delays or variations during the energy release can produce different results Such switching uncertainties as well as switch deterioration make it difficult to produce repeatable results.

All these problems are accentuated as the power levels increase. As the energy level is increased, the physical properties of the switching mechanisms are compromised. Switch deterioration through use is a significant factor limiting experimental repeatability. If the discharge time is reduced, then all synchronization delays have to be re-assessed and corrected to be within allowable limits. The electrical properties of the switches, such as the inductance, also become very important. The use of switches for experiment triggering can further compromise both the timing and repeatability. All these factors acting together create a distinct limitation on the maximum power levels attainable by a reactor. Consequently, high power switching remains the basis of extensive research.

ZT-40 FACILITY

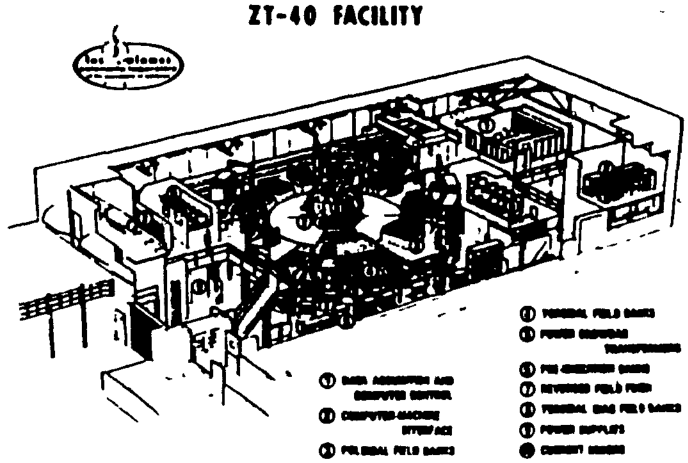


Figure 1.2 3. Los Alamos National Laboratory, ZT-40 Pulsed Power facility.

The power switching problem is not the only triggering difficulty. Any diagnostic recording instrument connected to the experiment has to be triggered and synchronized as well. All electronic recording equipment needs to be both synchronized together and to the power trigger. Consequently, multi-parameter experiments are more difficult to carry out because they require more equipment synchronization. This is significantly complicated by the fact that signal cable lengths can be long and can produce time delays which are significant in magnitude when compared to the overall experiment duration. Figure 1.2.3 shows the ZT-40 pulsed power facility at LANL and the distances involved between control room, energy bank and reactor[14].

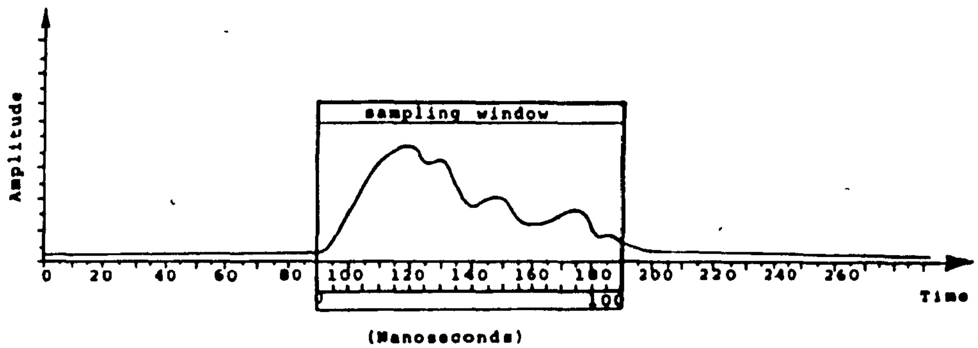
When propagation delays become comparable to experimental time durations, it becomes very important to synchronize the triggering of the recording equipment with the incoming data signals. Since the experiment is short, all the data will appear within a small time window. Similarly, to obtain a good resolution of the recorded signals, the recording time should be the same as the experiment duration. This is because high speed recording is usually limited by a fixed number of samples. Consequently, if the recording period matches the experimental time, then there is an optimal time separation between samples. Increasing the recording period increases the time period between samples and decreases the resolution of the recorded signal.

The triggering mechanism is then responsible for the precise overlay of the two events to record the entire diagnostic signal. Any delays in the data signals or in the recording trigger can offset the overlay of the two event windows. This problem becomes increasingly critical as experiment times decrease or recording windows get shorter. When large resolutions are desired, ie. the sampling window is smaller than the experiment duration, any trigger jitter can be a problem since any uncertainty in the real trigger time can make a significant difference to the recorded data. Figure 1.2.4 shows a graphical representation of a 20 nanosecond trigger delay. Certainly if the sampling window was made to be 10 nanoseconds instead of 100, a trigger delay of 20 nanoseconds would make a big difference.

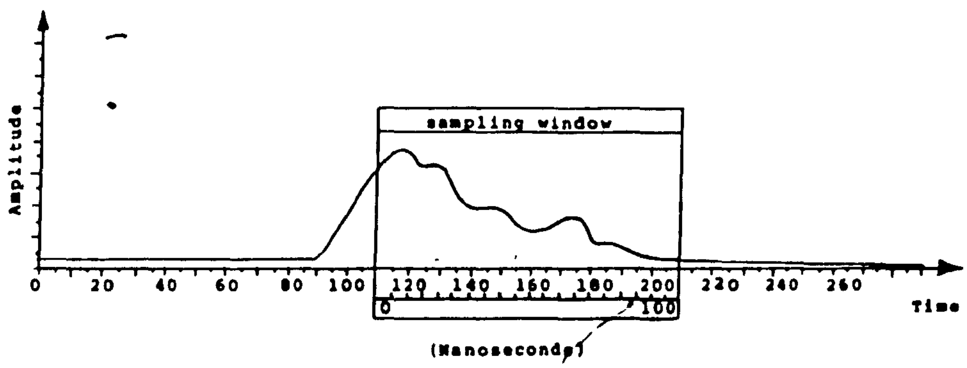
Any unresolved trigger jitter or delay problems can be accounted for by increasing the recording time window; although this would reduce the resolution of the results. These trigger jitters and delays play an important role in the reproducibility of the experimental data since the signal measurements are the only reference by which the results can be judged.

1.4. Bandwidth Requirements

A major problem of data acquisition for short duration experiments is the very high bandwidth requirement of the recording equipment. It is a severe handicap for any such experiments since the costs of proper



(a)



(b)

Figure 1.2.4 Trigger delay effects on high resolution signal recording. (a) Proper trigger, (b) delayed trigger.

equipment are prohibitive. The second problem is the high bandwidth requirement of the transmission line which connects the detectors to the data recorder. The problem there is two fold since the transmission line should be very fast and highly immune to noise. This part is a crucial element of high speed data recording since it directly controls the data that will be recorded. The following chapter will present the requirements of a transmis sion link to operate with a new high speed multi-channel data recorder.

CHAPTER 2

ANALOG DATA SIGNAL TRANSMISSION

2.

The need for high speed transient signal transmission is as crucial to high speed data acquisition as the recording instruments themselves Developments in optical communication offer high performance signal transmission together with excellent noise immunity. Present performance levels are the limiting factor in the new high speed data recording system and this chapter examines the source of these limitations.

2.1. High Speed Analog Transmission

A data acquisition system's prime function is to record experimental signals. This requires the use of sensors, to detect a phenomenon, a recording device, such as a digital computer, and a communication link to allow a pathway for the diagnostic signals to the computer. The quality of the results obtained from such a system depend on good recording instruments, and also on a good signal transmission facility. The recording instruments can only store signals with the quality with which they are received.

The three universal characteristics sought in any communication link, analog or digital, electrical, microwave or optical, are the following:

1 Low transmission losses
2 High channel bandwidth
3 Good noise immunity

It has been a standard practice in the design of communication links for data acquisition systems, involved with high energy experiments, to include a protection mechanism to prevent high power signals from reaching the computer system This generally involved an optical coupling section, where the information was passed over in optical form to a detector which continued to transmit the electrical signal to the recording instruments A general layout of such a design is shown in figure 2 1 1 The design involved a light emitting diode as transmitter and a photo-transistor as detector The separating distances were short but sufficient to isolate the computer side of the link from the eventual high power signal which could be induced on the other half of the channel.

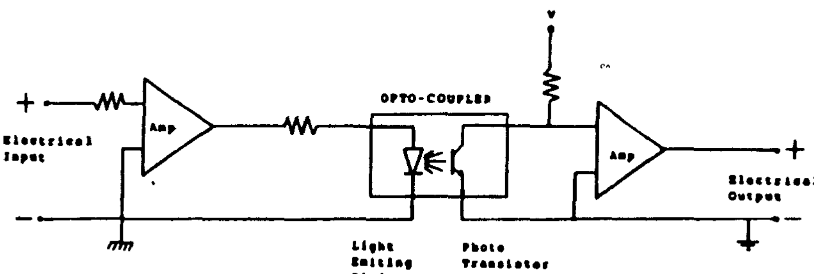


Figure 2 1.1 Early optical coupling in communication links

Today, with the advent of optical fibers, transmission technology allows for entire communication links to operate with optical signals The source and destination signals have to be electrical and hence such designs are simply extended versions of the previous principle Nevertheless, a great deal of performance improvement can be achieved and although it is not the ultimate in signal transmission, it is a great step forward

As mentioned earlier, pulsed power experiments exhibit a very adverse environment for the transmission of low amplitude electrical signals Consequently, optical signal transmission is a perfect solution to an extremely complex problem of data signal transmission in such experiments[13]

Optical communication links are characterised by First, high channel bandwidth through developments in optical fiber technology Second, low signal transmission losses in optical fibers, compared to electrical channels Third, high levels of noise immunity of the optical signals to any type of electromagnetic interference Figure 2 1 2 displays a standard circuit for one channel data acquisition

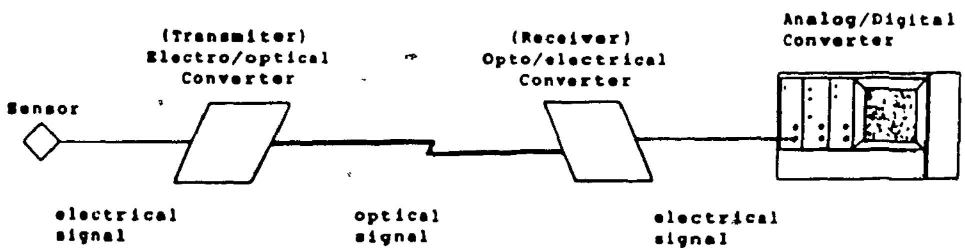


Figure 2.1 2 Standard circuit for optical communication

Such systems present some difficulties and limitations. Recording instruments usually involve oscilloscopes or analog-to- digital converter systems and require that the input signals be electrical. Sensors, for their part, produce electrical signals, which are well suited for recording purposes but not for signal transmission

The latter situation forces the optical communication link into serious performance limitations All sensor signals have to be converted from electrical to optical form Accordingly, at the receiver end, all optical signals have to be converted again to the electrical form in order to be recorded

Complete optical communication links for analog signals are available commercially and allow for high operating bandwidths of up to 250 MHz The fastest A/D converter system available is capable of 200 MHz sampling rates and such channel bandwidths are adequate It is not surprising that the same manufacturer offers both Oscilloscopes have higher frequency responses (GHz) but their widespread use is limited by two important factors First, they are extremely expensive, often three to four times the price per channel of a digital system Second, the results are not digital and require extensive effort to allow computerized processing of the data This leaves the options of a) using the optical links and lose channel bandwidth, b) using coaxial cables and worry about noise induction, or c) designing a faster link

The real answer is to a) design a faster link, and b) to determine the bandwidth limitations requires an investigation of the principles involved This will be discussed later in the chapter As an overall observation however, it is the necessity of electrical circuitry, to operate such links, which contributes most to the frequency response limitations

After some thought it becomes evident that the electrical circuits will always present a lower performance level than the optical mechanisms Therefore, the real solution to a new era in high speed data transmission is to completely eliminate any electrical device. This has particularly interesting aspects for high speed data acquisition. A completely optical data signal transmission system would do wonders for all aspects of experimental diagnostic capabilities. However, a fundamental piece of equipment is required before any such systems can be considered. This is the development of a instrument which can accept optical inputs and record them from their optical form without any conversion

Such an instrument is the focal point of this thesis The necessary optical signal transmission requirements are the subject of this chapter The instrument involves bandwidth possibilities of the order of several GHz and consequently, any considerations of an optical communication link are for GHz operating frequencies.

The following are the necessary considerations for a first generation communication link capable of providing GHz operation under pulsed power environmental conditions

2.2. Signal Transmission Under Adverse Conditions

As mentioned in chapter 1, an important part of the communication link is noise immunity and power signal protection. This entails proper ground loop protection and adequate shielding of all sensitive components. Optical signal transmission is an efficient solution to both problems, but only when it is operating properly or is receiving good signals. There can be signal distortion through 1] malfunction of the communication link, or 2] through signal corruption before conversion into optical form. In either case it is impossible to detect any distortion in the signals at the computer level. Consequently, any source of noise has to be eliminated or minimized.

In the first case, the data acquisition system should be provided with a facility to test the communication link before an experiment. This can be done through the use of a formal set of testing and calibration signals running in conjunction with a test program to verify the operation of each communication channel. Such tests are as important for the data channels as they are for the control channels Any fault in a control signal controlling high power devices in the energy bank can lead to experiment failure or even serious material damage

In the second case, since the sensors are mainly electrical devices, their output signals are electrical and are thus vulnerable to power signal induction and EM noise These sensors are also very close to the power discharge, where the conditions are worst Hence, all signal lines joining the sensors to the optical link transmitter have to be extremely well shielded

This also means that the transmitter circuit, which is the electical/optical converter, has to be close to the experimental setup and also requires heavy shielding Such shielding procedures are complex and require very careful design considerations[22] as shown in figure 2 2 1 below

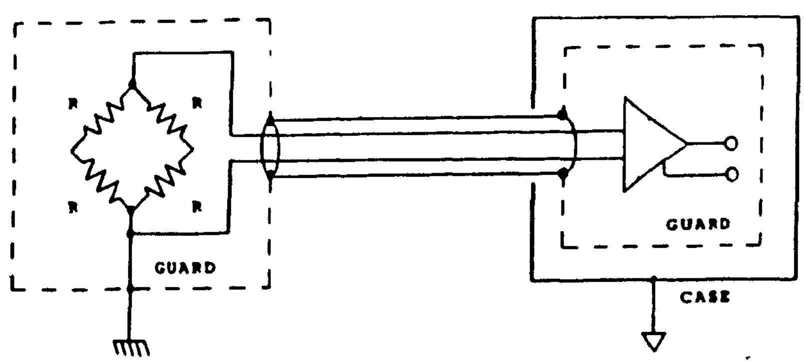


Figure 2.2.1 Ideal shielding

These circuits should also have a low power consumption to allow battery operation, thus eliminating any form of AC line coupling. Moreover, the circuits should be provided with a certain level of overload protection to avoid transmitter destruction by a power signal reaching the input. These units are expensive especially for transmitter circuits that operate at 1 GHz frequencies.

The first part, which consists of the communication link testing procedures, will always remain. However, the shielding problem of the sensor signals and electro-optical converter circuit could be eliminated through the development of photonic (photon sensitive) sensors. This would result in higher signal reliability as well as performance improvements through elimination of electron sensitive components

2.3. Optical Communication Link Design

Analog optical communication links are not common commercial items. This is mainly due to the low demand as well as the complexity level involved in the design of such a system Digital optical communication links are much more widespread and have been developed extensively by manufacturers because of the greater simplicity of the design Manufacturers who do sell analog optical links do so to complement one of their instruments. Consequently, the performances of analog links are only as high as required by the manufacturer's equipment No company is interested in developing a high speed link with performances much higher than their own needs.

The new high speed transient recorder investigated in this thesis has the potential to work at GHz frequencies, but there simply is no commercial communication system available Therefore a custom made system has to be developed with discrete components. This system would be based on a GHz electo-optical converter, which is the key component and very hard to find.

The long term goal is to depend on optical sensors which would eliminate any necessity of signal conversion before recording. As a more practical short term goal however, it is better to work at developing high speed electrical/optical converters; because this would allow both the immediate use of the recording instrument as well as the retro fitting into any existing data acquisition system The transmitter circuits might change a great deal according to the development of the converters. Despite all transmitter developments or even elimination, the optical fiber will always remain the key part of any new progress.

A full description of an analog optical communication link will discuss the problems faced with the development of high speed optical transmission.

2.3.1. Transmitter design

A communication link is characterized by three main segments. These segments are:

1. Transmitter
2. Transmission line
3. receiver

For optical communication, the hardest part to implement is the transmitter which is responsible for the electrical-optical conversion. The signal is transmitted through optical fibers and is demodulated in the receiver by a photodiode and transimpedance amplifier. Evidently, all circuits are analog and the difficulties in the transmitter design are mainly due to the high performance requirements of the electro-optical converters.

The obstacle in the transmitter design lies in the specification requirements of the conversion speed These converters are required to have a linear power output over a large dynamic range, all at very high response speeds. The response speed has the highest priority and all other characteristics will have to be accounted for thereafter The only components capable of operating at the speeds considered (GHz) are laser diodes.

Laser diodes are specialized LEDs which emit laser light when properly biased. They have been the subject of intense research for digital optical transmission. This research has also brought advances in laser diodes for analog communication[40,36]. Hence laser diodes come in two types; pulsed lasers and CW lasers Pulsed laser diodes produce more power and have a slightly faster response time They do not need to have any linearity considerations. They are used in digital links where the specifications require them to transmit a fast pulse or nothing at all.

On the other hand, CW laser diodes have to produce a continuous linear power output This reduces the maximum power output allowable for heat dissipation considerations The linearity requirement also imposes a slightly lower response time over the pulsed lasers. This makes it harder to find a laser diode with a GHz response time. The power levels are important for recording purposes and signal to noise reasons. However it is the response speed that sets the maximum bandwidth.

The laser diodes need a biasing circuit to operate in the linear region. This circuitry is crucial and is another prime source of bandwidth limitation. It is this electrical circuit which will always be responsible for frequency limitations even if the laser diode response speed increases.

The high cost of the laser diodes is a prime reason to include overload protection in the transmitter circuit. The voltage protection schemes protect circuits against voltage transients that rise above the rated input specifications but certainly not against power transients, ie. voltages of one or two orders of magnitude larger than expected. Any such occurrence will most certainly destroy the entire circuit, and it is a significant problem to consider, especially for pulsed power experiments. A standard method to avoid such possibilities is to measure a signal from its highest amplitude state and attenuate it down to the desired level. This has two distinct advantages in that it will increase the signal/noise ratio, and second it will avoid penetration of transients of much higher magnitude, through all the attenuation.

Individual instruments can be further protected against voltage overloads through new semiconductor developments. Some early results show a protection level up to 5 KV against input signal variations[35]. In its simplest form, the protection uses two fast switching diodes connected as shown in figure 2.3.1 below. Such a circuit is used in commercial high speed data recorders such as the TRANSIAC 100 MHz A/D converter.

This circuitry will also introduce a certain amount of bandwidth limitation. These diodes have some stray capacitance which makes them act as a low pass filter. The magnitude of their capacitance is in the pico farad range, thus allowing resistances of hundreds of ohms whilst still having a cutoff frequency in the GHz range. Therefore, it is not a limiting factor in the design and can be used without reservations.

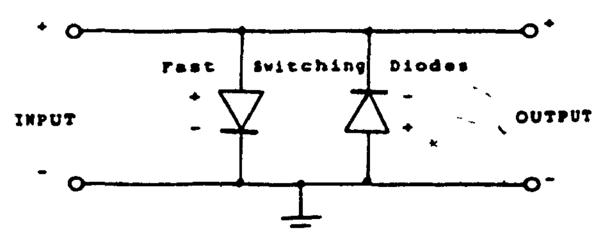


Figure 2.3.1 High speed voltage limiter circuit

Overall, the high response speed requirement of the laser diodes, their necessary linear power output, the electronic biasing and voltage protection circuits and the high-cost of each part make the transmitter design difficult.

Elimination of this segment would be a great improvement to the entire system response and is in fact the only real way to achieve full exploitation of the new optical data recorder

2.3.2. Optical transmission lines

The single most important factor in the progress of optical data transmission lies in the recent developments of optical fibers themselves. Light emitting diodes as well as photo diodes have been in existence for a good period of time. However, it is only since the commercial availability of optical fibers that this new technological horizon has come about.

The unequalled bandwidth potential of optical fibers is their highest praised characteristic The exceptional noise immunity is also an important characteristic which is nevertheless considered more as a favorable side effect, especially in digital links In the analog links as discussed herein, both bandwidth and noise immunity constrain the choice of medium with the same level of importance

Most of the development in the optical transmission area has been devoted to digital signal modulation schemes. However, most of the resulting developments have inevitably helped in the production of cost effective analog links. It is interesting to note that the Los Alamos Scientific Laboratory built a fusion reactor in 1979 and did extensive work for noise and crosstalk isolation of coaxial cables from the reactor's radiation of electromagnetic interference. Such isolation is easily accomplished using optical fibers but as shown in the quote below from a paper published in 1979[13], there has been significant progress:

> "...These bring with them the problem of shield penetration Most penetrations can be accomplished without compromise by using fiber optics,... This technology was not economic enough three years ago to be used to couple the diagnostics signals An elaborate conduit system was designed and built for this purpose."

It should be kept in mind that such research centers are very much at the forefront of new developments, which often produce early prototypes. It then suggests that the idea of optical transmission as little as ten years ago was not feasible, even at the prototype level. Today, they are commercial and have been so for a year or two.

The improvement of optical fibers has been significant. The main problem encountered in optical fibers is the dispersion effect of the signal. Over short distances this effect is small but over long distances it is the limiting factor which dictates how often a signal has to be regenerated.

The dispersive effect occurs because of group velocity differences in the optical signal throughout the cross section of the fiber The effect can be regarded as if the propagation speed was higher at the center of the fiber than close to the outside walls. The resulting hyperbolic signal front creates an uneven time of arrival for the signal. Figure 2.3.2(a) shown below shows the paths leading to two different group velocities in the optical signal Figure 2.3.2(b) shows the group velocity propagation front in the fiber

The first attempt made to solve the problem was to vary the refractive index throughout the cross section of the fiber so as to slow down the center and speed up the outside diameter. A proper balance would result in a significant reduction of the signal dispersion. This is referred to as graded index fiber.

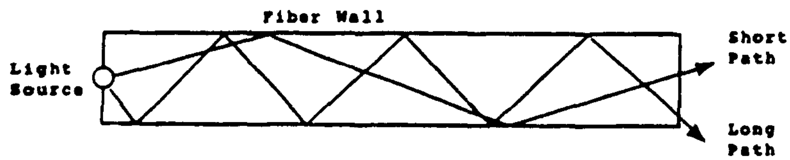


Figure 2.3.2(a) Light signal paths in an optical fiber showing dispersion effect.

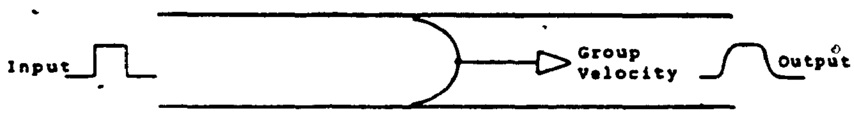


Figure 2.3.2(b) Group velocity of signal front in an optical fiber.

The latest development consists of limiting the signal to travel only through the very central part of the fiber and is referred to as "single mode" core fiber. The subsequent characteristics are exceptional. It does require more elaborate and sensitive circuitry but the improvements are well worthwhile.

In commercial digital links, the main emphasis is on reducing the number of repeater stations on the line. Hence, the less the fiber dispersion, the longer it can travel without regeneration. This results in direct reduction of support circuitry. In analog links, for short distance signal transportation, most fiber standards are generally so good that there is little problem of fiber constraints.

2.3.3. Receiver design

The receiver in the optical analog link will be required to transform the optical signal back to its proportional electrical level. The main element in the receiver is a photodiode This device will vary its conductivity according to the incident light intensity Coupled to a transimpedance amplifier, the current variations in the photodiode circuit are converted to an output voltage signal.

Photodiodes are widely available for various response speeds and the problem was one of making them faster with the possibility of a larger linear response to increase the dynamic range of the optical link.

The receiver is the segment which is to be eliminated by the new optical data recorder. It is not as much responsible for bandwidth limitation as the transmitter because photodiode response times are faster than for laser diodes The main grievance is the extra stage of conversion which will undoubtedly introduce more distortion onto the signal.

The receiver is a complex circuit. The main reason for this complexity is that the receiver is responsible for correcting many uncontrollable transmitter variations Hence, it will require an elaborate scheme for automatic gain control as well as automatic compensation for transmitter emission degradation in time This is a side effect due to no strict zero level as the ground level in an electrical circuit.

However, the receiver circuit requires less care than the transmitter does. First, it does not require extensive separate shielding since it is resident in the computer room; it is under complete protection with very little chance of being destroyed by power transients. Second, it does not need any voltage or current limiters; it's input is purely optical and it is impossible to receive an optical signal of a dangerous level.

2.4. Analog Links of the Future

With the emphasis on experimental signal transportation, everything seems to indicate that there is no going back and that optical analog links will make their breakthrough in the area of very high speed data acquisition. The physical limitations, introduced by active electronics, are the prime reasons for requiring the development of entirely new systems which can handle the optical information. This will avoid the many stages of signal transformation which inevitably lead to signal distortion and bandwidth reduction

At the present time, laser diodes can drive analog optical transmission lines for frequencies close to 1 GHz Even if such performances are only a fraction of the new data recorder's potential it remains a considerable gain over direct digitizing equipment Analog optical transmission lines of 500 MHz can certainly be realized, which is double the bandwidth of direct A/D instruments. At such relatively low performance levels the transient recorder is still justifiable and any improvements can only make it better.

An important consideration of any future data recorder is its ability to produce digital results Hence it is important to look at the basics of direct A/D conversion and determine its limitations as the basis for ultra fast data acquisition systems. This can then be taken as a reference point to compare the performance levels of new indirect recording techniques.

CHAPTER 3

CONVENTIONAL ANALOG-TO-DIGITAL CONVERSION METHODS

3.

This chapter will investigate the various methods of A/D conversion and seek a solution for high speed digitization Conventional direct A/D conversion methods are examined to determine their speed limitations and whether these limitations can be overcome with future technological developments Indirect methods such as analog memories are also analyzed to determine their potential for low cost, high speed A/D conversion

3.1. Digitizing Theory

The function of a data acquisition system is purely the collection of experimental data for later analysis, to help understand the dynamics of a specific experiment. In the majority of cases, such data is analyzed by computer, hence requiring that all the data be in digital form More often than not the experimental data will be in the form of analog electrical signals. To transform this analog information into a digital format requires an analog-to-digital converter.

This analog-to-digital (A/D) converter will convert instantaneous samples of an analog signal into a digital word which will represent the magnitude of the sample relative to its full swing. An A/D converter cannot produce a continuous digital replica of the electrical input signal, rather the output will consist of a series of digital values representing the instantaneous amplitude of the input signal at regular intervals. Therefore, digital recording will only consist of a number of samples from the actual signal. For this reason sampling theory is a critical part of A/D conversion.

Sampling theory states that

> "If a signal contains no frequency components for $|f| > W$, it is completely defined by instantaneous sample values uniformly spaced in time with period $Ts = 1/fs <= 1/2W$ If these samples are represented as weighted impulses, the signal can be exactly reconstructed by passing the impulse train through an ideal low-pass filter having bandwidth $W < B < fs-W$." (25)

This statement postulates that any signal can be completely defined, and hence stored, as a set of instantaneous samples Analog-to-digital conversion can only produce instantaneous samples with a quantized amplitude, but under the proper circumstances, is sufficient to completely describe a continuous signal. The key to digital recording practices under sampling theory, are the words "proper circumstances".

The three necessary conditions are: 1] The input signal has to be band limited, as much as possible, within a bandwidth W. 2] This bandwidth is important since it dictates the minimum sampling frequency to be 2W. This is called the Nyquist rate. 3] It is assumed that the samples are instantaneous samples, modeled as weighted impulse functions. This requires the sampling to be immediate which is not physically possible. Thus the circuit should greatly emphasize the minimization of the sampling time.

3.1.1. Aliasing

Such constraints seem reasonable theoretically but can meet with a number of practical limitations The first obstacle is the limit on the input signal bandwidth When a bandlimited signal is sampled at a rate fc such that fc > 2W, the frequency spectrum would look as shown in figure 3.1 1. If the input signal has a less well defined bandwidth, and is sampled at the same rate, there will be a spectral overlap Such overlap produces signal distortion in the reconstruction phase which is referred to as aliasing. The effect is shown in figure 3 1 2

In cases where the magnitude of this phenomenon is predictable, proper input signal filtering can solve most problems However, high speed data acquisition is generally concerned with transients which are short, non-repetitive analog signals often containing high frequency components Consequently, filtering techniques become inadequate in such circumstances since the input spectrum of the data signal is unknown.

Furthermore, the time limited aspect of transients conflicts directly with the band limitation requirement since the two are mutually exclusive. So the only possible option is to sample at the maximum frequency possible and analyze the data, trying to take aliasing distortion into account since the presence of spectral overlap is certain, only the extent of the distortion is not known. Aliasing is a major source of signal distortion in the area of transient recording and the most effective solution is higher sampling speeds. This is why transient recorders always involve state-of-the-art technology to obtain the highest possible sampling speed and why there is a constant quest for faster equipment

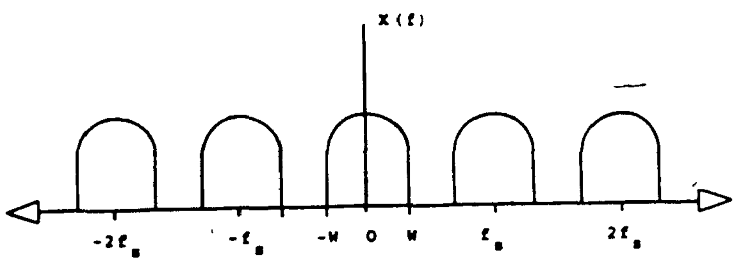


Figure 3.1.1 Sampled band limited signal in the frequency domain.

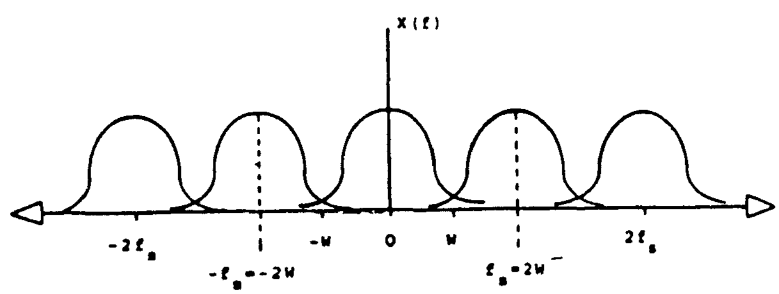


Figure 3.1.2 Spectral overlap in the frequency domain.

3.1.2. Aperture uncertainty

The second significant problem has to do with the sampling function approximation, modeled as an impulse function. The impulse function was used as a model because sampling theory requires the magnitude of the signal at an instantaneous moment in time. For an ADC to digitize any given sample, it has to be taken in the first place. Since the sampling circuit is not infinitely fast, some time will be necessary to sample the signal and hold its amplitude for digitization. The net result of this small time span necessary to capture the signal's amplitude is an uncertainty in the time which corresponds to the sample's amplitude Such inaccuracy in time is directly translated to an inaccuracy in signal conversion This effect is called aperture uncertainty and is one of the most important specifications governing the performance of a transient recorder The graph shown in figure 3 1 3[1] is a pictorial representation of the effect. Shown on the graph are three windows with similar aperture widths but showing the different effects of signals with increasing slew rates.

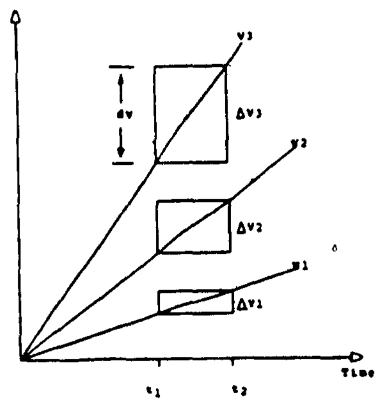


Figure 3.1.3 Aperture uncertainty

Clearly, there will be more inaccuracy in the signal with the higher slew rate. Eventually, a point is reached where the dV is larger than one quantization level in the ADC, for a fixed aperture time At that point, the LSB of the digital word has lost its significance and the effective resolution decreases Any further increases in signal frequency will produce significant reductions in resolution. Consequently this dictates a maximum frequency at which the ADC can operate with full resolution. The only solution to such limitations is to reduce the aperture uncertainty. This proves to be very difficult since the constraints are often physical limitations set by circuit designs and by noise in the sample-and-hold circuitry, and can at best be minimized.

Once the aperture times are minimized, the maximum value for the allowable sampling rate can be calculated The converse is also true, and hence the maximum allowable aperture uncertainty can be calculated for various sampling rates[1]. Assuming the Nyquist limit (sampling frequency/2), and that the error introduced be less than 2 LSB

Given a sinusoidal voltage signal:

1. $V = A \sin(2\pi f t)$

where f= fs/2 (sampling frequency)

2. $\Delta V(t) = A\ 2\pi f \cos(2\pi f t)\, \Delta t$

For the error to be less or equal to 1/2 LSB, it must be less than the full scale range times one half the resolution.

3. ΔV = allowable error = 2A (1/2) (1/N)

where N = ADC resolution

($N = 2^8$ for an 8 bit ADC)

From equation [2]

$$\Delta V = 2A\, \pi f \Delta t$$

and from [3]

$$\Delta V = A/N$$

Combining the two equation leads to the result:

4. $\Delta t = 1/\, 2N\pi f$ or $\Delta t = 1/\, N\pi fs$

If is clear from equation [4] that the allowable time error is inversely proportional to the number of resolved levels (N) and the sample rate According to these equations, the allowable aperture uncertainties for various sampling rates and ADC resolutions can be plotted on a graph Some calculations are shown in figure 3.1.4. It displays quite well the sampling rate limitations of a digitizer for a fixed resolution, for various aperture uncertainties.

An alternative look at the graph in figure 3.1.4 is the effect of the aperture uncertainty on the possible resolution of the ADC or its dynamic range.

3.1.3. Dynamic range

At a first approximation, the dynamic range could be thought to be directly related to the ADC's conversion speed. Thus a converter with a higher conversion speed can digitize more levels between two sampling periods than a slower device. The minimum sampling period would then be dictated by the time necessary to digitize and store the result Consequently the larger the number of bits to be resolved the longer the conversion time and the lower the maximum sampling rate.

This is true to a certain extent but conversion times can now be made very short (using flash converters). Hence the conversion speed is no longer the factor limiting the maximum sampling rate. The chart below demonstrates the aperture uncertainty to be the commanding constraint controlling the dynamic range.

A widespread technique used to boost the dynamic range of a high speed digitizer is to use a non linear digitizing function as shown in figure 3.1.5. The input voltage swing has to be designed so as to cover the occurrence of all extremes. This guarantees that the lower half of the input voltage swing

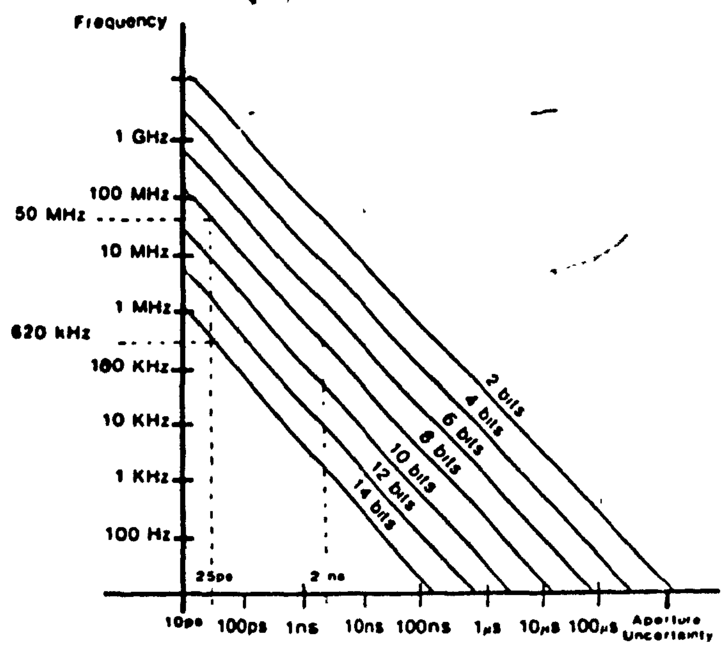


Figure 3.1.4 Maximum sample frequency vs aperture uncertainty for different resolutions

will contain most of the input and only a small percentage of the signal will have amplitudes which will reach the upper half swing. Consequently, the digitizing function is so designed to provide more resolution to the lower half swing than to the upper half. This can effectively increase the dynamic range by one or two bits.

3.1.4. Quantization error

A third source of distortion which is unique to A/D conversion is the quantization error. Sampling theory stated that the sample was an impulse function with its amplitude modulated by the input signal. In the case of A/D conversion, the samples can only take on a limited number of discrete levels. Consequently there is a maximum of +/- 1/2 LSB approximation to the real signal level. This is the reason for a drive towards higher resolution digitizers since such an increase would reduce the significance of the LSB

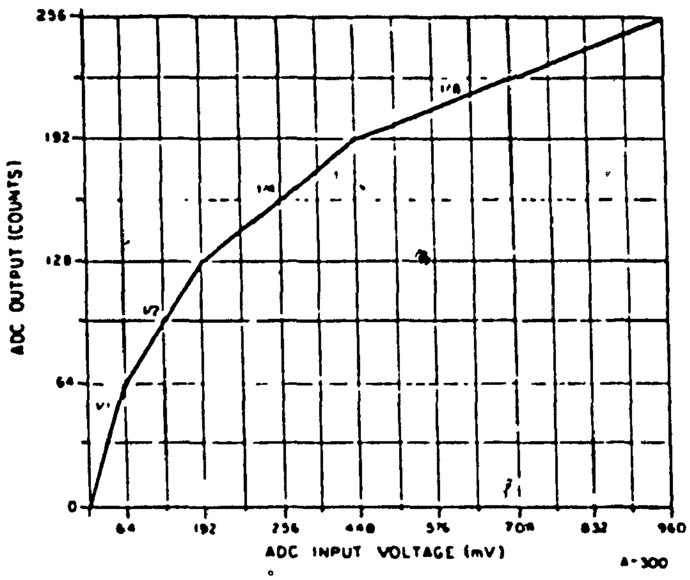


Figure 3.1.5 Non-linear digitizing function.

and also the magnitude of the quantization error. The effect on the signal reconstruction is the introduction of high frequency noise which generally appears as a staircase approximation of the original input. Such noise can be filtered out, however, using post processing analysis tools.

3.1.5. Performance specification and calibration

Taking into account these various problems, it becomes very complex to specify the high frequency performance of an A/D converter which will properly reflect the equipment's ability to resolve the individual limitations.

One method currently employed is to measure the rate of change of a high frequency input signal at its zero crossings. Such a method shows a strong dependence emphasis on the circuit's aperture uncertainty. A more recently developed method compares the measured RMS error of a digitized high frequency sine wave with the calculated RMS noise of an ideal A/D converter. The calculated RMS noise is based on ideal signal quantization and any difference with the measured noise will be relative to the amount of deviation from ideal quantization. This deviation will be representative of the aperture uncertainty. Both methods are quite rigorous but are not directly applicable to transient measurements.

It is very difficult to specify a standard test which would be of any significance for the performance specification of transient recorders. A typical problem is the task of specifying a standard transient. Such a definition would be extremely difficult to realize compared to that for a set single frequency sine wave

A direct extension of this problem is the difficulty in calibration of a transient recorder. Any calibration process requires a standard input. High speed recorders can be tested to reproduce a sine wave, but when the interest lies in transients, such operations are more complex and less complete. The best solution then remains direct comparison with a calibrated instrument such as high speed oscilloscopes. However, this method is limited to the frequency response of the reference equipment.

At present the problem is still under control since oscilloscopes are much faster than digital equipment. Such may not always be the case in the future, yielding an entirely new set of problems to overcome.

3.2. Analog-to-Digital Conversion Circuits

3.2.1. Sampling circuits

Presently, several circuits for performing analog/digital conversion are in use, each one performing according to its individual advantages. Yet they all have a common requirement for an instantaneous signal sample for the input waveform. In most cases this task is accomplished by a sampling circuit which preceeds the A/D conversion stage. The purpose of this circuit is to extract a voltage sample from the input waveform and store it, generally in a capacitor, for the duration of the conversion.

As was shown earlier, the process of sampling the input signal has a significant consequence on the dynamic range of the A/D converter output It is in fact the single major obstacle for high speed conversion advancements. In most cases the aperture uncertainty has nothing to do with the A/D conversion mechanism but depends entirely on the front end sample and hold circuit[7].

The definite importance of such circuitry has brought about important developments in the area, emphasizing more accurate and faster sampling circuits to reduce the aperture uncertainty to a minimum. The more successful results have been obtained from what is called a track-and-hold circuit. The latter contains a voltage tracking system, constantly monitoring the voltage of the input waveform, which can be frozen at any moment by a simple clock pulse. Since the circuit constantly tracks the waveform amplitude, there is no time spent during the sampling process to charge a capacitor to the waveform's amplitude, effectively cutting down on the overall aperture time. Times of the order of 5 picoseconds have been successfully obtained by this mechanism. These times basically represent switching times.

3.2.2. Flash conversion

Because of the aperture uncertainty introduced by the sampling circuits, developments for better solutions have been directed towards A/D conversion mechanisms which would eliminate the use of this front end stage. Such a method is called flash converting. It uses a number of comparators connected in parallel, each of which is connected to a different reference voltage. Typically, such mechanism will contain one comparator for each quantum level, resulting in large circuits. An n-bit digitizer would normally contain 2/un/d comparators.

To obtain a signal digitization a clock pulse is sent out and only those comparators with signal levels above the preset reference are set. The digital output word is determined by the combination of comparators which were set upon the receipt of the latch pulse. The limiting factor for this method is the need to simultaneously sample a large number of physically different comparator circuits. It is the switching and settling times of all the comparator circuits which will produce the equivalence of the aperture uncertainty. A rise in resolution can be achieved by increasing the number of comparators, but would also result in a rise in aperture uncertainty.

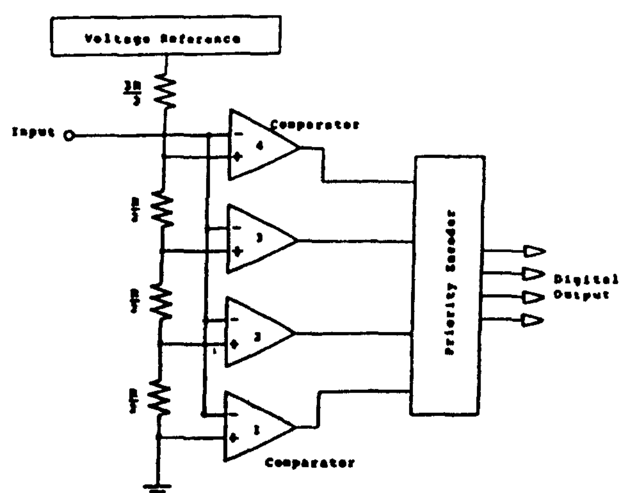


Figure 3.2.1 A 4 bit flash A/D converter

The popularity of this method, however, is not without foundation; flash converting offers aperture uncertainty times in the vicinity of 1 to 3 nanoseconds with discrete circuits, whereas monolithic circuits can reach times of 30 picoseconds. Even if these results still fall short of the 5 picoseconds available from track-and-hold circuits, flash converting remains attractive for its high conversion speed.

3.2.3. Pipeline method

In concept, flash converting is complex and expensive In an attempt to reduce both cost and complexity, the mechanism has been combined with a pipeline method. The result is a dual rank flash converter which claims to be able to produce 8 bit resolution using 32 comparators The pipeline method improves the throughput rate of the samples by using a coarse/fine conversion technique. A signal is initially digitized to a coarse 4 bit accuracy After subtracting the 4 bit value, the remainder is digitized, in a second stage, into another 4 bit word. The resulting output after the two stages is an eight bit conversion. The increase in throughput is achieved by having the two stages working concurrently. Hence, the coarse conversion stage can be processing the next sample while the initial sample is being processed by the fine conversion stage

This pipeline method can be applied to any conversion mechanism to increase sample throughput. Common to all pipeline circuits is the benefit of a correction scheme based on extra range in the first stage of conversion in order to obtain monotonic conversion characteristics[3].

3.2.4. Wilkinson rundown method

Other conversion techniques include the Wilkinson run-down method. This approach stores the sampled voltage in a capacitor which is then discharged linearly. A high precision clock measures the time it takes for the capacitor to discharge to zero. The count of the clock will be a representation of the sample amplitude. An increase in resolution can be achieved by increasing the speed of the clock.

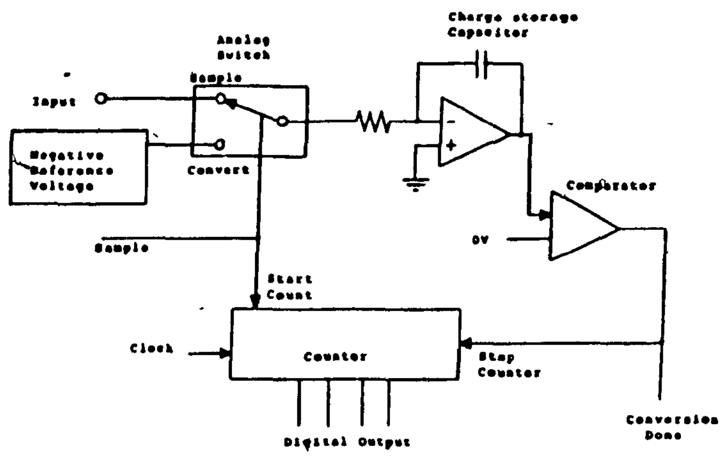


Figure 3.2.2 Dual slope A/D converter

Present state-of-the art current sources and clock stability provide this method with a very good differential linearity. This good linearity is however at the expense of speed. Minimum conversion times are 10-100 microseconds, which is significantly slower than flash conversion.

3.2.5. Successive approximation method

Today's most conventional and widespread conversion method is called the successive approximation technique. This method uses a comparator to match the sampled voltage, typically from the output of a track-and-hold circuit, with a succession of reference voltages. After each voltage comparison, the search range is reduced by a factor of two. Consequently, the circuit has to make one comparison and one voltage re-adjustment for each bit of resolution. Such comparison times are typically 100 nanoseconds, which would mean a conversion time of 1 microsecond for a 10 bit resolution

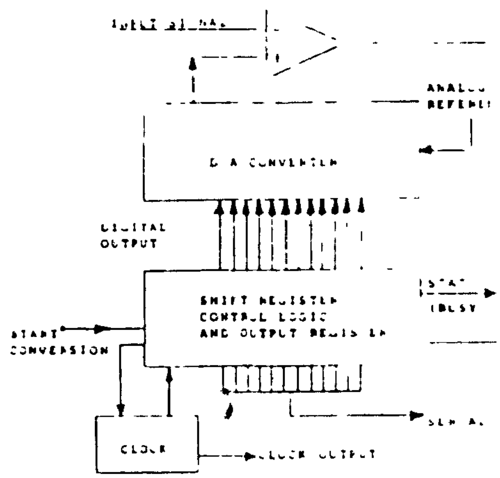


Figure 3.2.3 Successive approximation A/D converter

The differential linearity of this method is 20-30%, being limited by the analog settling times and the accuracy of the D/A converter reference voltages. Such performance is not as good as the Wilkinson method but is comparable to the flash technique. This is understandable when considering that the latter depends on the same reference voltage stability for its linearity performance.

The successive approximation method is faster than the Wilkinson method, but not as fast as the flash technique. The main reason of choosing this method over the flash technique is mainly a question of economics The circuits are less complex and less expensive.

The two diagrams shown in figure 3.2.3 and 3 2 4 show a successive approximation circuit and a dual rank flash converter. The differences are clear and the conclusions as expected· high speed conversion is available through flash converting making it the most popular conversion technique for transient recording despite the cost. It is also the basis for a great deal of development for data acquisition systems with a large number of input channels and high conversion speed requirements.

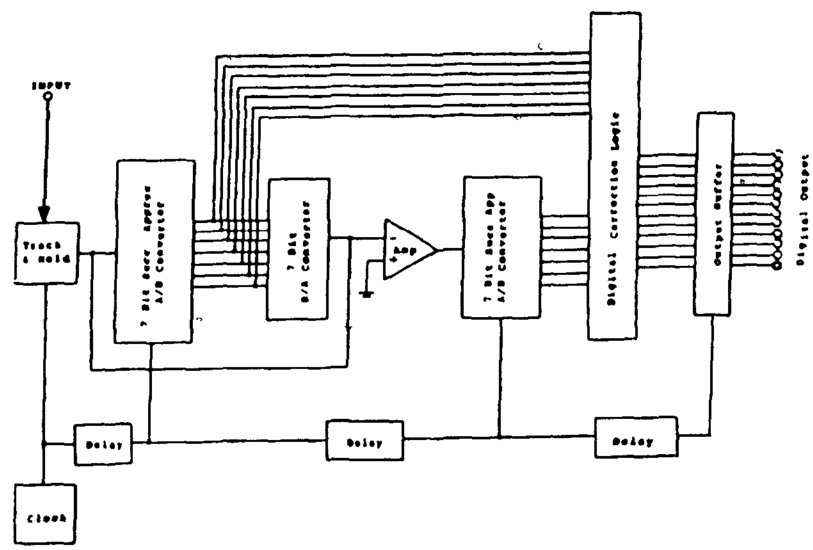


Figure 3.2.4 Dual rank successive approximation A/D converter

3.3. Developments in Fast A/D Conversion

The ever increasing demand for high speed data recording has caused two main approaches to be investigated in the search for a satisfactory solution. The techniques differ completely in their basic philosophy allowing for individual advantages in similar situations.

The first solution is based on flash conversion as described earlier. It presents an attractive alternative as it is the shortest path to the desired results The input signal in each channel is digitized at a fast rate using flash A/D converters (FADCs) and the results are stored in high speed buffer memory. The state-of-the-art in commercial systems is 100-200 MHz sampling rates with 6-7 bits resolution and up to 32 Kwords of fast buffer memory. The limitations of this method are primarily dictated by the physical constraints of the basic electronic elements such as transistor switching times Even though the performance is commendable any further increase in sampling speed or accuracy, although possible, tends to raise the costs to prohibitive levels

The second approach is based on analog storage devices such as charge-coupled-devices (CCDs) or discrete capacitor analog memories In an attempt to dissociate the high speed digitization process from the sampling speed requirements, dictated by the sampling theorem, the input waveform is stored as a series of analog samples The information is entered in the storage device at sampling speeds and is subsequently retrieved at a slower rate for digital conversion. The main characteristic of the method is the possibility of an increase in accuracy. CCDs have a resolution possibility of 9 bits whereas discrete analog memories claim 12-13 bits[26], both cases being better than FADCs. Sampling rates are comparable to flash conversion speeds. Higher sampling frequencies can be obtained by interleaving a signal measurement in several memory devices.

As a general observation, both solutions involve complex electronic circuitry whose physical electrical limitations are directly translated into digitizing performance losses Such relations facilitate the task of predicting the fate of high speed recording development employing either of these two solutions since the results will always be limited by the direct technological limitations of state-of-the-art components.

While continuing the search for better methods, to allow greater gains and future potential, it is important to note that the implementation of the above solutions is as important as the gain itself. Both solutions are well suited to take advantage of all the benefits of VLSI technology. The net result is the availability of high performance devices which are easy to use. Consequently they will find wide acceptance and use, hence maximizing the exploitation of the gains obtained. This truly projects the two methods as being large scale solutions.

Moreover, the advancements in VLSI may bring about performance improvements, although the extent is limited and more likely to lower the cost/channel through higher levels of integration

3.3.1. Flash Converters

Present commercial high speed digitizing equipment claiming 100 MHz sampling rates are all based on flash converters. The equipment is generally highly modular and available and compatible with most bus standards such as CAMAC, FASTBUS, QBUS, etc... These modules have all evolved around fully integrated monolithic FADCs manufactured by various large companies such as TRW (TDC 1029), or SIEMENS (SDA 5200 or SDA 5010).

The commercial trend is to use FADCs to produce very flexible modules which are capable of satisfying most market conditions This leads to the fabrication of standard modules having a fully integrated FADC embedded in complex overhead electronics making them multi-purpose investments. Such modules are indeed very expensive and thereby inhibit the spread and wide use of the new resources FADCs are still relatively new and have not yet reached a high level of implementation variety. This is caused on the one hand by the manufacturers who have economical reasons to market one multi-purpose rather than many different specialized modules, whilst on the other hand custom development is only available for large research centers, and thus occurs at a relatively low level In most places a basic design criterion for a data acquisition system is to use strictly commercial equipment to reduce implementation, operation and servicing costs.

In spite of all these economic factors, FADCs have their best use as a low cost, versatile unit which can be used wherever there is the need to have a rough idea of a signal but where the accent is on many input channels. The simplicity of the method makes it very attractive, leaving the majority of the work to be done on reducing the overall cost per channel Some attempts at a prototype have been made and the results are promising Specializing the function of each channel and reducing the overhead electronics to a minimum through the use of common control signals has been the major emphasis of the work The claim of reducing the cost per channel to $100 is most interesting[8] when considering that equivalent commercial costs would be closer to $10,000 per channel[4].

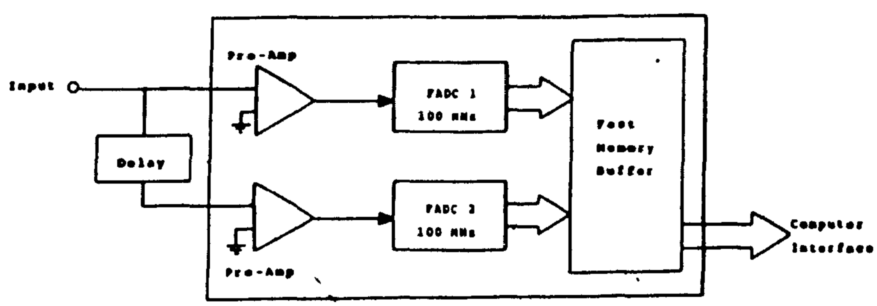


Figure 3.3.1 Sampling rate improvement using FADCs

At the other end of the spectrum, FADCs have also been used to produce a unit with a higher sampling rate[42]. This was achieved by interleaving the input signal through two FADCs concurrently making sure the two processes worked in phase with an offset of one half sample period between the two. The schematic in figure 3.3.1 shows the two 100 MHz FADCs separated by a 5 nanoseconds time delay. Each FADC produces a result every 10 nanoseconds but the overall sampling period is effectively halved resulting in an increase in sampling rate by a factor of 2. Although it might seem natural to develop this idea further for higher speed gains it would be difficult to exploit the project for commercial purposes due to the very high costs involved. It is nevertheless a possible solution to very high sampling speed requirements in situations where access to such performance is the primary concern and cost is secondary.

FADC's are unlikely to be the foundation of a solution for multi-gigahertz sampling rates. Nevertheless, they will play an important role in the progress of research due to the low cost availability of the high digitizing performances that they can readily offer.

Flash converters are limited in performance by the physical limitations of the state-of-the-art technology. Any further performance increase translates directly into technological improvements. Shorter transistor switching times are possible but orders of magnitude improvements are long in coming and may be impossible. Moreover, every step forward increases the complexity of problems such as the simultaneous emphasis on power reduction and speed improvement.

3.3.2. Analog Memory

A second approach to high speed digitization has turned away from ultra fast A/D conversion. It is based instead on the principle of storing the analog samples and retrieving them later, at a lower speed, and then digitizing the values with a slower and more accurate A/D converter. This philosophy is completely different from flash ADC techniques which attempt to process the transient signal as quickly as possible in real time whereas this technique attempts to catch the transient in memory and process it later.

This method uses various memory techniques, generally in the form of a series of memory cells performing as an analog shift register. Since the buffer has a physical size limit, all such systems will have a fixed number of samples that can be recorded, dictated by the size of the register. For purposes of high speed sampling, the writing speed of this memory will have to be very high, dictated by the sampling frequency, whereas the reading speed is more dependent on the storing capability of the memory element. All analog memories are dynamic and will require refreshing procedures which will impose minimum recirculation speeds

Such analog storage elements are primarily based on CCDs or discrete capacitor cells All these cells will store the analog information as a proportional electron charge. Discrete capacitor cells, such as the Stanford/SLAC analog memory[26], can achieve much higher resolutions from their devices because they can store a significantly higher number of electrons per cell. All devices are dynamic memories implemented in MOS technology. Consequently both devices benefit from the high density levels to allow space reductions, high operating speeds and low costs.

The CCD is intrinsically a simple and fast serial shift register. The input signal samples are stored as proportional electron packets which are then rippled through the length of the buffer. This simplicity of operation is the biggest asset of CCDs.

To store a sample in a CCD, a positive voltage is applied to a gate electrode, refer to figure 3.3.2, which will repel the majority carriers in the p substrate (holes) under the gate and create a potential well for negatively charged particles such as electrons. Since these electrons were injected into the substrate as an analog sample representation they can be held for as long as there is a positive signal on the gate electrode. Then by proper application of clock signals, the charges can be transferred from one cell to another.

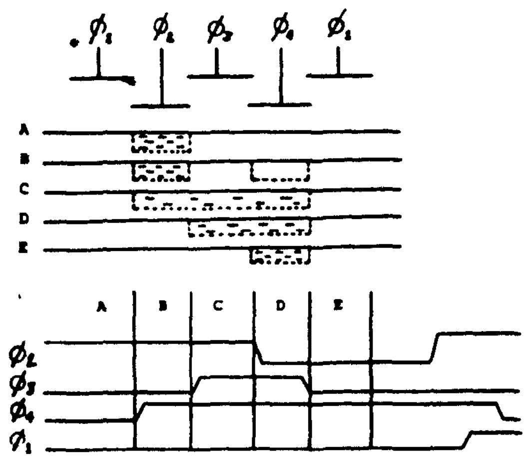


Figure 3.3.2 CCD cell charge transfer

The two most important types of information degradation in a fully charged CCD cell are the loss of electrons due to 1] charge leakage and 2] the filling of uncharged potential wells by thermally generated majority carriers, commonly referred to as 'the dark current effect'. Such degradations are characteristics of dynamic memory elements and are the reason behind periodic refreshing. This is usually done by cascading a refresh amplifier after a predetermined number of CCD cells. This refresh requirement consequently imposes a minimum frequency for circulating the data.

As part of an A/D converter, a CCD buffer will find its place between the sampling circuit and the digitizer, as shown in figure 3.3.3. The sampling rate is certainly limited by the writing speed of the CCD buffer but is also very much dependent on the sampling circuit for adequate aperture uncertainty. Hence CCD systems are just as limited by track-and-hold circuit performances as other A/D conversion methods. The major gain of CCD systems over flash converters is the increase in dynamic range with comparable sampling rates. Other secondary advantages are reduction of costs for the digitizer and the digital memory since they can both be operated at lower speeds, according to the minimum reading frequency of the CCD.

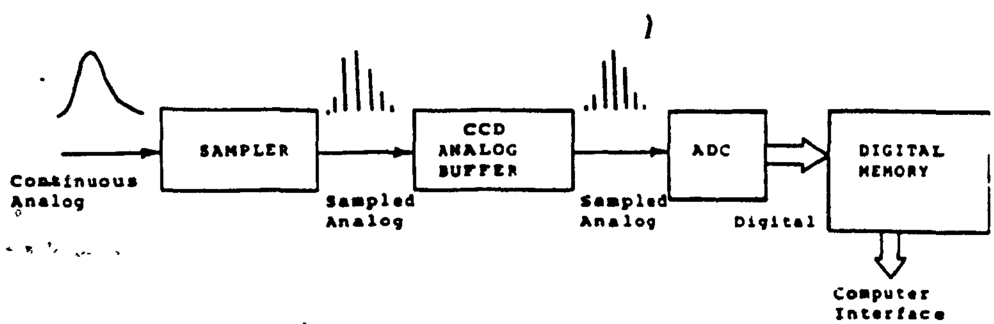


Figure 3.3.3 CCD based A/D converter system

Higher sampling rates have nevertheless been reached using several CCD registers interleaved with delay lines to create effective sampling rates of 1 GHz[30]. The principle is illustrated in figure 3.3.4. Each CCD register is clocked at a rate of 200 MHz, or with a period of 5 nanoseconds. Each consecutive register is then delayed by a 1 nanosecond delay line. The net result is an effective sampling of the input waveform at a rate of one sample every nanosecond for a sampling frequency of 1 GHz, with a claimed resolution of 10 bits. This is a serious step forward over flash converters which can claim 200 MHz sampling rates with 8 bits resolution.

The same principle can be applied to FADCs to obtain higher performance levels but there are several points in which CCD's show to be superior. First is the extreme difference in circuit complexity, which makes

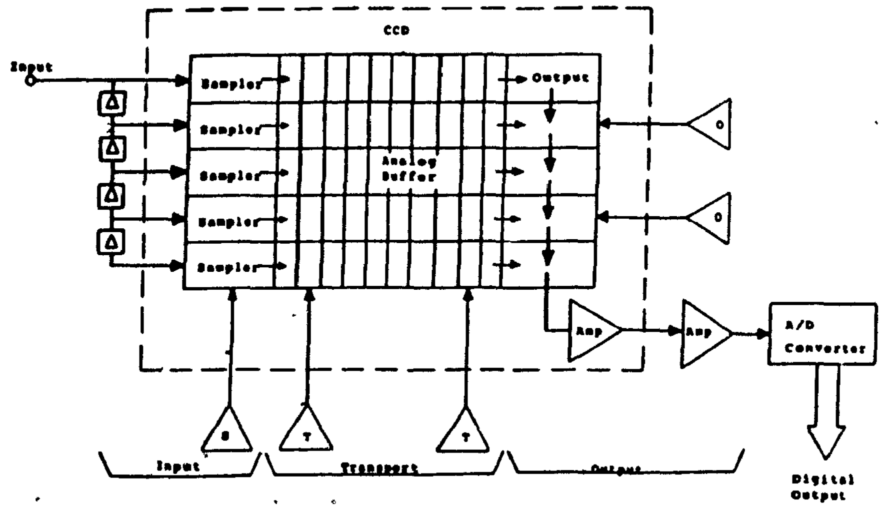


Figure 3.3.4 1GHz CCD based digitizer

FADC circuits more prone to defects. Second, these flash converters dissipate a lot of power. Both points contribute to make the FADC system more expensive.

Second is the fact that every converter in the FADC system will require its own page of high speed memory. This further increases the cost over CCD systems which can work on a single block of slower less expensive memory. Having all the information of the FADC system in separate blocks will also make it more difficult to produce the experimental data in a sequential file.

Any significant speed increase in CCDs is difficult to come by. Presently, the high power requirement of the phase clocks are a main obstacle in the development of faster devices. Another limitation is the charge transfer time from cell to cell, which although small will eventually become significant as other parts of the system are improved. One option to increase speed and decrease power consumption is to reduce the cell size through higher integrating densities, but this would result in a direct degradation of the possible resolution.

The Stanford/SLAC analog memory[26,41] is based on discrete capacitors and is a major step forward for speed increase and increased dynamic range. This achievement is based on using 'direct cell access' which entails a parallel input facility combined with a serial output, and by having a relatively larger charge store capacity per cell than CCDs.

However, both methods rely on sampling circuits to sample the input waveform and are therefore limited by the aperture uncertainties of the latter. Again the restrictions are crucial. The chances of reaching multi GHz sampling rates are just as improbable because the limitations of the electronic components are too closely related to the limitations of the process they control. Nevertheless significant resolution improvements have been obtained and made available at reasonable costs.

3.4. Directions in High Speed A/D Conversion

It is clear from this chapter that direct A/D conversion will always be limited by the physical properties of the electronic circuits involved. Technical developments can improve the conditions but there is little hope that multi-GHz conversion data acquisition systems can be based on such methods. Indirect A/D conversion methods such as analog memories have a higher potential but still rely on a large amount of electronic circuitry to support their operations. These methods then ultimately face the same forms of limitations for data acquisition as the direct methods.

The solution for high speed data recording lies in indirect methods provided that they involve as little, preferably no, electronics in the initial recording or signal sampling phase. The next chapter will introduce a new recording solution which can operate at very high frequencies, and can be developed to do all initial data acquisition in optical form. The elimination of any electronic circuitry in the front end makes it a possible contender for becoming the basis of a new standard for future high speed transient recording instruments.

CHAPTER 4

PHOTONIC DATA RECORDING TECHNIQUES

4.

An instrument capable of recording very high speed analog optical transient signals is described in this chapter. The bandwidth potential of such a device is large enough to dwarf any oscilloscope, and its multi channel capability provides a low cost per channel solution to high speed data acquisition. The instrument represents an indirect A/D conversion method to digitize the data signals. The lack of involvement of direct electronics, to temporarily record the optical signals, is the key to its high bandwidth potential.

4.1. State of High Speed Data Recording Instruments

The most widespread and trusted electronic instrument used for any form of signal measurement is the oscilloscope. Oscilloscopes have a large potential for broad band operation and are at the present time the basis of all high speed data acquisition systems. However, high speed oscilloscopes are very expensive instruments, highly specialized to serve a relatively limited market. The consequences are that any attempts to provide an experiment with multi-channel high speed data acquisition, based on such instruments, are generally confronted by severe economic problems.

Particle beam or inertial confinement experiments for example frequently require hundreds of data channels to monitor the power flow in the test. Present oscilloscope technology does not have the means to meet such requirements economically. This leads to classification and elimination processes to reduce the number of channels to a bare minimum, to form a small set of vital signals for the monitoring of the experiment dynamics. The performance of present data acquisition systems in such circumstances certainly leaves much to be desired.

The fields of pulsed power and other related short duration experiments are evolving quickly, consequently generating a growing demand for an economical solution for the coverage of large high speed multi-channel data recording instruments. The elevated cost and scarcity of high speed equipment is often found to be the most frustrating obstacle in carrying out large experiments. Such problems are easily put into perspective when considering that the cost of an electronic recorder/digitizer for a single channel is in the range of $30-35,000 US

At the present time there are only three countries which manufacture gigahertz single transient recording instruments [11]. Most of these instruments are related to research in nuclear weapons testing and it is no real surprise to find manufacturers in France, the USSR, and the USA. France produces a 5 GHz, single channel instrument, the TN-660, manufactured by Thompson CSF. The instrument has been in existence for several years and has received favorable reports. The USSR has a 3 channel, 7 GHz instrument, "LOTOS", and details about it are limited [11]. The United States has two companies producing GHz recording instruments; TEKTRONIX and EG&G. The latter manufactures a single channel, 2 2 GHz oscilloscope, the OS-40A, which is primarily used for nuclear weapons testing. Tektronix, on the other hand has always been involved with high bandwidth instrumentation and has a long history of instruments[11]. One of their more popular devices is the 1 GHz oscilloscope (R-7912) which has been developed into the new 7912AD and presently allows digital readout and computer interfacing (IEEE 488).

All instruments mentioned above are oscillographic in nature and only TEKTRONIX presently offers digital readout of the signal All other companies are working to provide digital readout capability to their instruments THOMPSON CSF are developing a new instrument capable of 7 GHz bandwidth with a fiber optic output faceplate coupled to the CRT to digitize and store the image in local memory. EG&G are upgrading their instrument to 3 GHz, whereas TEKTRONIX are working on new digital readout techniques using Silicon Target electron guns or optical fiber coupled VIDICON or CCD cameras.

The general attributes desired in an ideal oscillographic instrument have been described as follows[11].

1 Self calibration
2 Computer control and monitor of essential functions
3. 5-10 GHz bandwidth
4. < 25 pico second trigger jitter
5. Memory for one or two traces
6. Computer interface bus (IEEE 488,Q-BUS,etc...)
7. Signal conditioning (attenuation & equalization)
8. A precision time base

This can be summarized as an instrument which would be computer controlled and programmable to increase its ease of operation, with a wide bandwidth, a precise time base, and multi channel with memory (digital if possible).

All other points aside, the development of instruments with GHz bandwidth is a major challenge in itself. As discussed in chapter 3, digital recording instruments are inadequate when used at GHz frequencies. Thus oscilloscopes are the sole remaining resource. However, state-of-the-art high speed oscilloscopes still depend on coaxial cables and Cathode Ray tubes (CRT). This immediately restricts all signals to electrical signals. Coaxial cables are lossy and highly dispersive at high frequencies Thus distances must be kept as short as possible and various compensation techniques to maintain adequate frequency response are required Moreover the CRT has a fixed limitation on its response speed.

This chapter proposes a better system than oscilloscopes to fulfil the requirements of high speed data recording. The system's main characteristics are:

1. Economy
2. High Bandwidth
3. Electrical Isolation
4. Compactness

The system is a photonic alternative to the conventional analog electrical data recording techniques. The field of photonics is concerned with the generation of photon analog signals from physical observables. The physical observables act on sensors which will either generate light or modulate a light beam. These signals can then be transmitted through low loss optical fibers and recorded on low cost, high speed, photon sensitive multi-channel data recorders.

Photon analog signal recording techniques are better suited for high speed data recording due to their inherent broadband nature, and cost effectiveness. The key to this alternative is an instrument called a streak camera. This is normally used to obtain time resolved pictures of a short event such as X-ray generation or plasma formations. Such a camera is the basis of a system which can offer multi-channel recording, digital readout capability, on board memory and easy interfacing to a control computer.

For imaging purposes, the input to the camera is a simple slit The camera will produce a time resolved picture of the light intensity variations which occur through this slit for the time of the streak For data recording purposes, instead of focusing the camera onto the slit, the camera is focused onto a linear array of optical fibers, as shown in figure 4 1 1.

Figure 4.1.1 Optical fiber array as seen by the streak camera

Individual fibers in the array will carry signals from independent channels. The streak camera will then produce a time resolved picture of the light intensity variations at the end of each fiber. Subsequently, every channel will produce a separate streak of light resulting in a number of adjacent streaks with the intensity variations along the time axis (vertical) representing the signal's amplitude modulation. The streaks will be analogous to oscilloscope traces with the advantage that there can be many simultaneous channels. The small size of optical fibers permits large numbers of input signals within the slit width. Considering that there can be as many as 40 fibers[19] in the array, this can create a very compact multi-channel system at a low cost per channel by simultaneously recording many signals on the same instrument.

Without considering the details of its operation, the system has many advantages with respect to the wide field of pulsed power experiments. First, the optical sensors and signal carrying fibers used are insulators and can therefore access high field regions where electrical sensors are prohibited. The benefits of this possibility, for better and more complete experimental diagnostics, are evident.

Second, optical fibers provide isolation against electromagnetic interference, greatly increasing the signal/noise ratio and reducing problems related to ground loops. For any pulsed power experiment, such characteristics are extremely important and the solutions can be very complex and expensive for coaxial cable systems[13].

Third, the broadband characteristics of the photonic sensors, optical fibers and streak camera make the system well suited for multi-GHz operations. In addition, the synchronous recording of many channels automatically time correlates them, something very difficult to achieve with oscilloscopes. This certainly provides an increase in overall performance level.

Finally and most importantly, the multi-channel capability of the system reduces the effective cost per channel to more manageable levels when compared to conventional methods, even more so when considering possible performance levels never before attained. It also produces a much more compact instrument with lower power consumption, significantly facilitating the system's installation and operation.

On the whole, the photonic system can offer improved performance with cost effectiveness. As an added performance advantage it will allow the possibility of making measurements which are currently almost impossible.

4.2. A High Speed Multi-Channel Data Recorder

A general layout of the recording instrument is shown in Figure 4.2.1 below. The main parts integrated in this system are:

1. Sensors (electrical or photonic)
2. Electro-optical transmitters
3. Optical fibers
4. Optical fiber array
5. Electro-optical streak camera
6. Digital readout system
7. Data handling computer

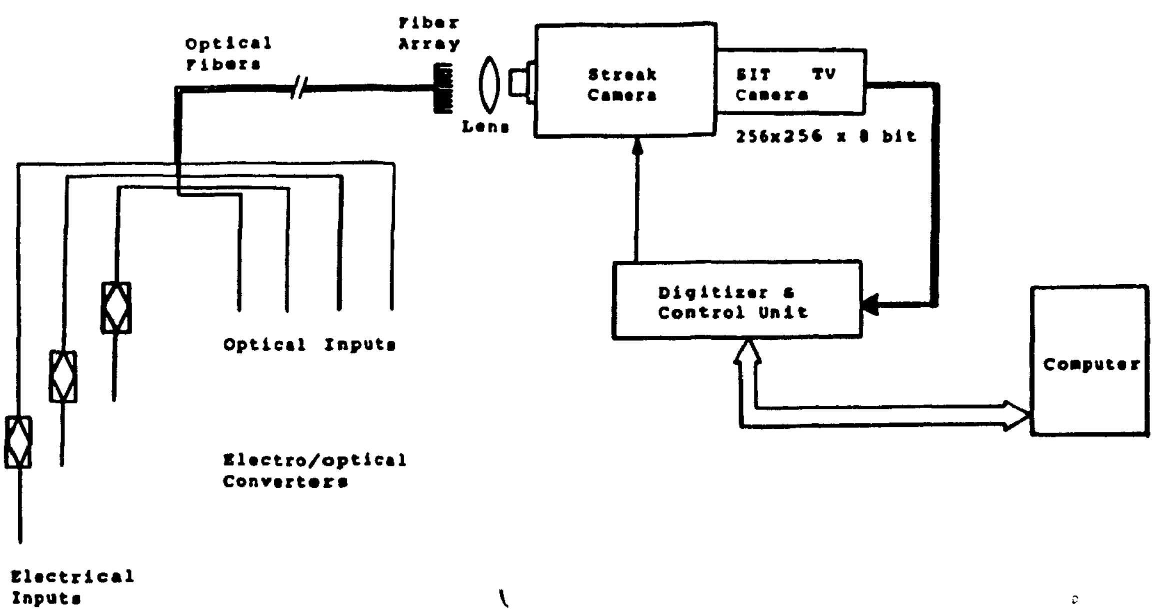


Figure 4.2.1 Schematic layout of the high speed multi-channel data recorder system.

Ideally all inputs to the camera should be primary optical signals, ie. produced by photonic sensors. However, to allow the instrument to be retro-fitted into existing systems, which already contain a large number of electrical sensors, it should provide the capability of recording primary electrical signals as well. This task is performed by the electro-optical transmitters which are based on laser diodes. The function of these converters is to emit a laser light intensity proportional to the amplitude of the driving electrical signal. The laser diodes function much like normal light emitting diodes (LED) but with an extra emphasis on lasing power and linearity.

With the availability of such electro-optical converters, any type of signal can be recorded by the instrument, whether it originates from photonic or conventional electrical sensors. All channel signals will be optical before they reach the optical fiber array which is simply a linear array of adjacent optical fibers, each one carrying an independent channel. The fiber array is subsequently lens coupled into the streak camera which will proceed to record all the channels simultaneously. Each channel signal will be recorded as a separate streak on the camera's output phosphor screen. A typical picture of the phosphor screen output for a four channel streak is shown in figure 4.2.2.

The digitization of the multi-channel picture is achieved via a VIDICON TV camera. The picture is recorded on a typical 256x256 target array and each pixel is digitized into 256 levels of intensity. The digitization of the VIDICON video signals is performed by a fast A/D converter and is stored as picture information in a local frame buffer. Both the A/D converter and the frame buffer are resident in the streak camera control unit. The control unit is also responsible for providing an interface to allow communication with an external computer for data handling and processing functions. This will allow individual channel signals to be analyzed and plotted in the familiar amplitude versus time format.

A system as described herein can be completely assembled from commercially available components. Optical transmitters are available to convert an analog electrical signal into its photon counterpart at bandwidths up to 1

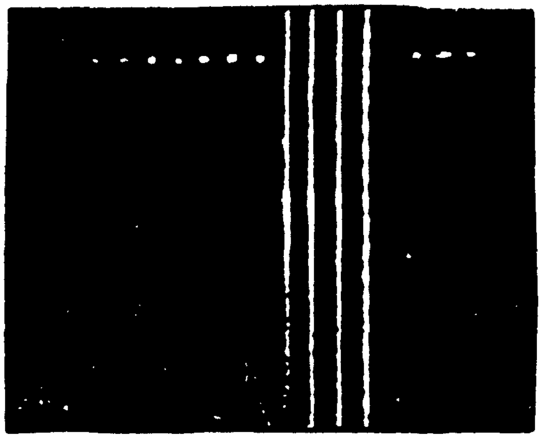


Figure 4.2 2 Streak camera output for the recording of four simultaneous channels.

GHz. Optical fibers are readily available with a large range of specifications. For this application a fiber with a bandwidth in the vicinity of 10 GHz would be desired. Requirements of such magnitude can be fulfilled by graded index multi-mode fibers which display bandwidth specifications of 400-800 MHz-Km with an attenuation coefficient of 2-3 dB/Km. Since general channel lengths are within 100 meters a channel bandwidth of 4-8 GHz is available. The streak camera system and its control unit is also independent commercial equipment.

A major characteristic of this recording system is the multi-channel capacity which is controlled by the streak camera, the VIDICON TV camera and the size of each fiber in the array. There will be a minimum separation necessary between each fiber, which is determined by the distance necessary between two fibers to prevent any significant cross talk between adjacent channels. The separation distance is a fixed value, therefore only a limited number of fibers will fit within the camera's input. It is possible to increase the input width through adequate lensing but it will remain a question of the

TV camera, with its fixed resolution, to be able to resolve two adjacent streaks. On a test in[18] for a 256x256 pixel camera, a minimum width of five pixels was required for proper channel resolution.

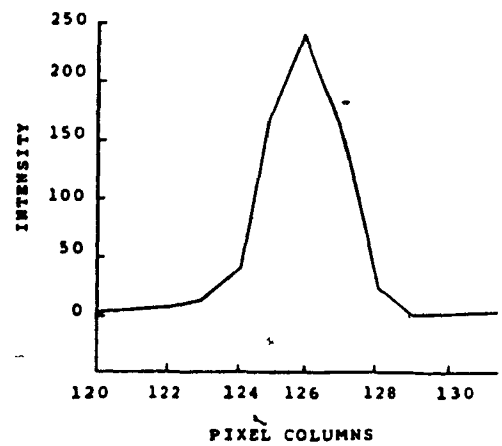


Figure 4.2.3 Single channel streak width as seen by the TV camera.

Figure 4.2.3 shows the typical distribution of a single channel streak as seen by the TV camera. Theoretically, 256 pixels at 5 pixels/channel would allow approximately 50 channels to fit on one screen width. However the necessity for a guard band between channels for cross talk purposes will reduce this number. Thus if 1 pixel is reserved as guard in between each channel, the maximum number of channels would drop to 40.

4.3. Streak Camera

The most important element in the development of this system is the streak camera itself. The device is a photon sensitive instrument which transforms a temporally varying optical analog signal into a spatially varying optical analog signal. It is stressed at this point that for all intents and purposes, the spatially varying output signal is analog, much as in an oscilloscope.

Hence the main function of the streak camera is to transform a time dimension into a space dimension, similar to a normal movie camera Figure 4.3.1 shows a schematic diagram of the streak tube which is the basis of the instrument

The first part consists of a photocathode which is responsible for emitting electrons proportional to the intensity of the incident light signal This is followed by accelerating and focusing electrodes which guide the electrons through the deflection electrodes. The electron signal is then amplified through the micro-channel plate (MCP) and stops on the phosphor screen where it will be recorded.

To produce a streak of the input, the camera will, first, transform the incident light beam into a proportional electron signal through the photocathode. This signal is focused through the deflection plates, through the MCP and onto the phosphor screen. Initially, the electron signal is kept deflected to the top of the phosphor screen and as the deflection plates are activated by an electrostatic voltage ramp, the electrons are swept downwards. This displays the time varying input amplitude of the signal on the phosphor screen as a spatially varying intensity light streak. The image of the phosphor screen is recorded by a silicon intensified target (SIT) VIDICON camera in a digital form and the results are stored in memory.

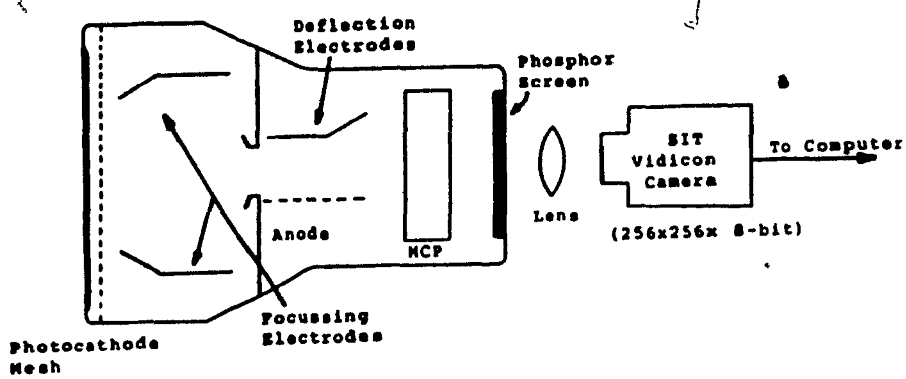


Figure 4.3.1 Schematic diagram of the streak camera

The entire data recording system capability is highly dependent on the streak camera specifications. Hence the camera will dictate the available range of sweep speeds, the sensitivity of the system, its dynamic range, and linearity.

4.3.1. Sweep rates

The sweep rates available on the streak camera are controlled by high voltage ramp generators which feed the electrostatic deflection plates. These are electronic modules which can be interchanged to allow different ranges of streak times.

The slope of the ramp will determine the streak period. The larger the slope the shorter the streak time, thus being equivalent to changing the time base on an oscilloscope. The linearity of the ramp signal is crucial for undistorted results, just as in the horizontal sweep generator of the oscilloscope.

The sweep speeds available for the streak cameras are the standard time bases of 10-20-50 nanoseconds, 100-200-500 nanoseconds and the same patterns for sub-nanosecond and microsecond times. Interchangeable modules will generally contain overlaping ranges to allow flexibility within each module's speed range.

The voltage ramp is directly connected to the deflection plates and is necessarily a high voltage signal. It is the sweep speed of the ramp generator which will limit the frequency resolution, just as the smallest time base of an oscilloscope will determine the maximum frequency which can be resolved on the screen. The fastest streak speed available will determine the highest frequency component that can be resolved on the output streak.

Eventually, it becomes increasingly difficult to produce shorter ramps which will preserve a linear response. However, despite such design effort requirements, it still appears that the development of ramp generation technology has more potential promises for high speed data acquisition than similar developments in sampling circuits for direct digital recording Ultimately, the lowest sweep speed is specified by the temporal resolution of the streak tube, which is dictated by the streak tube's sensitivity.

4.3.2. Sensitivity

It is the temporal resolution of the streak tube which will determine the full bandwidth capability of the streak camera. The camera tube has a finite response time which will determine the smallest unit of time that can be resolved on the output phosphor screen. To temporal resolution is defined as the full- width at half-maximum (FWHM) of the streak output corresponding to a short input pulse[39]. This can be measured by applying a known short pulse to the streak camera and reading out the FWHM of the streak image from the intensity profile on the camera output. Streak cameras with time resolutions of 2 pico-seconds are available today. Time resolutions of this magnitude would theoretically allow for 100 GHz operation, assuming 5 samples per cycle. This makes the streak camera a serious contender for the basis of a new generation of high speed transient recorders.

The sensitivity of the system depends a great deal on the photocathode. It is the camera's photocathode which is responsible for releasing a proportional electron signal in response to a light signal excitation Hence it is the photocathode's ability to detect input intensity variations and to produce a related change in electron emission, which will determine the minimum amount of light necessary to create any detectable output. This basically represents the camera's sensitivity. The phosphor screen is involved in the sensitivity because it dictates the minimum electron beam intensity change necessary to produce a detectable change. However, this limitation can be overcome by the MCP amplifier which can amplify the electron signal to the necessary level.

Practically, the time resolution is limited by the VIDICON TV camera resolution. The fixed number of pixels in the target array give rise to a time quantization error in the digital picture. This will be developed further in a later section. Despite these limitations, the streak camera allows for outstanding performance levels.

The advantage over oscilloscopes is due to the simplicity of the electron beam deflection trajectory. Oscilloscopes have to deflect the electron beam through two dimensions; the input signal's frequency, in the horizontal direction, and amplitude, in the vertical direction. The streak camera will always have a simple linear sweep. All frequency and amplitude information is provided by the electron beam intensity modulation. Although the advantages of such a simple sweep mechanism are unequaled, one disadvantage is the dependence of the entire system on the characteristics of the phosphor screen. Hence, any non-linearity and uneven intensity decay due to the phosphor screen will affect the quality of the signal recording

Phosphorescence is a complex subject in itself. As a side note, it is good to remember the basics. Fluorescence and phosphorescence are processes in which radiation is emitted by atoms which have had their electrons excited to various quantum electronic states by the absorption of other radiation[6]. If the states from which these emissions originate and terminate have the same multiplicity, then these emissions are called fluorescent Electrons in fluorescent state transitions will always preserve their original spin direction and have a lifetime of the order of 10^{-7} to 10^{9} seconds. When the transition states originate and terminate with a different electron spin, the resulting emissions are called phosphorescent In these cases, the transition states do not have the same multiplicity and the lifetimes are much longer, milliseconds to seconds[6].

A phosphor screen will display intensity variations of one spot on the screen proportional to the energy variations of the incident radiation. In this case, the incident radiation is the intensity modulated electron beam The proportional reaction works for a limited range, after which it has been observed that increasing intensities produce an increase in the illumination area [39]. At that point, the translation is no longer linear and the phosphor screen has reached its limits for data acquisition.

Phosphorescence intensity decays after the withdrawal of the exciting source according to an exponentially time varying first- order rate equation

$$I = Io\, e^{(-t/\tau)}$$

where $\tau = 1/Kp$

and Kp is the rate constant for phosphorescence. Consequently, when the incident source intensity is too strong, resulting in a broadening of the illuminated area, the decay will not be proportional over the entire range.

The concern over the limitations induced by the phosphor screen and further mechanisms for image digitization has lead to the development of charge-coupled-device (CCD) streak tubes [10,21,37]. This involves the replacement of the phosphor screen and multi channel plate (MCP) amplifier with a CCD array. The advantages are a simpler streak tube design, a much simpler readout system, eliminating the SIT TV camera, and allowing decay control of the image information through adequate cooling CCD's can retain their information for seconds when cooled at low temperatures Their analog shift register type memory also makes it ideal for data readout and digitization. The diagram of a CCD streak tube is shown below in figure 4.3.2.

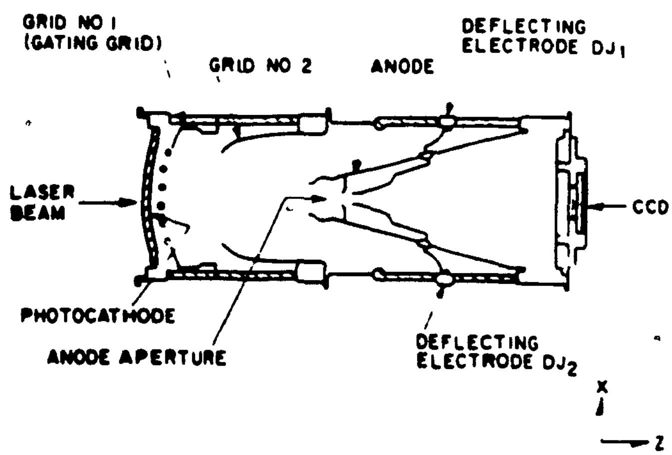


Figure 4.3.2 Schematic cross section of a CCD streak tube

4.3.3. Dynamic range

The dynamic range of the camera will also be determined by the phosphor screen sensitivity. It is defined as the ratio of the lowest input which will produce a measurable pulse width, to the input which will create a 20% broadening of the pulse width. This concept is illustrated in figure 4.3 3 According to these limitations, a dynamic range > 1 100 has been confirmed[39].

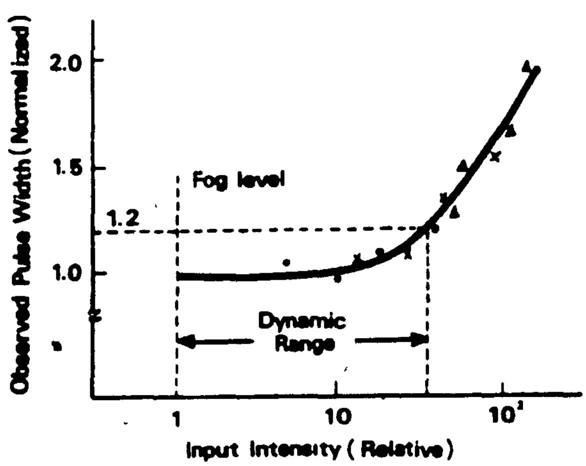


Figure 4.3.3 Plot of intensity dependent pulse width and the concept of dynamic range.

Practical values for the dynamic range have been reported to be > 40-50 [19,24] but will be lower in practice for the overall system. One main limiter is the use of electro-optical converters for electrical signal conversion. The laser diodes composing such devices will dictate the dynamic range with which the electrical signals are converted. The response of these diodes is highly limited in linearity, power and dynamic range which will usually vary from 30 to 40 [24] according to the specific laser diodes used. This will invariably reduce the overall system dynamic range and stresses the development of photonic sensors or better laser diodes Improvements in laser diodes are a better and more likely short term solution whereas the photonic sensors are a long term goal.

4.3.4. Non-linearity

Non-linearity in the sweep will produce distortions in the time axis as well as in the intensity values Any compression in time due to a non-linearity of the sweep ramp will cause an increase in the output intensity and thus is a major limitation to the sweep speeds As mentioned earlier, it is very difficult to produce picosecond ramps that will be perfectly linear. Non-linearity figures have been reported to be less than 1% for 1 nanosecond resolutions [39], and generally in the vicinity of 5% for picosecond resolution [39,24].

However, when considering the entire system, the non-linearity of the laser diodes is mainly responsible for introducing harmonic distortions into the signals. Although limited in amplitude they were measured in [24] to be below -20 dB for 2nd harmonic and below -30 dB for 3rd harmonic distortion with the laser diodes operating at maximum output power.

4.3.5. System bandwidth

The overall bandwidth of the instrument is dependent on the individual bandwidth limitations of the various parts of which it is composed. The streak camera has a practical bandwidth which is close to 10 GHz, due to the output resolution available by the recording VIDICON TV camera. This performance is reduced by the bandwidth of the optical fibers to values of 4-8 GHz depending on the cable lengths. Performance levels of this amplitude are respectable and are a good short term goal to aim for with this system. For the cases where laser diode interfaces are required, a significant drop in bandwidth is witnessed. State-of-the-art devices provide performance levels of 100's of MHz but very few allow for GHz operation. THOMPSON CSF is one of the few companies to manufacture laser diodes capable of 1 GHz operation.

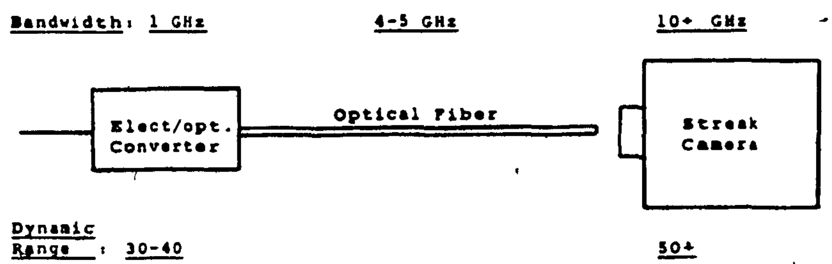


Figure 4.3.4 Bandwidth and Dynamic Range limitation distributions of the recording instrument.

Clearly the breakthrough lies in photonic sensors which would ensure a minimum of 4 GHz and up to 8 GHz operating bandwidths. Another alternative is to develop faster and more powerful optical transmitter interfaces. Nevertheless, without any loss of generality, multi-channel capability with 1 GHz bandwidth is still a large step forward despite its being only a fraction of the ultimate potential.

4.3.6. The Streak Camera digitization process

It is interesting, at this point, to investigate the digitization process of the streak camera. A major conclusion drawn from chapter 3 observed that high frequency signal digitization was possible through the use of an intermediate storage element. An intermediate storage stage provides a means to temporarily store the analog signals and permit later retrieval of the information for digitization. This formed the governing philosophy for analog memory recording instruments

The same philosophy provides an interesting view point from which the presently described system can be examined. The streak camera can be considered as the analog storage device and the TV camera as the retrieval mechanism for digitization. Unlike the analog memory which stores analog samples, the streak camera stores a continuous signal on the phosphor screen. The important part to remember about the intermediate storage stage is that it need not have a very long signal storage life time If the phosphor screen can increase the life time of the experimental signal from nanoseconds to a few milliseconds, a great time gain has been obtained. The digitization process has thus a much larger time period to digitize the information and fast conversion methods can assure that the digitization is finished before significant degradation of the phosphor screen picture has occured.

4.3.7. Image Digitizing

The digitization process which occurs in this system should be well understood to appreciate the results. As in all other such processes there is information loss through the sampling mechanism. It is exactly this sampling mechanism which was the major stumbling block in chapter 3 and to which the photonic system seems to provide a solution. To a certain extent it does. However, the output of the system will still be a string of digitized samples and it is important to determine the level of information loss.

The most important cause of distortion in direct conversion methods was aliasing, which was due to the aperture uncertainty of the sampling procedure. In the case of this system, a VIDICON TV camera is responsible for digitizing the information. It performs the task of sampling the streak image on the phosphor screen and producing an electrical signal for each pixel to represent the magnitude of the average intensity covered by the pixel. These analog electrical signals representing the pixel's intensity are sent to the A/D converter The TV camera certainly has an advantage with respect to signal sampling since the signal on the phosphor screen is practically permanent.

This does not, however, eliminate aperture uncertainty problems/ The streak on the phosphor screen will have no variations in time but the vertical axis of the screen represents the time axis. The VIDICON camera has a limited number of pixels on its target array. The total number of pixels determines the number of samples by which the picture will be approximated Consequently a target array with many pixels will provide a better picture resolution. The relation to aperture uncertainty is that each pixel of the target array will cover a certain area of the picture on the phosphor screen. Since the vertical distance represents time, the intensity variations within the area of a pixel will be the equivalent of the aperture uncertainty in electronic sampling circuits.

Although both systems are faced with some form of aliasing, the streak camera does have an advantage over electronic sampling circuits in that the aperture uncertainty can be controlled. It is important to remember that the actual streak on the phosphor screen is an analog signal recording, just as in an oscilloscope. The sampling is completely dependent on the TV camera. To increase the resolution of intensity variations within the streak, and consequently the frequency resolution, simply requires a camera with a larger number of pixels. This coincides with theory since the area covered by each pixel will represent a smaller time span and consequently a smaller aperture uncertainty allowing greater sampling rates and therefore more frequency resolution.

A simpler alternative to increasing the frequency resolution would be to increase the sweep rate and keep the same TV camera. This would reduce the time span covered by each pixel area and consequently the aperture uncertainty. Since theory states that larger sampling rates are possible with smaller aperture uncertainties, the faster sweep rate would increase the effective sampling rate and therefore the frequency resolution. This makes practical sense; when the sweep speed is increased a smaller part of the signal is spread over the screen allowing smaller changes to become noticeable.

The temporal resolution of the streak camera will govern its potential resolution performance. Practically however, it will be the TV camera which will dictate the smallest unit of time that can be resolved and hence set the streak camera's operational resolution. There is certainly the possibility of using fast sweep speeds to allow the VIDICON camera's resolution to be matched to the streak camera's high resolution capability. The major problem with this practice is that it only allows a very small part of the signal to be analysed. It is generally preferable to see a majority of the experimental signal which dictates longer sweeping times. Therefore an increase in the VIDICON camera's resolution would prove a better improvement for the system's overall performance than high sweep speeds

Overall, the main emphasis in digitizing a streak is the fact that the image is recorded as a number of continuous signals. The instrument bandwidth is not dependent on any sampling limitations, just on its response speeds. Furthermore, the digitization process is independent of the recording performance and can be controlled separately to minimize signal distortion or information loss. However, any errors strictly related to A/D conversion, such as quantization error, still remain.

4.4. System Operation and Integration Considerations

All cost, space and power reductions are based on the ability of the system to record a large number of channels simultaneously on one screen. One disadvantage is that this system only becomes justifiable for a large number of channels since the overall cost will be the same for any number of channels. A slightly more serious problem is the high level of risk involved with information loss of an experiment. If the recorder is responsible for the acquisition of many signals, any failure in the instrument will involve the loss of large amounts of data. The operating principle of the system is relatively simple but operating conditions are usually unpredictable and nothing is really foolproof.

Despite such problems the advantages over oscilloscope systems, which are the only instruments with comparable performance, are significant and make this system a serious contender as an alternative solution for high speed data acquisition needs. A list of the main gains over oscilloscopes, regarding general performance levels as being comparable, have been reported as listed below [19]:

1. 6:1 reduction in cost per channel
2. 10:1 reduction in space utilization
3. > 20:1 reduction in power consumption
4. > 20:1 reduction in installation cost

All these points are practical advantages but they stress an important characteristic which is as important to the data acquisition system as the actual performance level. For example, installation costs take on a real meaning when considering the task of providing 100 oscilloscopes with input signals, trigger synchronization and photography. Such an operation can be tedious. Similarly, space utilization is also a significant factor especially in pulsed power experiments where all the instruments have to be housed within a shielded room. It can be very difficult to stack a large number of oscilloscopes in a small room, without mentioning the heat produced by the power dissipation of all these instruments.

These factors, combined with the streak camera's exceptional performance potential prove to be an outstanding alternative. However, before such systems become widespread, many more details have to be settled. The biggest problem remains the optical signals as inputs to the camera. Developments in that direction are the subject of the next section. The second problem is to develop cameras with larger channel capacities. It is a very important step to making such devices feasible. The next step would be to allow for more flexibility in sweep times. Ideally, each channel should be individually selectable for any sweep speed. Finally, the output screen should be longer or digitizing resolutions be higher to obtain a larger number of samples for each streak.

4.5. Photonic Sensors

Future developments in photonic sensors will play a key role in the success of photonic data recorders. Photonic sensors will be responsible for the production of a photon analog signal in response to a physical observable. This will permit completely optical communication systems for all measurement signals. Optical fibers combine low loss qualities with high bandwidth performances. The isolation characteristics of the fibers immunize all signals against any EM interference in the environment and subsequently boost the effective signal/noise ratio available.

The field of research is wide and varied, covering a large area of sensing methods and techniques. However, photonic sensors can be divided into two main groups: Active or passive sensors [19].

[1] A passive sensor will involve the absorption of energy from a physical observable and emit the absorbed energy in the form of photons.

[2] An active sensor will modulate a light beam (laser) with some functional dependence on the physical observable.

Two successful photonic sensors have been developed and tested [19,20]. One such device was designed to measure voltage whereas the second was designed to measure current. Both are very basic measurements in any pulsed power experiment

4.5.1. Photonic voltage sensor

The developed voltage sensor is an active device. Consequently its output will be an intensity modulated laser beam whose modulation describes the voltage measurement.

The sensor uses a linearly polarized laser beam which is used as the carrier signal. The laser light is aimed at a KDP (potassium dihydrogen phosphate) crystal which has a polarization angle which is 45 degrees with respect to the electrically induced birefrigent axes. A last polarizer is used after the crystal with a polarization angle of 90 degrees with respect to the laser's initial direction of polarization.

The net effect of an electric field acting on the crystal is to create a phase retardation in one component of the light beam as it crosses the crystal. This phase delay which is proportional to the magnitude of the electric field, causes the beam to become elliptically polarized. The beam intensity will be modulated as the elliptically polarized laser beam traverses the final linear polarizer. The magnitude of the modulation will be dependent on the magnitude of the phase delay produced in the crystal which is directly related to the applied electric field. Thus the voltage can be deduced [20]. A schematic diagram is shown in figure 4.5.1.

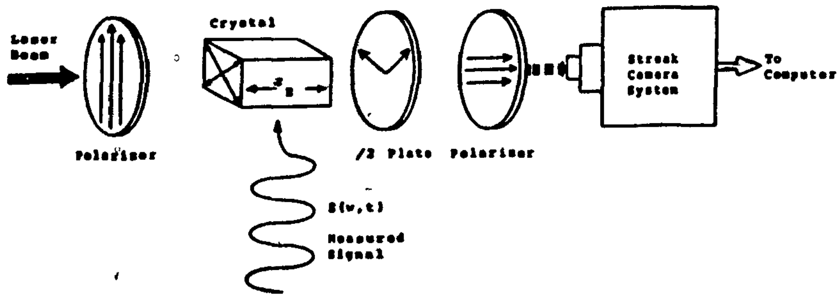


Figure 4.5.1 Schematic diagram of a photonic voltage sensor

4.5.2. Photonic current sensor

The current sensor is also an active device and will therefore modulate a laser beam proportional to the current it is measuring by exploiting the Faraday effect on silica [15,16].

If a magnetic field is applied to a silica fiber, the fiber will become circularly birefrigent. Hence left circularly polarized light will travel through the fiber at a different speed than right polarized light. This difference in speed will cause the plane of linear polarization to rotate by an angle Θ. This angle will be proportional to the magnetic field applied to the fiber.

To measure current a single mode fiber is wound several times around a current carrying wire so as to subject it to the magnetic field produced by the current. A linearly polarized laser beam is applied at one end of the fiber and a linear polarizer at the other end. Since the rotation angle of the polarization plane in the fiber is controlled by the magnetic field, the output of the laser beam after the linear polarizer will be amplitude modulated due to the polarization changes which occurred in the fiber. These amplitude modulations can be related to the linear polarization rotation Θ which is controlled by the magnetic field From the magnetic field the current can be calculated.

Increased response can be possible by winding the fiber more times around the current carrying wire. The main difficulty is to wind the fibers around small radii and avoiding any stress in the fiber due to bending and twisting. Such resulting stresses on the fiber will couple linear birefrigence to the Faraday induced circular birefrigence to produce a polarization rotation which will not be proportional to the current[19]. A schematic diagram of the sensor layout is given in figure 4.5.2.

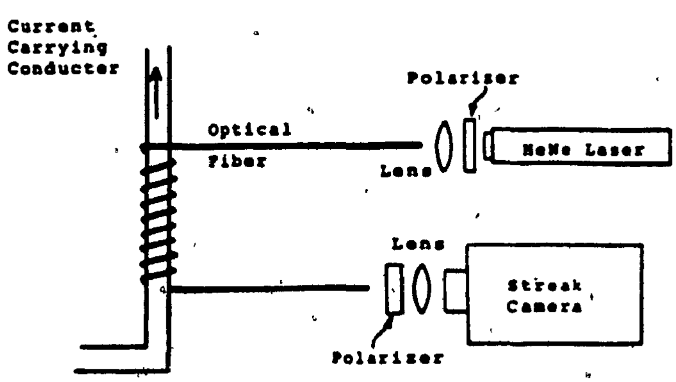


Figure 4.5.2 Schematic diagram of a photonic current sensor

4.5.3. Future directions

Photonic sensors certainly have their place in the area of pulsed power experiments. The same conditions that are so devastating for electrical components can be taken advantage of by the new optical detectors. Small effects can be exploited by such detectors due to the magnification process originating from the large magnitude of the physical observables responsible for producing these effects.

Nevertheless, the widespread use of photonics will depend on the development of fundamental elements such as the photonic equivalent of the following coaxial components:

1. attenuators
2. splitters
3. inverters
4. power T's

Further developments should include changes in the streak camera, which is actually the most costly element in the system, to allow individual sweep rates for each fiber in the multi channel instrument. The aim is to obtain a photonic equivalent of the CRT where each channel can be controlled individually but maintain the high number of channels per instrument.

Furthermore, totally integrated fiber sensors for current, voltage, field and radiation measurements would be necessary. Finally and importantly, a large amount of software will have to be developed to handle and process the large data bases that will be produced by improved diagnostic possibilities in each experiment.

CHAPTER 5

A HIGH SPEED MULTI-CHANNEL ANALOG TRANSIENT RECORDER PROTOTYPE

5.

The following chapter describes the results from the development of a small scale version prototype of the high speed data recorder described in chapter 4. It illustrates the findings relating to the streak camera system as well as the immediate problems involved with the production of single and multi channel streak images. This involves results from laser diodes, optical fibers, and a streak camera system.

5.1. System Introduction .

The following system description is for a reduced version of the High Speed multi channel data Recorder similar to that presented in the previous chapter. The speed range considered is of the order of GHz, with the capacity of 16 channels of high speed digitization and the possibility of expansion. The system could be upgraded to 21 channels with some effort. Long run improvements could bring this figure up to 30.

A streak camera system responsible for capturing and digitizing the time resolved input signal images is available commercially. Such a system can only store one image in its memory, thus requiring external storage capabilities to permanently save the results. This is achieved through a serial link to an IBM-XT personal computer which can provide disk storage as well as some post-processing facilities for the data

Certainly, the major concern of a transient recording system, apart from channel volume, is the ability to reconstruct the original signals produced by various sensors. This necessitates the linear transmission of signals from the sensors to the computer. The optical fibers are relatively worry free and any non-linearity in the streak camera system, which in this case is very small, has to be accounted for. The biggest problem is the electrical/optical conversion process necessary to couple the sensor signals into optical fibers. For both linearity and dynamic range, these converters are the bottle neck of the system.

This chapter describes the work involved in a feasibility investigation to produce a small scale High Speed Multi Channel Data Recorder The streak camera unit, the HAMAMATSU C979, was interfaced to an IBM-XT personal computer. Most of the work was directed to produce the necessary equipment and conditions to obtain a standard channel streak, digitize it and save it on the computer. This would allow verification of the maximum channel capacity, camera and converter linearity, and indicate the necessary work involved to uphold operational conditions.

The scarcity of powerful laser diodes, used as the electrical/optical converters, combined with the streak camera's low sensitivity were a serious limiting factor in the extensive development of the prototype system. The system layout is shown in figure 5.1.1.

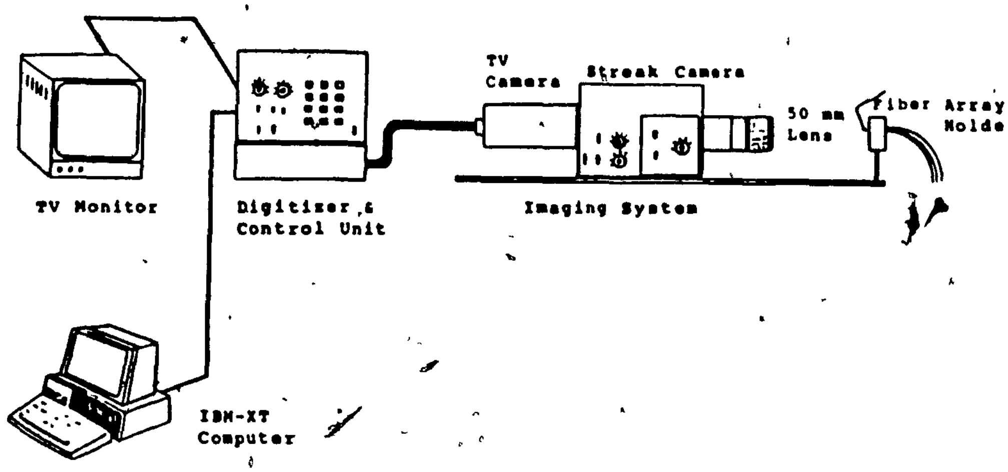


Figure 5 1 1 System layout for the prototype system

5.2. Streak Camera Technical Details

5.2.1. Introduction

The streak camera is the basis of the high speed multi- channel analog transient recorder. It receives a number of optically modulated signals at its input lenses and records their variations in time. Multiplexing is practically nonexistent since all signals are streaked simultaneously. Such a process seems simple enough to be feasible but does require a number of sub-systems to be properly integrated.

To facilitate the following discussion of work involved in the transient recorder development, it is easier to separate the system into three parts as shown below:

1. Input Optics (lenses and slits)
2. Streak Unit and TV Camera
3. Control Unit

The work involved relating to the CW laser diodes and optical fibers is discussed separately later. The following section will present the findings and details about parts 1 and 2, as well as the changes that had to be made in order to make the unit work as desired. Part 3, the control unit, remained unchanged and was used as delivered by the streak camera manufacturer.

5.2.2. Streak tube dimensions

Before mentioning the input specifications of the transient recorder, the streak tube dimensions and operation should be clarified.

The streak tube contains a photocathode with physical dimensions of 4x4 mm. This 4 mm wide image is projected through the MCPT amplifier onto a 15 mm wide fluorescent screen. The TV camera, for its part, only digitizes a 10 mm section of this picture. Consequently only two thirds of the input image width can be seen at the camera output. The input window width is therefore 2.7 mm instead of 4 mm, an important fact to know when calculating the physical limitations of the fiber array width.

In as far as the input requirements are concerned, the camera should allow 16 inputs within a slit width of 2.7 mm. With the built in lens, only six fibers can be seen by the TV camera. To bring up this value to 16, a 3:1 reduction scheme was devised by focusing the fiber array through an extra 50 mm lens. This moved the focal point back by approximately 30 cm and required the fiber array to be fixed away from the camera to be in focus, as shown in figure 5.1.1. This lens configuration offers a window width allowing up to 18 fiber inputs. The system is expected to display 16 channels, and the optics allow more inputs than required.

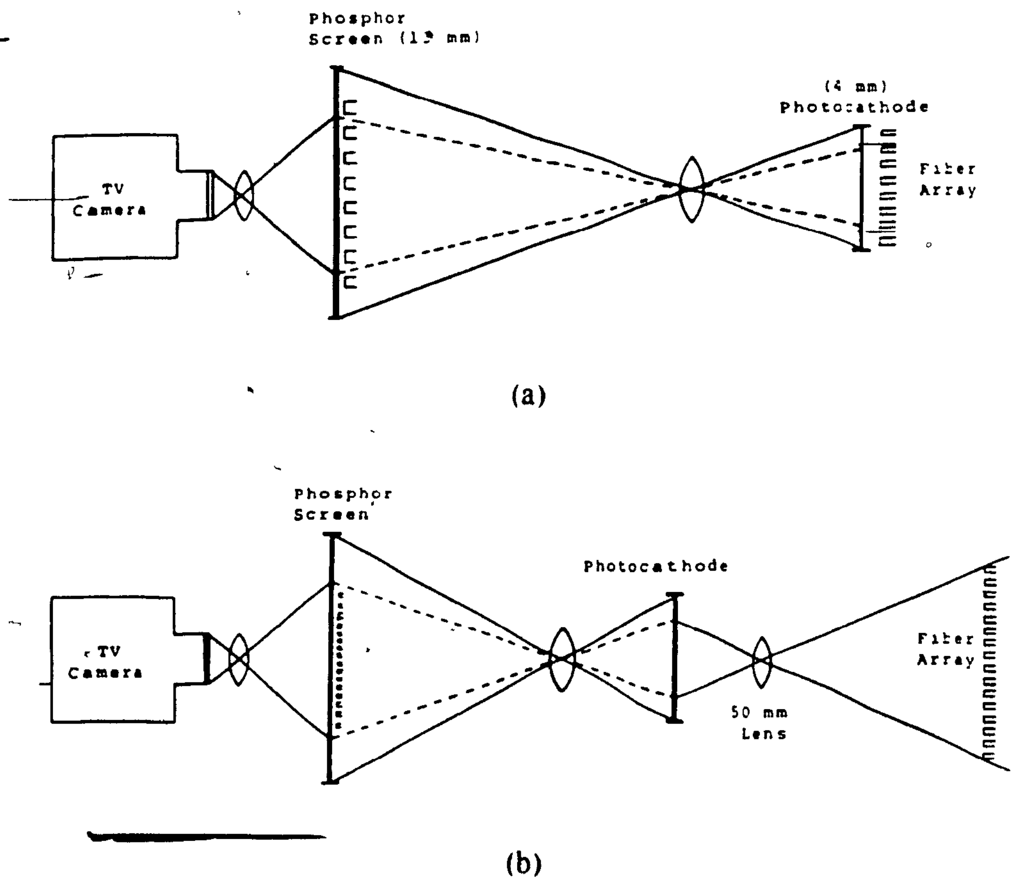


Figure 5 2.1 Streak camera input lens (a) before, (b) after

5.2.3. Description of streak unit operation

As mentioned earlier, the input optics should provide sufficient capacity to fully exploit the capabilities of the system. Being adjustable, the optics should be designed so as not to limit the performance of the system in any way. There are many other limiting factors which cannot be changed in the streak camera unit. These limitations will dictate the initial system possibilities, and the design of the rest of the system will set the final specifications.

The aim of the streak unit is to record as many input sources, as linearly, and with as much discrimination among individual channels as possible. The linearity of the streaks is inherent in the camera. Any distortion in the output must be accounted for. The number of possible inputs and the quality of signal discrimination are two very inter-related problems along with various other device specifications These will be discussed later.

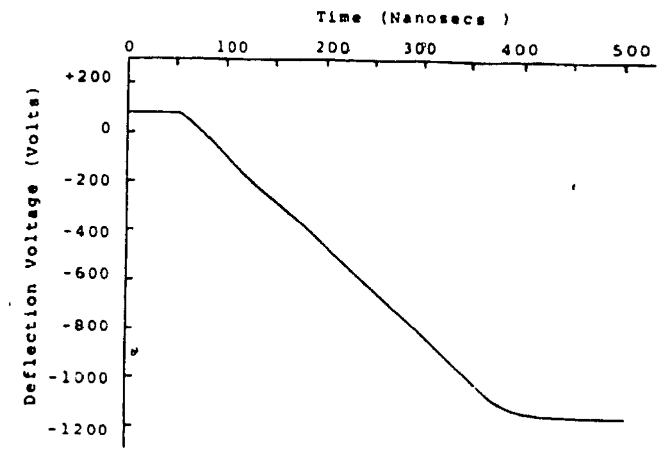


Figure 5.2.3 Streak Camera Sweep Ramp

On the other hand, the streak linearity is completely dependent on the streak tube sweep signal. Figure 5.2.3 shows the sweep ramp for a 100 nanosecond sweep and displays the linearity of the high voltage ramp It should be noted that the sweep ramp is three times longer than the effective sweep time seen on the screen A close inspection shows a rise in non-linearity in the lower 25% of the ramp. The middle section, which is the most important, is very linear.

The diagram shown in figure 5.2.4 shows the relative timing of the entire sweep process from the moment of triggering. The diagram shows that it takes approximately 800 nanoseconds before the sweep ramp is triggered. It is important to notice that the deflection plate signal is a relatively low positive voltage as long as the camera is not sweeping. This positive voltage keeps the electron beam deflected upwards above the visible portion of the fluorescent screen. If a constant light signal is present at the input, the electron image simply remains at one location and creates a large accumulation of electrons on the screen This will create a large spot of light, and although it is out of the visible part of the screen, will eventually diffuse into the visible part. This can cause non-linearities in the top part of a streak or simply generate background noise This demonstrates the importance of not having any input present for long periods of time before the sweep occurs.

Following the trigger delay is the actual sweep ramp The voltage of this ramp varies from +50 to -1100 volts. This negative voltage is directly applied to the deflecting plates to produce a downwards deflection force on the incoming electron beam. This will produce the time resolved intensity variations of the input signal on the fluorescent screen. It is the slope of the sweep ramp which will dictate the time resolution of the output streak image. A 10 nanosecond sweep signal would display 10 percent of a 100 nanosecond input pulse over the same screen thus increasing the resolution of the output signal.

Following the sweep is a hold time which lasts for approximately 30 microseconds This will keep the electron beam deflected at the bottom of the screen. This hold time is crucial because it is immediately followed by the retrace signal and no provision is made on the camera to turn off the electron beam intensity. Therefore the presence of any light at the camera inputs after the hold time causes a new streak to over-ride the old one but with much more intensity since the retrace is slow. Any information is subsequently lost and cannot be retrieved. This was not realized at first and required significant changes to the original design. Only after this discovery was made did the input power problem really surface. It was found that a

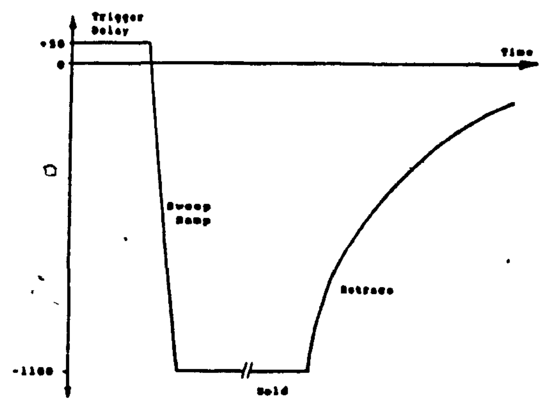


Figure 5.2.4 Streak Tube complete sweep control

100 nanosecond streak required much more laser input power than expected to produce a detectable image. This also meant that such a system could not be utilized to extract a 100 nanosecond window from an input signal with a duration of more than 30 microseconds. All of the above mentioned problems were related to the specifications of the streak camera system and had to be accounted for.

The biggest design problem was the adjustment of the number of possible inputs to obtain the maximum number of recognizable streaks on the camera output screen. The first step was to set a starting point to determine a practical value for the number of inputs physically possible. This was partly controlled by the input optics and was thus set to 16 channels. The next step was to make sure that these design specifications could be met by the streak camera outputs.

The first problem was to determine the width of each streak. Naturally, the narrower each streak the more input channels were available Furthermore the dispersion at the tips of the fibers creates a noise band around each streak, and the smaller the noise band, the greater the crowding capability This could also increase the channel capacity of the system.

To reduce the streak width would require that the fiber be smaller. The smaller the point source the thinner the streak. This could be achieved easily since there were many optical fiber types and single mode fibers offered very small diameters. It was found, however, that the major difficulty was not to be the fiber size but a simple matter of input power to the camera

For reasons of response speed, as well as low dispersion levels, laser diodes were the only choice to act as the electrical/optical converters. The response time was relatively low compared to the rest of the system's capabilities but was still adequate. The power output of these diodes however, was minimal and the problem of fiber size became a question of getting as much of the laser light to enter the camera lenses as possible Compounding the problem was the low sensitivity of the photocathode to the long wavelength laser light emitted by the laser diodes. The camera had its best sensitivity in the visible range, 400 to 500 nm, while most of the laser diodes operate in the 800 to 1000 nm range.

The options left were to choose a large diameter fiber which allowed more light into the camera. The larger diameter fibers were expected to produce wider streaks and hence reduce the total number of possible streaks. However, the tests showed that the streak widths on the phosphorescent screen were reasonable and that a much more important limitation was the low digitizing resolution offered by the camera control unit. The streak widths seemed reasonable but the TV camera added its own restrictions.

The HAMAMATSU system used had a digitizing unit which offered a resolution of 64 pixels horizontally and 256 lines vertically. Each pixel could have a value from 0 to 63, providing 64 levels of grey to encode the intensity of each point on the screen. The main restriction which emerged from these specifications was the low resolution in the horizontal direction, thus intro ducing a large quantization error. Ideally, if all the streaks were aligned perfectly with the TV camera and if each channel was one pixel wide with one pixel separation, the system could accomodate 32 channels Such possibilities, however, are very slim since the streaks might not always be aligned with a vertical window one pixel wide as shown in figure 5.2 5. If the streak was aligned between two windows, then the streak width would be two pixels wide. This is the more reasonable situation and is certainly a difficult situation to correct since it is directly controlled by the TV camera digitization unit.

Consequently a more practical value for the system's capacity would be to account two pixels per channel and one pixel separation for the noise guard band; one half pixel on each side. This would bring the total number of channels to 21, assuming that the noise band is small and that adjacent channels can share the same noise window. For safer results it might be desirable to keep one pixel wide of noise guard on each side of the streak to have a separation of two pixels. This would bring the total input volume to a safe 16 channels.

It is possible to think that if stronger laser sources were available, a smaller diameter fiber could be used to obtain better streak width results and thus a higher capacity. However the poor digitizing resolution in the horizontal direction is just as much a stumbling block as the power coupling. Digitizing systems with better resolution, such as the one described in chapter four (256 x 256 pixels), are available but are also more expensive.

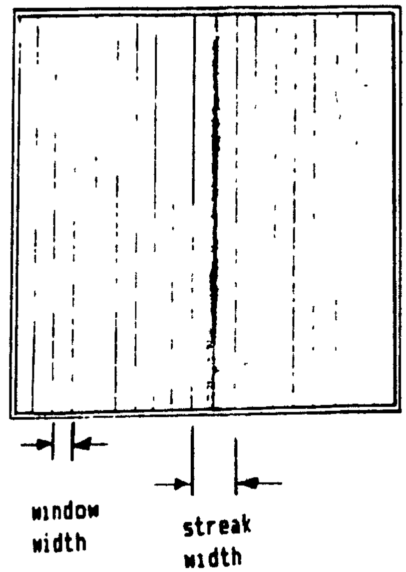


Figure 5.2.5 Resolution problem with respect to streak width.

High powered laser diodes on the other hand are scarce especially for high speed operation and short wavelengths.

5.3. Laser Diode Details

5.3.1. Laser diodes for electro-optical coupling

The system mentioned herein depends on the presence of optical signal inputs to the streak camera for recording purposes. There are two ways to obtain such optical signals. They are either generated directly by the sensors or are electrical signals which were converted into analog optical signals. The laser diodes are precisely the converter devices necessary for the latter operation.

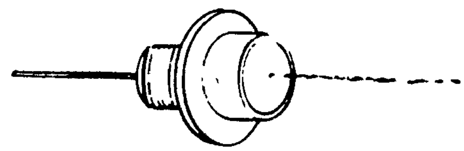
The requirements of these diodes are quite stringent First, they need to have a very fast response time due to the high frequency response of the electrical signals. Second, they have to have a linear response between output power and input biasing current. Third, the linear biasing swing should be as large as possible to allow a good dynamic range Fourth, the diodes should produce a lot of power over the linear swing

There exist two types of laser diodes: Continuous wave (CW) lasers and pulsed lasers. The CW lasers will output a constant light whereas the pulsed laser will only put out pulses of light when biased adequately The main difference between them is in the output and input power. The CW lasers only put out a few milliwatts of power and require minimal input currents (10's of milliamps). The pulsed lasers deliver watts of output power but require amps of input current to trigger the lasers. Due to the laser intensity modulation requirements for the electrical/optical converter, the pulsed laser is not suitable for such use.

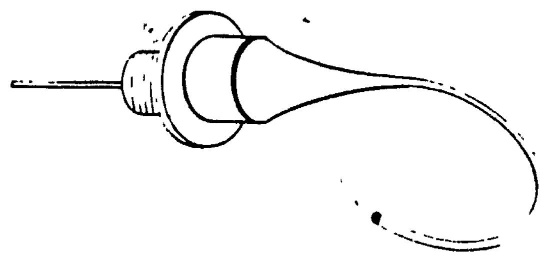
5.3.2. Investigating CW laser operation

There are a number of CW laser diodes produced by many manufacturers. The main characteristics are: Small size, low power output, small biasing requirements and low dynamic range. All CW laser diodes also operate in the vicinity of 800-1000 nm wavelength, close to the infrared spectrum.

A major difficulty in working with the laser diodes was to direct the output light. For our purposes, the laser light had to be coupled into an optical fiber which lead to the camera input lenses. It was found that because of the camera's lack of sensitivity to infrared light, compounded with the low output power of the diode, this laser/fiber coupling was of prime importance.



(a)



(b)

Figure 5.3.1 (a) Normal laser diode package.
(b) Pigtail mounted laser diode.

The coupling was originally performed manually but failed to produce proper results on the camera output. This lead to the conclusion that the laser diodes should be bought with a pigtail mount as shown in figure 5.3.1(b). This provides the laser diode with optical fiber output. The manufacturers provide the proper coupling to maximizes the amount of laser power transmitted into the optical fiber and the claimed output power is the power available at the fiber. This makes a very big difference because more than 50% of the power from a laser diode can be lost in simple laser diode/fiber coupling. This brought up another very important consideration. These diodes are both very sensitive and very expensive devices, which makes a bad combination.

Apart from the low power output and restrictive bandwidth, the laser diodes also had a low dynamic range The output power of the diode was only available over a small range of biasing currents A typical output response of a CW laser diode used in the tests is shown in figure 5.3.2. The curve is characterized by a threshold current and a maximum current allowed through the diode. The threshold current is the minimum current necessary to trigger the diode into producing laser light The difference between the two currents is the working biasing swing, which is not necessarily linear. The linear swing generally starts a little above threshold and stops earlier than the maximum allowable current. Such small linear swings offer small dynamic ranges reducing the quality of the conversion process.

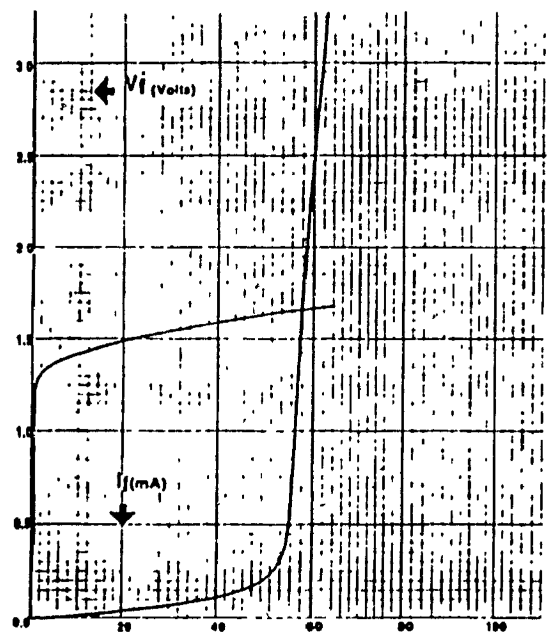


Figure 5.3.2 Output response of a CW laser diode

Moreover, for the diode to operate as a converter, all inputs have to be higher than the threshold level. Consequently, a DC bias is necessary on each diode in order to hold it just below threshold. Nevertheless there will be a range of inputs for which there is a non-linear output response. Small signals will have most of the information concentrated in the non-linear region whereas for large signals, which seldom cross the region, the distortion is minimal.

There are two ways to overcome the distortion problem The first, is to make sure that all inputs span the entire full scale swing so that the non-linearities in the converted signals are insignificant. The second solution is to bias the diode above threshold, just below the linear region However, this would produce a constant low intensity output on the top part of the fluorescent screen and eventually produce noise by diffusion on the visible screen. This option is easier to work with but might create a problem with the picture signal/noise ratio

For similar reasons, such converters can never be used for bipolar operation with the above mentioned camera system. Bipolar operation would be possible by simply biasing the laser diode in the middle of its linear range. Any negative input would bias the diode closer to the threshold and thus emit less power. Such bipolar operation would produce even more noise than the previous case since the constant DC bias would be a much stronger optical input and hence diffuse much more noise in the visible screen.

At present, the major problem with the CW laser diode converters is the power limitation of the devices. This is one area where technological progress can eventually provide a better solution[36,40].

5.3.3. Experimental results of system linearity

A number of experiments were performed, testing many variables in the quest for a linear streak with an acceptable width and a good signal to noise ratio. A number of fiber types were used, ranging from single mode to multimode core and finally to large 80 micron graded index fiber The main goal of all these experiments was to get a plot of the laser diode's linearity over its input range. However, to obtain such results the diodes had to produce a reasonable streak quality on the screen.

The biggest problem was the lack of power received at the input of the camera, due to inadequate fiber/diode alignment. The laser diode power could not be increased and since there were no specialized alignment facilities available, the diode was sent to Northern Telecom for installation of a pigtail mount. The results were good, with excellent width characteristics and a fair signal to noise ratio. Some extra power would have been preferable though. The mounting structure failed after a few tests and the actual experiments were done with the laser beam coupled directly into the camera

The results of the linearity test are shown in figure 5 3 3, showing the intensity variations of a constant input for input currents ranging through its effective range. The results show that even though the threshold current was 50 mA for the specific diode, the linear region only starts at 52 mA. The linear range lasts up to 58 mA after which saturation is clearly noticeable.

Figure 5.3.4 shows the effects of smaller current variations on a short duration pulse over the linear range of the laser diode. These results show with more detail the effect of the degradation of the signal as the threshold level is approached and that any signal level between threshold (50 mA in this case) and the beginning of the linear region produces negligible outputs. It also shows the sudden saturation of the laser output after 58 mA. Figure 5.3.3 was aimed at getting a broad view of the laser diode response over the

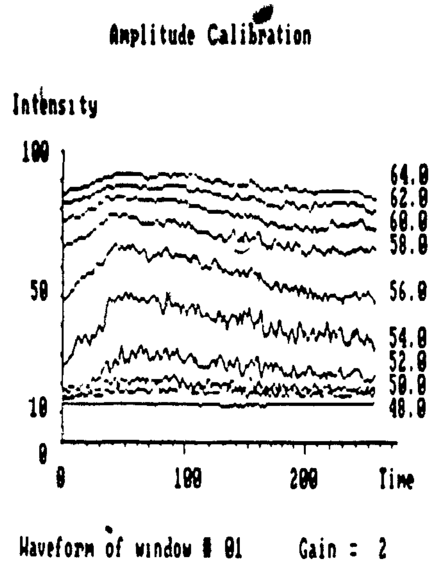


Figure 5.3.3 Linearity test for a constant input

entire range, whereas figure 5.3.4 was aimed at getting a better sensitivity measurement within the diode's linear range (52 to 58 mA)

What these figures do not show is the quality of the streak for each waveform. In general, all streaks were done with certain output norms. This included the requirement of the streaks to be within two pixel widths, and not more than one pixel width of noise on either side The actual signal to noise ratio obtained can be observed by comparing the signal levels with the background noise level shown as the bottom straight line on the graphs of figure 5.3.3 and 5.3.4 The streaks were generally one pixel wide, but the camera digitization forced the reservation of two pixel windows to account for misalignments All streaks had no problem in being confined within two pixel windows. Considering that the input power to the camera was in the vicinity of 5 mWatts, laser diodes with power levels of 10 mWatts would

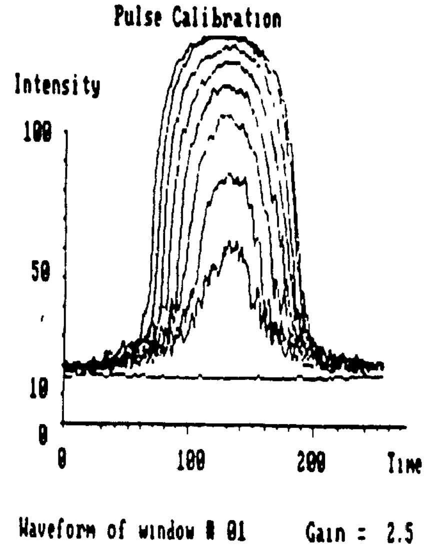


Figure 5.3.4 Laser diode Linear swing, 52 to 58 mA

ensure very stable conditions.

The last test performed was to measure the temporal linearity of the streaks, to verify the linearity of the streak time axis It should be kept in mind that all the graphs shown here contain the results of a number of independent streaks. All waveforms were separately obtained from the streak camera, transferred and saved on the IBM-XT computer and later plotted by overlaying all the different waveforms on one graph

The same method was used to produce the graph of figure 5 3.5 which represents four different streaks of the same pulse delayed by different times. The delays were 2, 4, 8, and 16 nanoseconds which were produced using the HAMAMATSU delay unit. The distance between the edges of the pulse at various delays is consistent with the difference in time between them The delays are doubled each time and so does the separation between them. The pulse was not delayed any further because of the unit limitation.

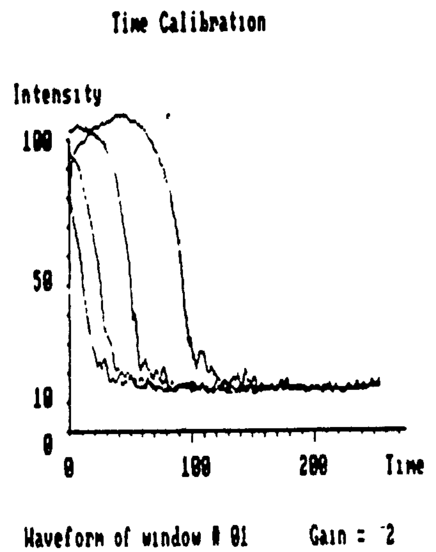


Figure 5.3.5 Test for temporal linearity of a streak.

Following all these tests of the laser diodes, an unsuspected problem arose which is so far still unresolved. As mentioned earlier, these laser diodes are quite sensitive and expensive devices. This is especially critical considering that these devices will be very close to the experiment sensors and consequently close to a harsh environment It is therefore possible that dangerous noise signals might be induced in the electrical transmission lines leading from the sensors to the converters. This makes it essential to incorporate an overdrive protection into the converter circuits to prevent permanent damage to the laser diodes. If not for conveniance purposes then surely for economical reasons.

The problem is that any form of current or voltage limiting circuitry is incapable of operating at such high frequencies. Very few active devices operate at GHz frequencies and if they do, are probably as delicate as the laser diodes themselves Although some advances have been made in high speed voltage limiting[35], it remains a serious problem in the development of a functional electro-optical converter

5.4. Summary of Results

From the design and construction work involved with this prototype high speed data recorder, the following conclusion were drawn

First, because of the streak camera was designed without any automatic intensity cutoff system during retrace, it is impossible to measure any event or signal which lasts longer than 30 microseconds.

Second, laser diodes with output powers of 10 mW are necessary to produce proper signal/noise ratio streaks This output power should be available at the output of the optical fiber and consequently recommends that the laser diodes be bought with manufacturer installed pigtail mounts

Third, the input optics of the streak camera had to be changed to allow for a greater number of fibers to be coupled into the camera lens The low resolution of the digitized image also forced the channel width to be relatively wide, for security reasons, thus limiting the number of possible number of channels to 16-20.

Four, the photocathode in the streak tube should be changed to be more sensitive to long wavelengths, since most laser diodes emit in the 800 to 1000 nano-meter range Its present sensitivity is best for visible light and is poor at these infrared frequencies.

Five, the dynamic range of laser diodes, although fairly linear, is somewhat small and the response speed is too low. These diodes are sensitive, expensive and very difficult to protect. It adds up to an expensive solution for marginal results. The most important priorities are then, the increase in response speed, dynamic range and output power.

Six, the streak camera system is easily operated as a stand alone system and can be easily interfaced to a small personal computer for data storage and displaying

In general, the system is feasible for reproduction on a small scale for high performance data acquisition. It does however require the assistance of many new components which might not yet have reached their full development. The rate of technological advance is certain to develop these necessary components It is only a question of time for this system to become one of the best high performance instruments for high speed multi channel transient recording.

CHAPTER 6

CONCLUSION

This thesis has presented a new alternative for the growing needs of high speed transient data recording. The new instrument has been shown to be capable of performance levels surpassing all other known techniques, and can offer these performances at multi channel level, within reasonable economic constraints. At the present state, the system requires a number of details to be refined, but as soon as the necessary hardware becomes available, through technological advances, it will become an extremely powerful data acquisition instrument. It's potential for high speed data recording is big enough to keep it in existence for a very long time.

Improved Operation in Harsh Environments

A major problem for any high speed data recording instrument is the environment in which it has to work. The new system was shown to be capable of perfectly integrating the high bandwidth and high noise immunity requirements of short duration, high energy experiments. The ability to directly record incoming diagnostic signals in an optical form, allows the use of optical fibers for signal transmission. This solves the two problems of bandwidth and noise immunity simultaneously. In the first case, optical fibers offer low transmission losses and high channel bandwidths allowing the efficient transmission of weak diagnostic signals. In the second case, the photonic medium of the signal renders these diagnostic signals highly immune against any level of electromagnetic interference.

Other advantages associated with optical signal transmission and recording are; [1] the reduction in shielding costs for the transmission lines, [2] the improved isolation of the diagnostics equipment through better ground loop protection, and [3] a reduction in the number of medium conversions, electrical/optical and vice versa, thus minimizing any performance limitations originating from extra complex circuitry.

The Limitations of Conventional A/D Conversion Techniques

The increase in complexity of new high energy experiments often requires data analysis which would be impossible without the aid of sophisticated computer programs. Consequently, there is an unquestionable necessity for efficient digital signal recording methods. Photographic methods were until now the only way of obtaining results from ultra fast data recorders.

The necessity for analog-to-digital conversion is indisputable The problem is to find a method which will allow the digitization of extremely high frequency transient signals. This thesis has shown the potential of both direct and indirect digitizing methods and concluded that the only solution to future high speed digitization lies in various indirect methods.

Direct A/D methods are based on conventional approaches of sampling and digitizing the input signal in real time. It was found that although conversion times can be accelerated considerably, at the expense of power, the sampling circuits are incapable of providing short enough sampling times to satisfy the sampling theory requirements. These sampling circuits will always be directly handicapped by the technological speed barriers since the limitations are directly controlled by the transistor switching times, and consequently offer little potential for significant improvements.

Indirect methods are based on an approach which temporarily stores the signal and retrieves it at a later time for digitization. The biggest problem with this method is to find a storage medium which allows analog signal storage, with a reasonable storage time, and most important with a fast writing capability. Charge-coupled-devices and other analog memories were investigated, but they are also limited by the inadequate response time of the sampling circuits.

Indirect Conversion Methods for High Speed Data Recording

The solution for a high speed multi channel transient recording system, as described in chapters 4 and 5, is a form of the indirect digitization method and makes use of a commercial instrument, called the streak camera. The first and foremost characteristic of this system is its ultra fast writing speed capability. The secret to its potential success is its temporary storage medium, which in this case can be a phosphorescent screen or an array of charge-coupled-devices (CCD). The combination of these two distinctive features enables the system to record events at remarkably high speeds, and store the information for a relatively long time. This information can subsequently be retrieved at a rate which allows for accurate A/D conversion.

Although direct A/D conversion methods are not best suited for the development of ultra fast transient recording systems, they play an important role in the transient digitization. Once the signal is in temporary storage, fast A/D conversion facilities are still required. Any developments in that direction would then represent the ability to digitize the streak images with better accuracy and resolution, which directly translate into better frequency response.

Streak Tube Performances for Better Data Acquisition Systems

The streak tube itself has a multi GHz bandwidth (>10 GHz) and a dynamic range in excess of 200, limited only by the interfacing equipment which makes up the rest of the system. The fundamental principle has enormous potential, protecting it from the risks of early obsolescence due to a too rapid achievement of its full capability. It is always good to know that a certain instrument will be in use for many years. Presently, the system can only be exploited at a minimal level. As technology in optical electronics evolves, however, this data recording system can take full advantage of any advancements to increase its performance level.

The oscilloscope is the only instrument that can be used for any form of comparison, and the preliminary performance results indicate drastic improvements for data acquisition system designs. Such improvements are:

[1] A 6:1 reduction in cost per channel of high speed data recording.

[2] A 10:1 reduction in space utilization.

[3] A reduction in power consumption exceeding 20:1.

[4] A drastic improvement in installation time and cost also exceeding 20:1.

All these features are essential for the economical and technical feasibility of larger and more complex data acquisition system designs, and this instrument is a step towards a break through in high speed data recording.

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