AN ELECTRO-OPTICAL AND FIBER-OPTICAL MEASUREMENT SYSTEM FOR HV TRANSIENTS

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CONTENTS

Chapter 1	Introduction	3
Chapter 2	The measurement system	4
2.1	Principles	4
2.2	The complete system	4
Chapter 3	The components	9
3.1	Risetime and bandwidth	9
3.2	Optical fibers	9
3.3	The diode laser	10
3.4	The detector	11
3.5	Gradient-index lenses	12
3.6	Lenses	12
3.7	Polarizers	13
3.8	The $\lambda/4$-plate	14
3.9	The Pockels cell	14
3.10	Summary of used components	16
Chapter 4	Mechanical arrangement	17
4.1	The gradient-index lens assembly	17
4.2	The laser assembly	17
4.3	The probe assembly	19
4.4	Adjustments on probe and laser	20
Chapter 5	The electrical system	21
5.1	The total electrical system	21
5.2	Power supply	21
5.3	Circuits for the laser	22
5,4	Amplifier circuits	23
Chapter 6	Some characteristics of the system	25
6.1	The laser	25
6.2	The amplifier	26
6.3	The Pockels cell	28
6.4	Estimations of measurement precision	29
Chapter 7	Tests and measurements at Uppsala	31
7.1	Tests	31
7.2	Summary of results	36
Chapter 8	Conclusions	37
	History	38
	References	39

CHAPTER 1 INTRODUCTION

It is often a difficult task to measure fast HV transients with conventional equipment. The frequency range is often limited and strong precausions against sparking and discharges has to be made.

Electro-optical methods features many advantages compared to these conventional methods (1):

1. low cost
2. small size
3. easy connection to low voltage instruments
4. completely passive measurement technique
5. good electrical isolation and low level of noise
6. good bandwidth
7. good sensitivity

Especially 1,3,4 and 5 are important when measuring very high voltages > 400 kV.

In the following chapters an account of a Diploma work - a construction of a fiberoptical system for measurements of fast HV transients - will be given. The system is based on a capacitively coupled Pockels cell which acts as a passive voltage probe.

The principles of capacitvely coupled Pockels cells are described in Ref.2. That system, however, was a laboratory arrangement with a HeNe laser as light source. Furthermore, the laser beam propagated in free space, not in fibers, and the setup was thus sensitive to external disturbances.

The aim of this work was then to put this principle in a more practical form - to build a robust an easy to use system that is as fast as possible (ns) for use in i.e. industrial measurements. The result is a system that is compact, with few needed adjustments when operating. The system is easy to handle and can be used in a wide range of measurements - and it is fast.

CHAPTER 2 THE MEASUREMENT SYSTEM

2.1 Principles

The system is based on the ideas presented in Ref. 1. A Pockels cell changes its refractive index with an applied voltage. If one puts the cell between two crossed polarizers the transmission will depend on the voltage. Thus one can measure voltages by sending light through such a setup and monitoring the transmitted intensity. The Pockels cell is not connected directly to the voltage. It is instead coupled capacitively to the source (see Fig. 2.1).

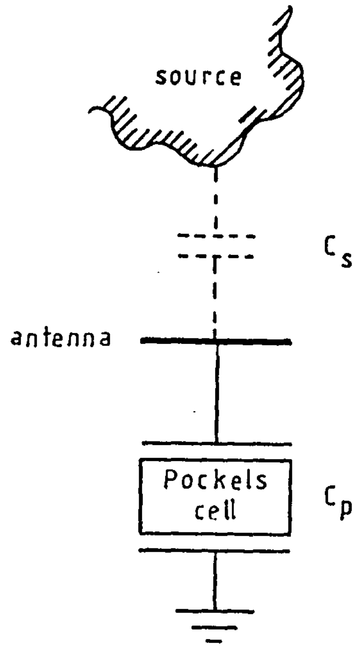


Fig. 2.1 The capacitively coupled Pockels cell

The voltage V over the Pockels cell will then be related to the voltage at the source V_0 according to

$$V = V_0 \frac{C_s}{C_s + C_p} \qquad \text{(Eq. 2.1)}$$

Thus it is possible to adjust the voltage over the Pockels cell by altering the setup and thereby the capacitance C_s and one can then measure a wide range of very high voltages.

2.2 The complete system

The complete system consists of two parts: the laser/detector box and the probe. When the system is operating these two boxes are connected with two 100 m optical fibers (see Figs. 2.2-4).

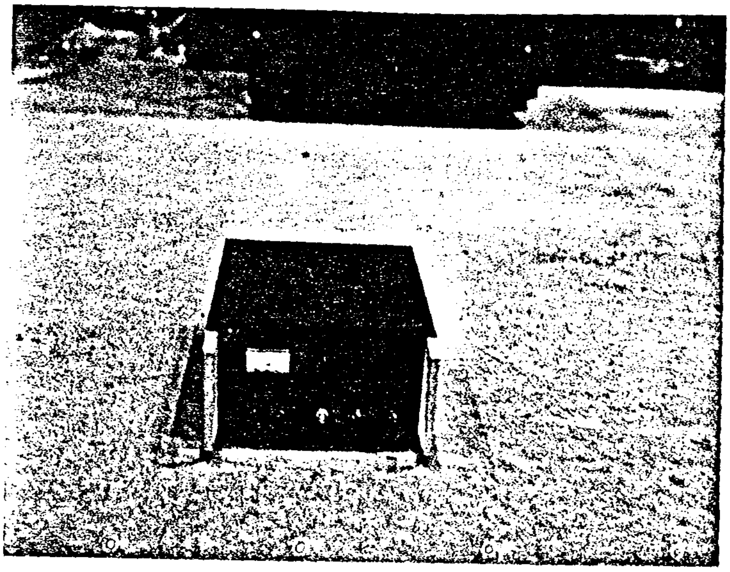


Fig. 2.2 The detector/laser-box

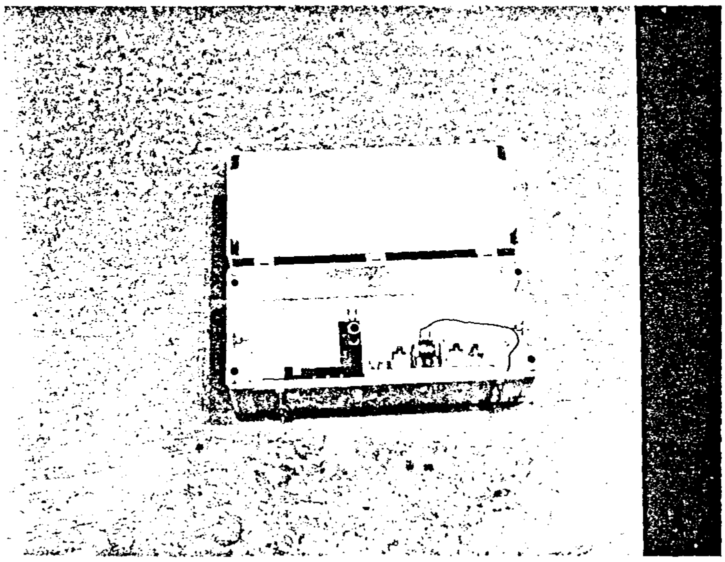


Fig. 2.3 The probe

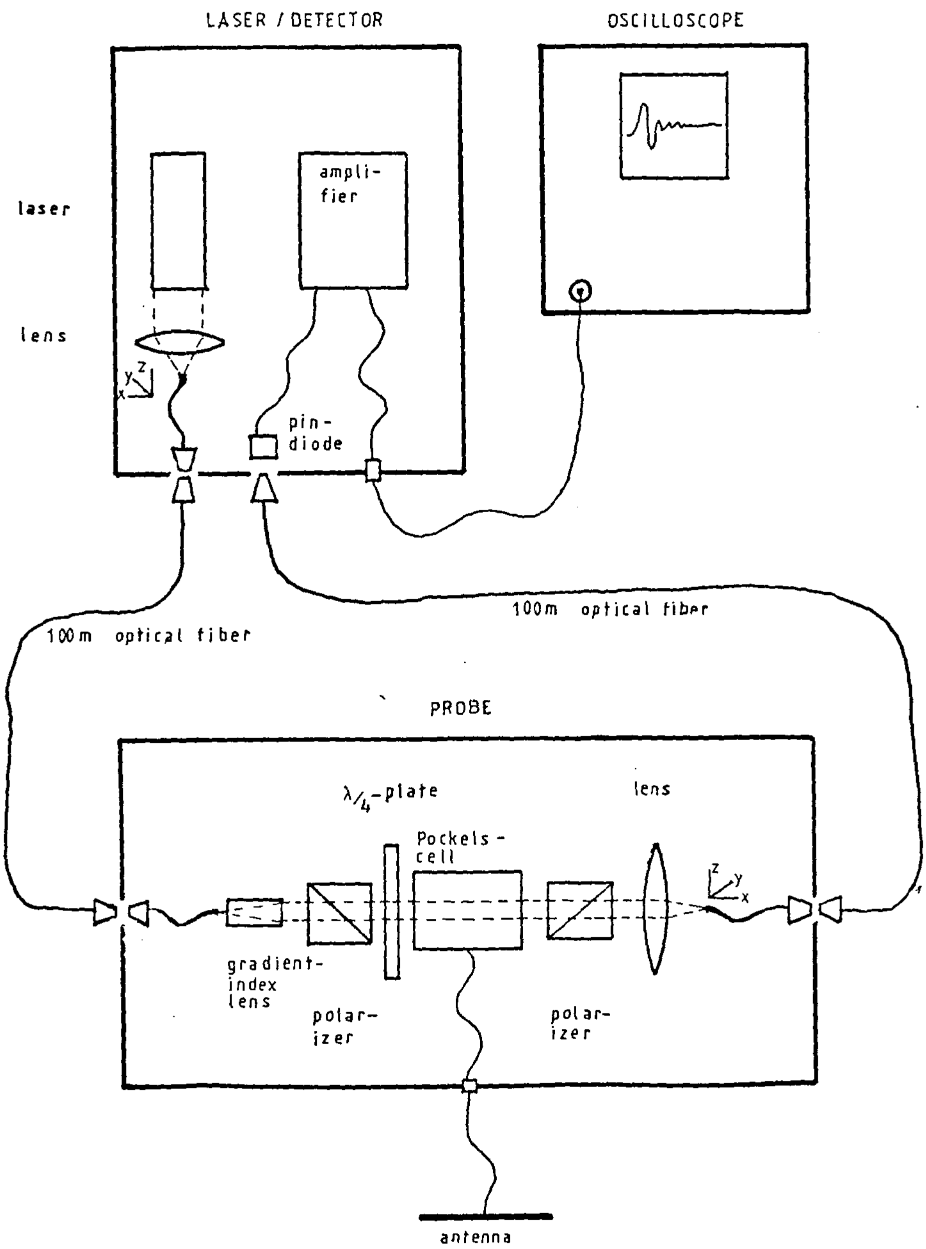


Fig. 2.4 The total system

The 820 nm light from the diode-laser in the laser/detector box is focused with a lens on the end of an optical fiber. The fiber end is mounted in a XYZ-translator. It is thus possible to adjust and optimize the position of the fiber. This short fiber is then connected to one of the 100 m fibers and the light thus reaches the probe. The light is collimated with a gradient-index lens and is then fed through the first polarizer. Then it passes a λ/4-plate before it enters the Pockels cell. After the Pockels cell the light passes the second polarizer which is crossed with the first one. Then the light is collected with a lens and again focused on a short fiber also mounted on a XYZ-translator. Via the second 100 m fiber the light is returned to the laser/detector box where it strikes a pin-diode. The signal is amplified either with a slow (0-10 kHz) amplifier, or with a fast one. Finally the electrical signal is connected to an oscilloscope.

The Pockels cell is sensitive to changes in an applied voltage. The antenna picks up the signal one wishes to study and connects it to the Pockels cell which then alters the polarization of the light passing it. Thus the total transmission through the probe changes with the signal and can be studied on the oscilloscope. For a Pockels cell between two crossed polarizers the transmission is related to the applied voltage according to (3)

$$I=I_0\sin^2\left(\frac{\pi V}{2V_{\lambda/2}}\right) \qquad \text{(Eq. 2.2)}$$

where I is the transmitted light intensity, I_0 is the intensity after the first polarizer, V is the applied voltage and $V_{\lambda/2}$ is a material constant depending primarily on the crystal material used in the Pockels cell and the wavelength of the light. As a $\lambda/4$-plate is inserted before the Pockels cell a phaseshift of $\pi/4$ is introduced and the relationship becomes.

$$I=I_0\sin^2\left(\frac{\pi}{4}+\frac{\pi V}{2V_{\lambda/2}}\right) \qquad \text{(Eq. 2.3)}$$

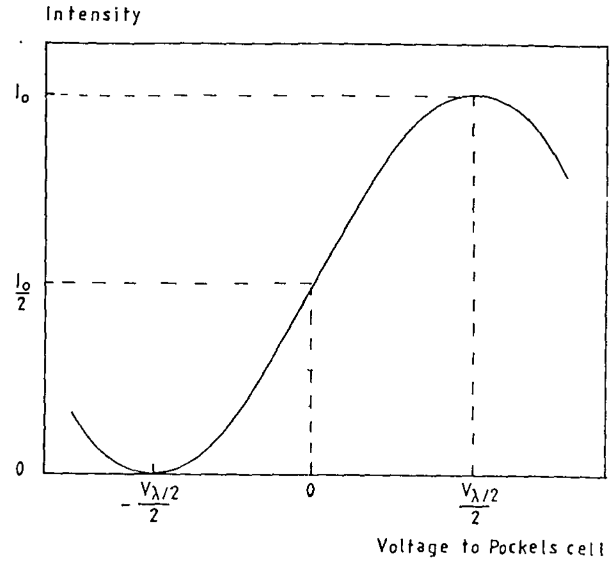


Fig. 2.5 The relationsship of Eq. 2.3

It is desired to get a nearly linear relationship between the applied voltage and the change in transmission. This is achived when the voltage lies between -0.9 kV and 0.9 kV. The antenna acts as an capacitive coupling between the Pockels cell and source of the signal. It is thus possible to meet this requirement by altering the size and shape of the antenna or the distance between the antenna and source.

The optical fibers makes it possible to put the electronics 100 m from away from the probe and high voltage source and one thus gets good electrical isolation and suppression of rf-noise.

CHAPTER 3 THE COMPONENTS

In this chapter the components in the system are presented. Also presented are the reasoning and calculation behind their selection.

3.1 Risetime and bandwidth

For a system with risetimes t_1, t_2, t_3 ... the total risetime is

$$t_r = (t_1^2 + t_2^2 + t_3^2 + \ldots\ldots)^{1/2} \qquad \text{(Eq. 3.1)}$$

Furthermore, the relation between the bandwidth f_b and risetime of the total system is

$$f_b t_r = 0.35 \qquad \text{(Eq. 3.2)}$$

This relationship depends upon the type of frequency distribution in the signal but 0.35 is a good approximation for several signals.

From this one concludes that for the system to be built with the goal of a risetime of 1 ns the bandwidth should be 350 MHz. We also conclude that the different components that will constitute the system should have better risetimes and bandwidths than this.

3.2 Optical fibers

In consultation with ASEA Research the length of the optical fibers were choosen to be 100 m. This affects the choice of the fiber.

When a lightpulse runs through a fiber its shape alters - the width increases and thus the bandwidth is limited. Single-mode fibers have good bandwidth but their small corediameter makes them difficult to couple with each other. Therefore only step-index and graded-index fibers was considered.

The reason for the increase in pulsewidth are 1) material dispersion 2) waveguide dispersion and 3) mode dispersion. The dominant part is the last. For a step-index fiber the modedispersion is (4)

$$\Delta t = L(n_1-n_2)(1-\pi/V)/c \qquad \text{(Eq. 3.3)}$$

$$V = 2\pi a(n_1^2 - n_2^2)^{1/2}/\lambda_0 \qquad \text{(Eq. 3.4)}$$

and the material dispersion is (4)

$$\Delta t = \frac{L}{c}\lambda_0 \frac{d^2 n_1}{d\lambda^2}\bigg]_{\lambda=\lambda_0} \Delta\lambda \qquad \text{(Eq. 3.5)}$$

were Δt is the widening of the puls

L the length of the fiber
c the speed of light
n_1 index of refraction for the core
n_2 index of refraction surounding the core
a the radius of the core
λ_0 wavelenght of transmitted light
$\Delta\lambda$ width of the wavelength distribution

For a standard step-index fiber, a=50µm L=100m, this gives Δt of approximately 5 ns in modedispersion. This is to much! And this means that we have to choose a graded-index fiber.

With the same value for L and with $\Delta\lambda$=15 nm and the second derivative from table to 0.025 in Ref. 4 for quartz the materialdispersion is calculated to 340 ps. That is acceptable.

Ericsson Cables manufactures a twofiber cable GNKD of the graded-index type. The bandwidth at 850 nm is better than 200 MHzkm. This means that for 100 m the bandwidth is 2 GHz. That is far better than needed. Furthermore, the fact that it is a twofiber cable is an advantage. One cable one uses to feed the probe and the second one uses to return the light to the detector.

But the final choice is a cable from ASEA KABEL: OC1 - a semi graded-index fiber. At 850 nm and 100 m the bandwidth is 1 GHz. That is more than needed. The core diameter is 100 µm compared with the 50 µm for the cable from Ericsson. This is what decided the selection and depends upon the choice of laser and the problems thereby encountered (see Secs 3.3 and 4.2). A decrease in the 1 GHz bandwidth above could come from materialdispersion, but as have been seen above this effect is small for relative large $\Delta\lambda$ and a step-index fiber. And as there is no possibility to make a more accurate calculation for the OC1 fiber the calculation above is taken as an approximation.

To this fiber connectors were bought from Holtec.

3.3 The diode laser

The choice of laser affects the rest of the system; primarily it affects the choice of fiber and detector.

A natural choice for a fiber optical system is a laser with pig-tail. They are, however, quite expensive (5-6000 Skr).

Another alternative was chosen: Philips collimator-pen N513CQL-A (2800 Skr).

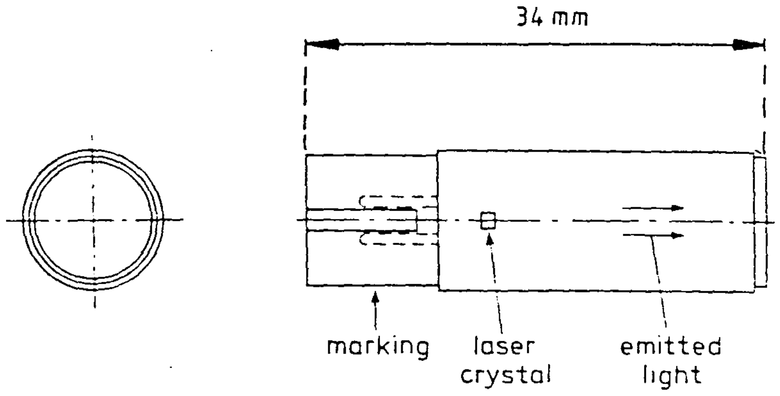


Fig. 3.1 The collimator-pen

It is a Ga-As diode laser that gives a maximum output power of 20 mW CW at 820 nm and a maximum width of 8 nm. The laser is a new product and became available at the end of 1985. The laser in the present system is no 54 from the initial test production. The characteristics of this laser are presented in Sec. 6.1.

In the collimator-pen there is a lens system that collimates the strongly divergent light emitted from the diode. The light after the lenses has a diameter of 4.5 mm. It is thus necesary to use a further lenssystem to feed the light into the fiber. Therefore it is desireble with a large core diameter in the fiber.

Besides the price, another factor influenced the choise of laser: the output power. During the the study of different lasers an output power exceeding 5 mW was never encountered for those with pigtail at a reasonable price. To get a fast system requiers that as much power as possible is transmitted, because the less one needs to amplify the photodiode signal the faster the system becomes. In the constructed system the power supplied to the fiber is 75 % of the output power. Thus 15 mW is entering the fiber loop. And all this power is needed because only about 0.5 to 1 % is transmitted through the complete system.

3.4 The detector

There are specially made detectors for fiber optical systems. These often have a pigtail and in the case of avalanche photodiodes the bandwidth is extremly high (Mitsubishi FU-02AP has a bandwidth of 2GHz). Furthermore, there is a possibillity get an internal amplification by applying a constant voltage accros the avalanche diode. They are also very sensitive and have little noise However, the electronics get quite complicated and the voltage over the diode has to be carefully held at an constant level.

Because of the simpler electronics and lesser price a pin-diode was choosen. The one in the presented system is manufactured by Hamamatsu and is of the type S-1188-03. It has a risetime of 0.8 ns when the applied voltage is 40 V. Its case is of the type TO-18 which fits the special fiber connector purchased from Holtec. The sensitivy is the greatest, 0.4 A/W, around 8-900 nm and is thus excellent for the wavelength of 820 nm of the laser.

3.5 Gradient-index lenses

The gradient-index lens is purchased from Melles-Griot (larger quantities are bought directly from the manufaturer and to a lesser price).

The lens has a pitch of 0.23 . That means that the fiber end has to be positioned 0.21 mm from one of the end surfaces to get a collimated beam from the lens. Its diameter after the lens is 1.8 mm and the length is 4.4 mm (6).

Without going into details a rough calculation gives an approximation of the divergence. The principle behind the calculation is shown in Figure 3.2.

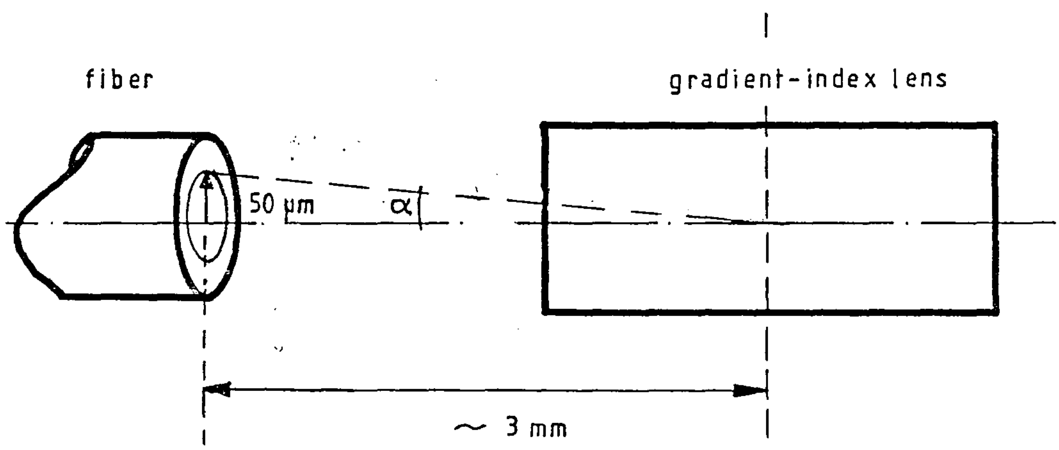


Fig. 3.2 Calculation of the divergence

The figure gives

$$\alpha = 50/3000 \text{ rad} = 17 \text{ mrad}$$

The diameter of the beam then becomes 3 mm over a distance of 100 mm (the legth of the probe). In tests the diameter was measured to 4-5 mm over the same distance and when viewed through an IR-camera.

The conclusion from this, which was confirmed by experiments, is that the losses when one collects the light whith another gradient-index lens after the Pockels cell are great. More than 75 % doesn't strike the lens. A way to improve on this is to make the probe shorter and to choose a fiber whith a smaller core radius.

3.6 Lenses

There is a need for two conventional lenses to focus the light onto the ends of the fibers (see Secs. 4.2-3). The choice of lenses is crucial because the spotsize in focus is dependent upon the type of the lens. And it is of course self evident that this spotsize should be smaller than the core of the fiber.

The spotsize in focus is related to 1) the diffraction of the light in the lens and 2) the aberration of the lens (5)

Diffraction $\theta_d = 1.22\lambda/D$ (Eq. 3.6)

Abberation $\theta_a = 0.5K(n)(D/f)^3$ (Eq. 3.7)

where
- θ is the angle error
- λ the wavelength of the light
- D the diameter of the light that passes the lens
- f the focal length of the lens
- $K(n)$ a function depending on the shape of the lens
- n the relative refractive index of the lens

At the Dep of Physics suitable lenses were available. They are positive and symmetric. When focusing parallel light with this type of lens K(n) is (5)

$$K(n)=(n^2-n-1/4+1/2n)/32(n-1)^2 \quad \text{(Eq. 3.8)}$$

A value n=1.5 yields K(n)=0.104 and if we make the approximation that the total angle error θ is just the sum of diffraction and abberation

$$\theta = \theta_d + \theta_a$$

then at λ=820 nm

$$\theta = 0.0521(D/f)^3 + 1.0\ 10^{-6}/D$$

and thus the spotradius r in focus becomes

$$r = \theta f = 0.0521D^3/f^2 + 1.0\ 10^{-6}f/D$$

From this it is possible to make a short table of the spot radius for different values of D and f. In the table below the value of r is given in µm.

	D=2mm	D=5mm
f= 8mm	10.5	-
f=12mm	8.9	47.6
f=33mm	16.9	12.6

The values of the focallength are those of the available lenses. From this we choose the 33 mm lens to the laser and the 12 mm lens to used in the probe. Either is not the optimum choise but they are good enough.

3.7 Polarizers

As polarizers two Glan-polarizers were chosen. They were made by B. Halle and have the dimensions 16x8x8 mm - smaller ones would have been preferable.

3.8 The λ/4-plate

The λ/4-plate was also bought from B. Halle. It is made of MICA and is specially made for the wavelength 820 nm.

The choice of λ/4-plate is also important. Because of the width of wavelength distribution in the laser one can not expect the retardation to be exactly λ/4 over the whole wavelength range. However, the experience at the Dep. of Physics was that this was not a great problem. It is ofcourse possible to calculate the retardation if one knows the thickness of the MICA and the birefringence around 820 nm. Ref. 6 , however, doesn't give the birefringance and as have been seen in the experiments it has not been a problem. A further discussion on this is found in the next section - 3.9.

A disadvantage with MICA retarders is that the transmission is not as good as for ones made of quartz. The later can also be made to give an exact path difference of λ/4 and not something like λ(1/4 + k) where k can be relatively large integer. Thus the effect discussed above could be held at a minimum and also calculated in advance because of quartz well tabulated birefringence (6). Plates of quartz are, however, two to four times more expensive than those made of MICA.

3.9 The Pockels cell

As there already is some experience at the Dep. of Physics with a Pockels cell from Gsänger there is no need to choose another type. The cell has a risetime of 0.6 ns and is made of KD^*P. The cell has piezo-electrical resonances between 0.1 to 1 MHz.

Gsänger manufactures several different types. There is one cell with the crystal immersed in a fluid with a transmission of 99% but as there are much greater losses throughout the system there is no need for this high transmission. The Pockels cell LM 8 has a transmission of 92 % and a more favourable price.

In this section a short calculation is also performed to check that the Pockels effect works when the choosen components are used.

As earlier stated in chapter 2

$$I=I_0\sin^2\left(\frac{\pi}{4}(\lambda) + \frac{\pi V}{2V(\lambda)_{\lambda/2}}\right) \qquad \text{(Eq. 3.9)}$$

$$V(\lambda)_{\lambda/2} = \lambda/2rn_0^{\;3} \qquad \text{(Eq.3.10)}$$

where

I	is the transmitted intensity
I_0	the intensity after the first polarizer
V	the applied voltage
$V(\lambda)_{\lambda/2}$	the half-wave voltage
λ	the wavelength of the light
r	electrooptical coefficient
n_0	refractive index of the crystal material

Eq. 3.10 is true for one wavelength as indicated by the dependance of wavelength. It is worth noting that although r and n_0 are also dependant of wavelength the variation is small compared to λ itself. Both can then be approximated as constants . Thus for light with a

wavelength distribution $g(\lambda)$ the relationship becomes

$$I=\int \sin^2(\frac{\pi}{4}(\lambda) + \frac{V}{V(\lambda)_{\lambda/2}})g(\lambda)d\lambda \qquad \text{(Eq.3.11)}$$

where

$$I_0=\int g(\lambda)d\lambda \qquad \text{(Eq.3.12)}$$

From this one conclude that one has to be careful. If $g(\lambda)$ is to wide the argument in the $\sin^2$ factor will vary over several periods and then the Pockels effect could not be detected. There is reason to investigate Eq. 3.11 further.

At first glance this expression seems impossible to handle. There are, however, possiblities to make some approximations and simplifications. First of all, one neglects the dependance of λ in the retardation (see Sec. 3.8). Then study

$$h(\lambda) = \frac{V}{V(\lambda)_{\lambda/2}} = \frac{V2rn_0^3}{\lambda} \qquad \text{(Eq.3.13)}$$

taking the logaritmic differential yields

$$\frac{dh}{h} = -\frac{d\lambda}{\lambda} \qquad \text{(Eq.3.14)}$$

With the values $\Delta\lambda$=8nm (max), λ=820 nm this equation yields a relative variation of h of 1 %. Thus a one can approximate Eq.3.11 with a constant $\sin^2$ factor and then the integral reduces to Eq. 3.9.

Finally, without these simplifications, one sees that with the collimator-pen one cannot expect total transmission or total extinction when the voltage V applied over the Pockels cell is $V = \pm \frac{1}{4} V_{\lambda/2}$ because there is allways light of a slightly different wavelength that is not totally transmitted or extinguished. The fact that the light through the Pockels cell is divergent will also contribute to this effect. This phenomena is seen in Figure 6.4 in Sec. 6.3. Furthermore, $g(\lambda)$ of the collimator-pen is shown in figure 6.1 in Sec. 6.1.

3.9 Summary of used components

Component	Type	Supplier
Optical fiber	ASEA KABEL OC1	ASEA KABEL AB Box 42108 S-126 12 STOCKHOLM
Fiber conector	Holtec	Holtec Optronics AB Box 10010 S-750 10 UPPSALA
Laser	Philips N513CQL-A	Philips Komponenter AB S-115 84 STOCKHOLM
Pin-diode	Hamamatsu S-1188-03	LAMBDA electronics ab Grevegatan 39 S-114 53 STOCKHOLM
Pockels cell	Gsänger LM 8	Gsänger Opt. Komp. GMBH Robert Koch-Strasse la D-8033 Planegg-Steinkirchen BRD
Polarizer	B. Halle 280 PGT	B. Halle Nachfl. GmbH&Co. Hubertusstrasse 10-11 D-1000 Berlin 41 BRD
λ/4-plate	B. Halle RGZ 10	as above
Gradient-index lenses	Melles Griot 06 LGT 214	SAVEN AB Box 49 S-185 00 WAXHOLM
Lenses	E. Scientific	Edmund Scientific 101 E. Gloucester Pike Barrington, N.J. 08007 U.S.A.

CHAPTER 4 MECHANICAL ARRANGEMENT

The mechanical solutions are reviewed in this chapter. It concerns mainly how to mount the different optical components together.

4.1 The gradient-index lens assembly

A piece of plexiglass in which two grooves where cut was used to position and fix the fiber end and gradient-index lens in relation to each other (Fig. 4.1). The lens was first glued in one of the grooves. The fiber was prepared by gluing it in a thin syringe needle which then was grinded and polished at the end. The needle was then mounted in a XYZ-translator and positioned in the other groove. The laser was turned on and the spot of light after the lens was studied with an IR-camera on a screen. The spots position was adjusted and the spot size minimized with the translator. Finally glue was applied to the groove with the needle.

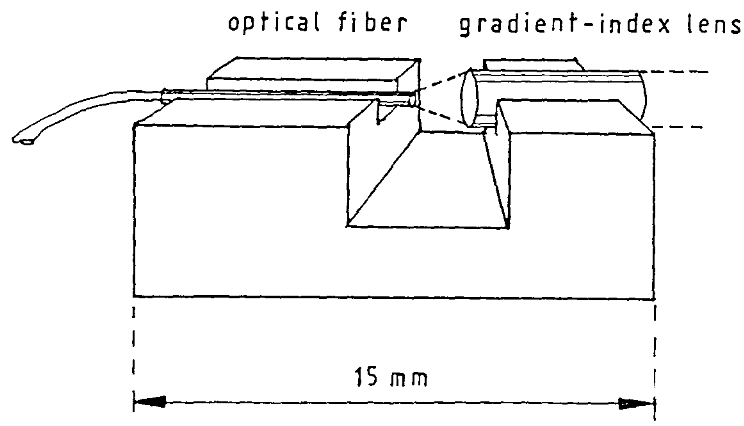


Fig. 4.1 The gradient-index lens module

Thus the gradient-index lens module was finished and the XYZ-translator was removed.

4.2 The laser assembly

One of the most important problems that had to be solved was how to feed the light from the collimator-pen into the fiber. Several different methods were considered, but finally the safest one was selected. The fiber end was mounted in a XYZ-translator. Then it was possible to position the end in the focus of the lens in front of the collimator-pen.

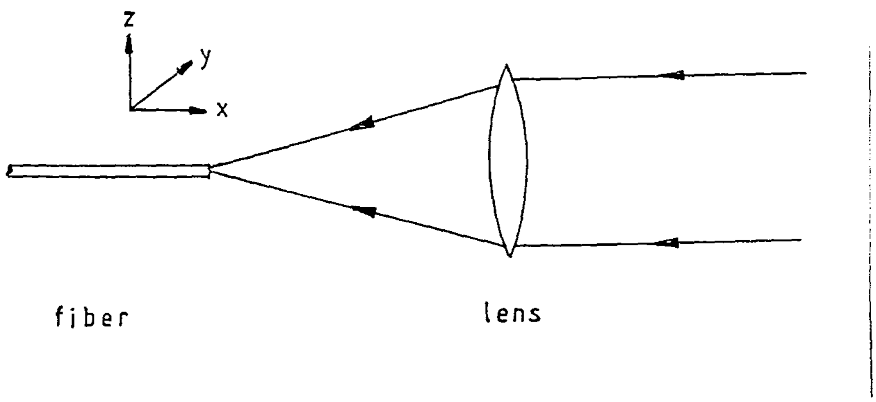


Fig.4.2 A scematic of the laser arrangement

This solution made it possible to make changes as the work progessed - to change lens and to change fiber. It is worth mentioning that there is often little need to adjust the translator and that the setup is rather robust.

Two other possible arrangements are also worth to mention. One method that was considered was to reduce the diameter of the laser beam with two lenses and then feed the laserlight into a gradient-index lens module built with the metod described above (Fig. 4.3). A rough prototype was built, but it was found that the light transmission was very sensitive to the position of the gradient-index lens. It was thus necessary to mount the gradient-index lens on a positioner. Furthermore the total transmission was never better than 50% compared to the 75% reached with the method finally selected. The conclusion is that the method isn't as simple and robust as originally hoped. Maybe further tests can improve this.

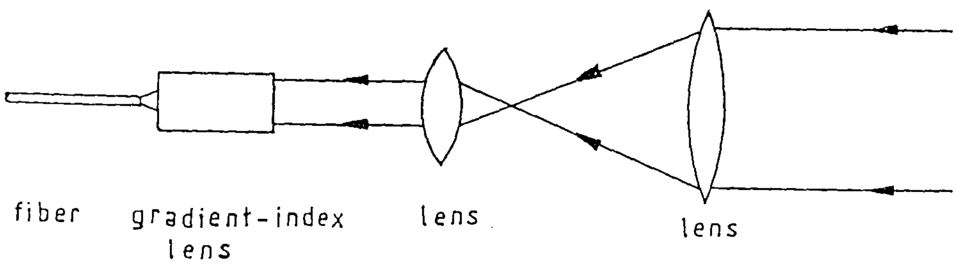


Fig. 4.3 A possible arrangement of the laser

The second method considered was to use the same technique as with the gradient-index lens: position the fiber end in the focus, glue and then remove the translator. It is definetely the most simple and elegant method and the one that should be used if one decides to use a collimator-pen in any futher development of the system. The method was never tried because it requiers that the laser, lens and fiber are firmly fixed together - probably glued. There would the be few margins of error and little possibility to alter anything afterwards. To try it would require at least a couple of collimatorpens.

4.3 The probe assembly

Originally it was hoped that it would be possible to couple the light through the probe with two gradient-index lenses. But as work and calculations progressed (see Sec. 3.5) it became obvious that another solution had to be tried. The reason for this was that the length of the probe would be approximately 100 mm, and that the divergence makes the spot too wide over that distance to be collected with a gradient-index lens to the output fiber.

The components in the probe are mounted seperately on pieces of plexiglass which then are screwed tight to a metall plate. It is possible to adjust the components 1 mm sideways before tightening the screws. The Pockels cell can be rotated around its optical axis before it is fixed. The λ/4-plate is mounted directly on the the Pockels cell.

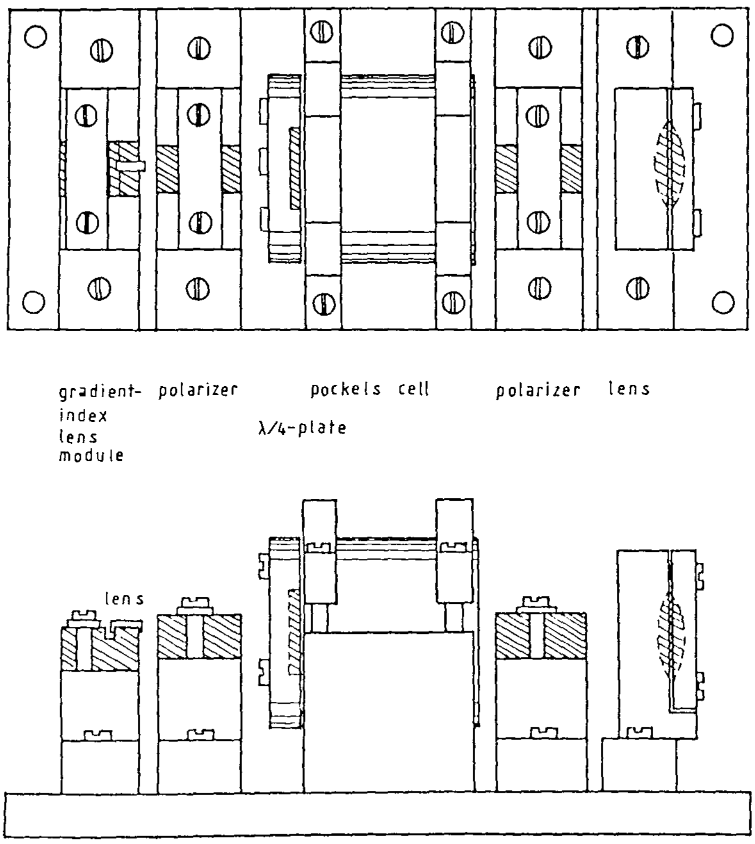


Fig. 4.4 The mounting of the optical components in the probe

After the lens that collects the transmitted light a XYZ-translator with a fiberend is mounted. The setup gives several opportunities to adjust the components in relation to each other.

4.4 Adjustments on probe and laser

To maximize the power that enters the fiberloop one monitors the power transmitted into the fiber with a photodiode - most easily done at the end of a fiber connected to the laser output on the laser/detector box - and then adjusts the XYZ-translator in the same box.

WARNING! Don't touch the electrical circuits in the box.

For most photodiodes the intensity is to high, but this can be avoided by letting only a part of the light strike the diode.

The same procedure is used when one adjusts the translator in the probe.

The adjustment of the optical components is quite straightforward. First of all the optical axes of the Pockells cell and $\lambda/4$-plate was found by putting them between two crossed polarizers. With the $\lambda/4$-plate the transmission was optimized by rotating the plate. The axes were now in 45 degrees with the direction of polarization. With the Pockels cell one applied an voltage and noted the change in transmission. Then this change was minimized by rotating the cell. Now the axes of the Pockels cell was parallell with the direction of polarization. Finally the cell and plate was mounted together with the axes overlapping.

The optical components was then was mounted according to Sec. 4.3. The polarizers was crossed and aligned by eyesight. The light through the setup was viewed with an IR-camera. When one optical-axis of the Pockels cell $\lambda/4$-plate module is parallel to the axis of polarization one sees a cross in the divergent light. The lightspot was centered around this cross by adjusting the gradient-index module. Then the Pockels cell module was rotated 45 degrees. Finally an DC-voltage was applied and the transmission was measured and plotted. The result is presented in Sec. 6.3.

CHAPTER 5 THE ELECTRICAL SYSTEM

5.1 The total electrical system

The electrical system consists of three parts: power supply, control circuits for the laser and finally amplifiers for the pin-diode. How these parts are connected are shown in the figure below.

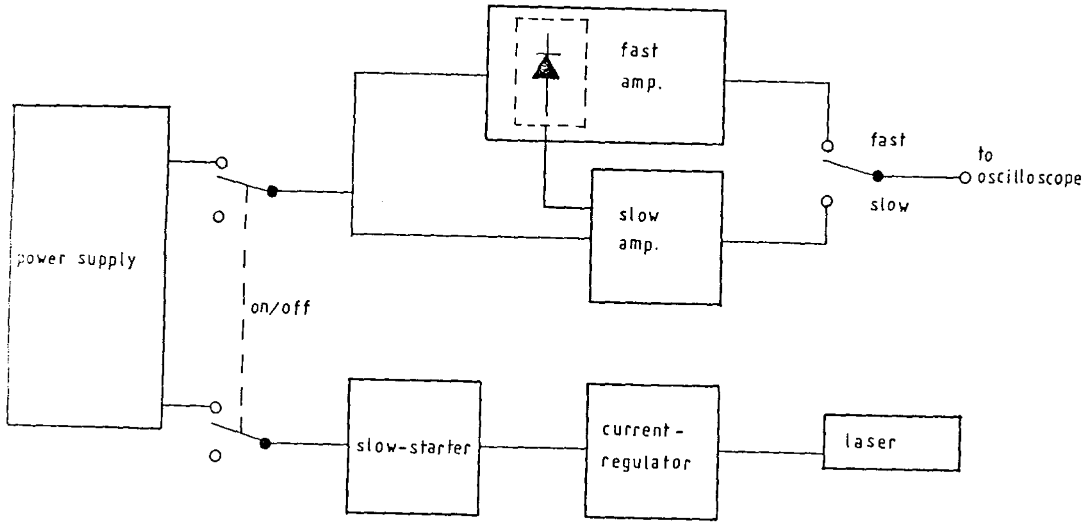


Fig. 5.1 The total electrical system.

5.2 Power supply

The diode laser require a negative voltage. Therefore the power supply gives a voltage of -15 V. The maximum current is 0.8 A.

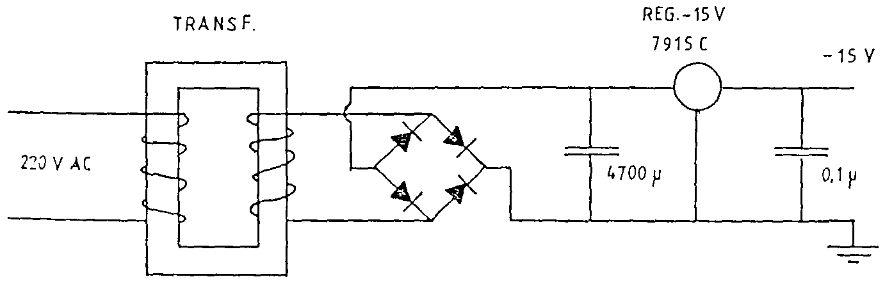


Fig. 5.2 Power supply.

5.3 Circuits for the laser

A great deal of effort has been put on these two circuits: the slow-starter (Fig 5.2) and the current regulator (Fig 5.3).

The slow-starter is a circuit, that when turned on, smoothly increases the output voltage to -15V over approximately 2 seconds. The purpose of this cicuit is to avoid current transients when the system is turned on. Such transients can seriously harm the laser. The circuit also acts as LP filter during operation.

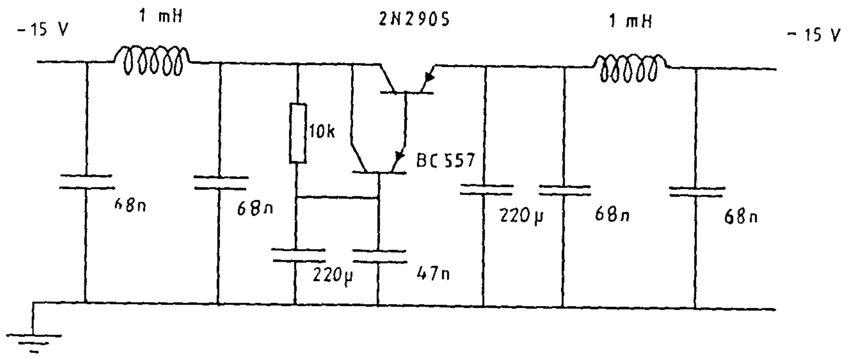


Fig. 5.3 The slow-starter.

The current-regulator is connected to the output of the slow-starter.

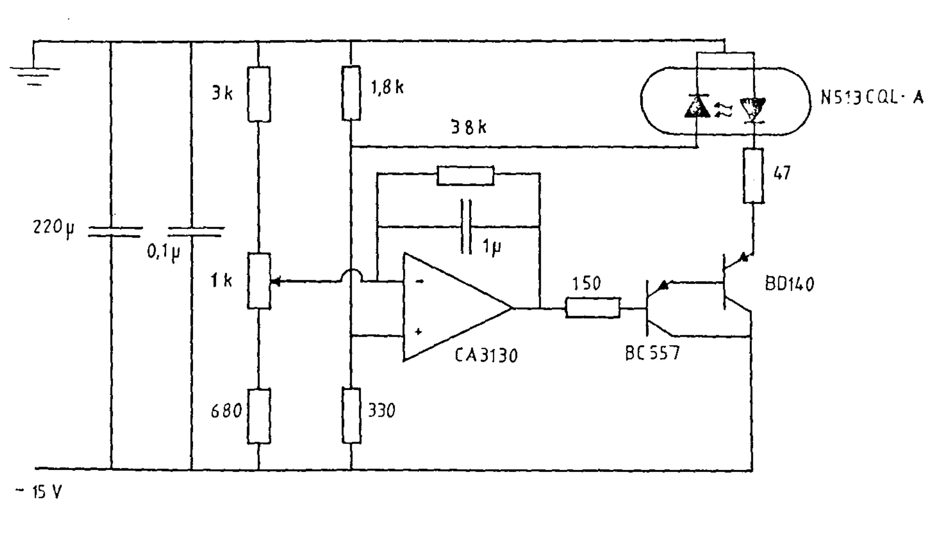


Fig. 5.4 The current-regulater

The current-regulator uses the lasers internal photodiode as feedback to the OP that drives it. The choice of transistors that is regulated by the OP is important. At voltages less than -6 V the output from the OP is 0 V. With NPN-transistors the circuit would during this period drive maximum current through the laser because the the voltage over the base and emitter would follow the voltage from the slow-starter until the OP started to regulate. This is avoided by using PNP-transistors which opens only when the OP starts working. The feedback from the output of the OP to its input made improvements on the fluctuations in the driving current. With this feedback the laser intensity output is fluctuating less than 1%. Finally a resistor is placed near the laser and will limmit the current if the circuit would fail. There is no point in using fuses because they are to slow.

Before the laser was connected to these circuits they were assembled and tested with two light diodes and a phototransistor from Texas Instruments. How the laser was simulated is shown in fig. 5.5.

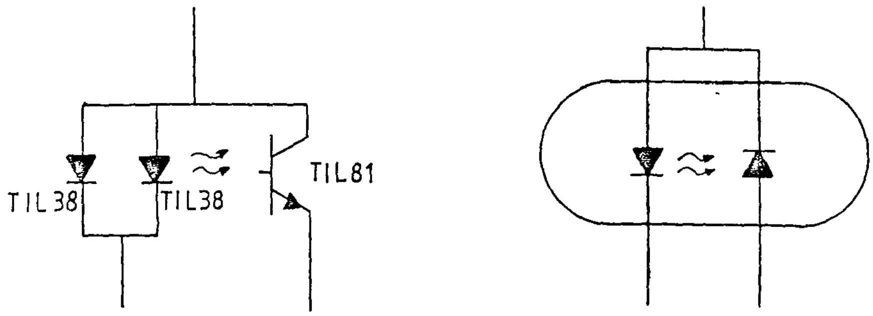


Fig. 5.5 The simulation of the laser

The components were adjusted in relation to each other giving roughly the same characteristics of the laser. The current through the diodes was monitored on a oscilloscope.

5.4 Amplifier circuits

The primary function of the amplifier circuits are to amplify very fast pulses, but one also has to be able to decide in measurements when the system is working in the linear region of the Pockels cell. The output voltage from the amplifier depends on how much light that is transmitted through the system and this can vary slightly between setups. Thus it necessary to have a DC amplifier that monitors $I_0/2$ (see fig 2.5), as well as a very fast amplifier for the fast pulses. This is however difficult (but not impossible) to implement in just one amplifier.

Thus it was decided to build two amplifiers - one slow for frequencies ranging from 0 to 10 kHz, and one faster than 1 MHz. This had the advantage that the slow amplifier could be built with a simple OP. Furthermore, the fast amplifier became simpler. There is only need for one pin-diode and it is located on the board for the fast amplifier but is then also connected to the slow amplifier.

The slow amplifier is based on a LM324N and uses two out of the four available OPs. As seen in the figure 5.6 the first OP is a follower with a high input impedance and thus the circuit acts as a low load on the pin-diode on the fast amplifier board. The following OP is the amplifier and due to the feedback the amplification is 100 times.

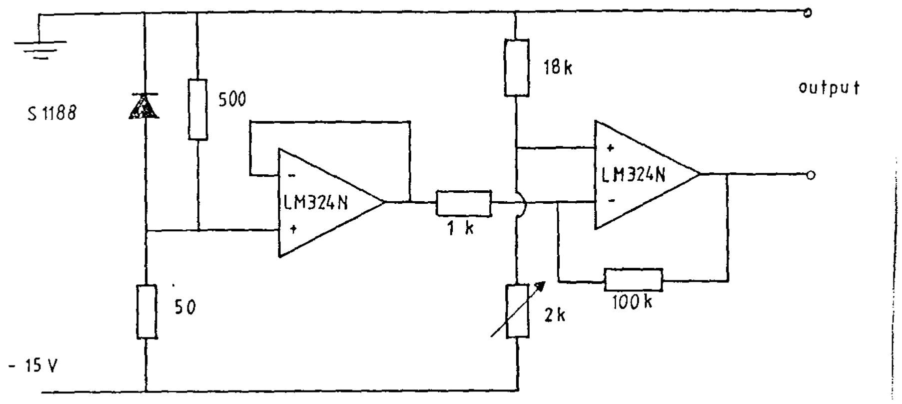


Fig. 5.6 The slow amplifier

The fast amplifier consists of four transistors of the type 2N5179 with a bandwidth of 1.2 GHz. The three first ones are the amplifiers while the last on gives the circuit a out-impedance of 50 Ω. The resistors at the collectors and emitters on the three first ones are choosen as low was possible (to much current gives to much heat in the transisors) to make the amplifier as fast as possible.

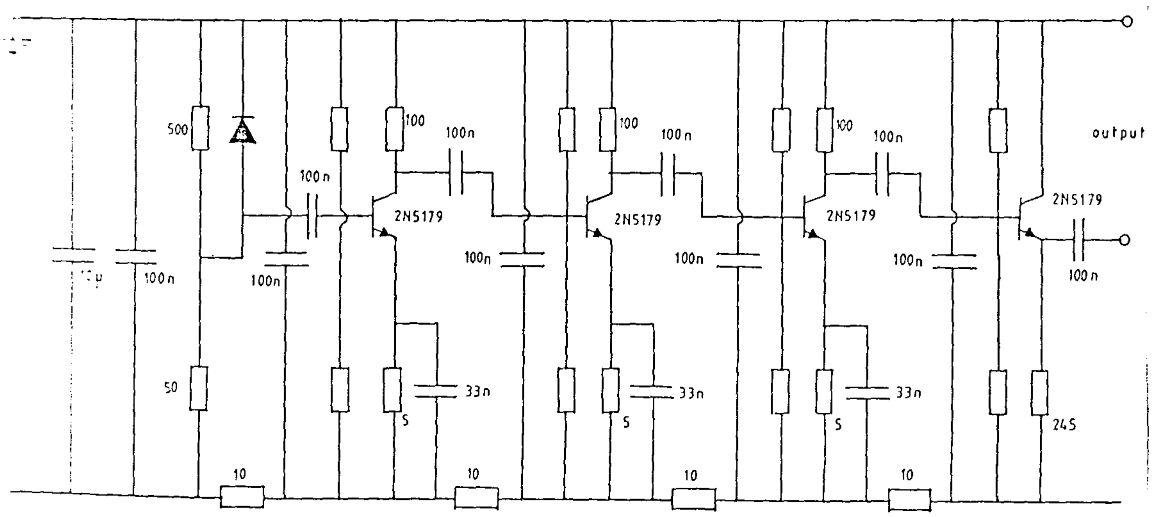


Fig. 5.7 The fast amplifier

Tests of the fast amplifier revealed that it was not as fast as hoped (see sec. 6.2). To show the measurement systems full potential a simple box with a diode was built consisting of a pin-diode with an applied voltage from batteries and connected directly to a Ortec, AN302/N, amplifier whith a coaxial cable. This amplifier was much faster and was used in many of the later measurements.

CHAPTER 6 SOME CHARACTERISTICS OF THE SYSTEM

In this chapter the results of measurements and tests on the components in the system are presented. The performance of the the total system under working conditions is deferred to the next chapter.

6.1 The laser

To verify and check the wavelength distribution of the light from the laser the light was analysed in a spectrograph.

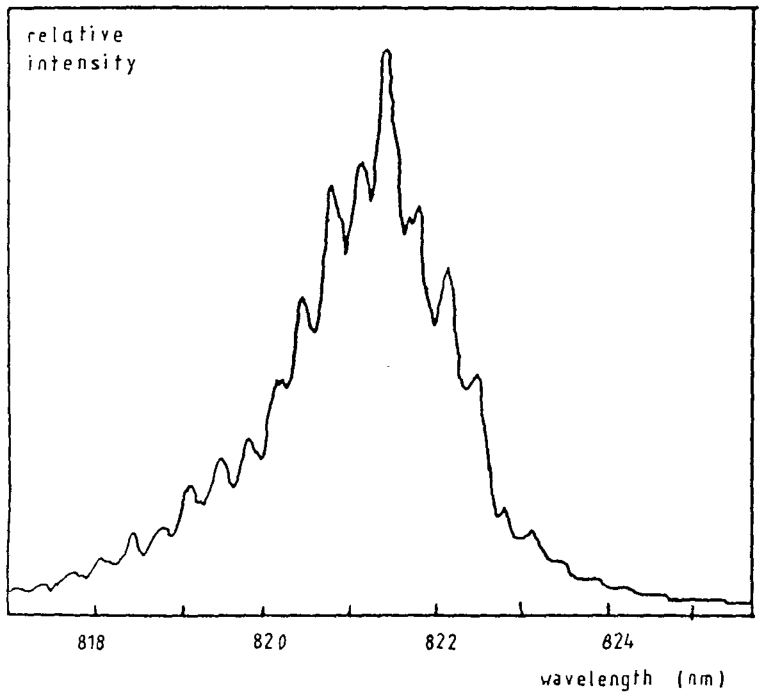
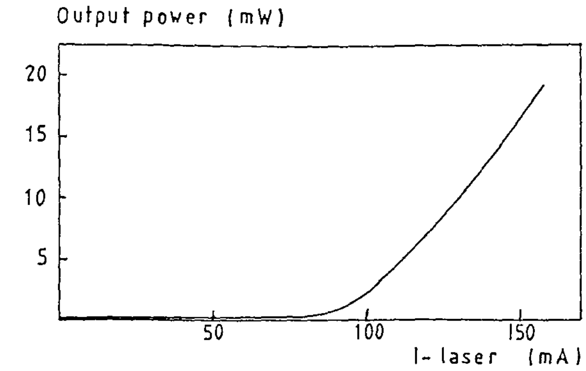


Fig. 6.1 The wavelength distributuion of the laser

It is seen that the width of the light is roughly 2 nm which is better than the value stated by the manufacturer - 8 nm.

The electrical characteristics of the laser are taken from the test-sheet that accompanied the laser when it was bought.



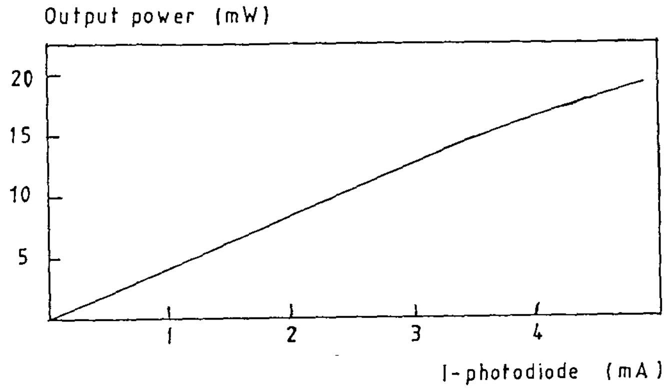


Fig. 6.2 The electrical characteristics of the laser

From these diagrams it was possible to make a dummy-laser that simulated its characteristics when the electrical circuits were tested (see Sec. 5.2).

6.2 The amplifier

To test the impulse response of the detector it was tested with a very fast (ps) light puls from a pico-second laser system.

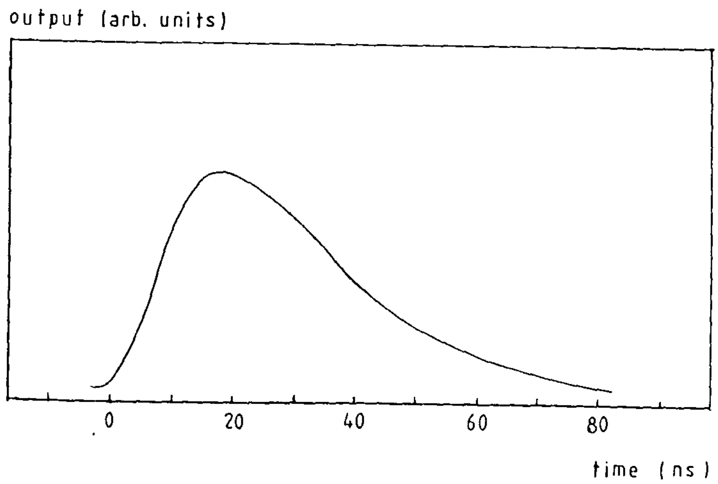


Fig. 6.3 The impulse response of the fast amplifier

Furthermore, the two amplifiers were calibrated with each other. First the slow amplifier was tested when 220 V , 50 Hz was applied directly to the Pockels cell. Then the fast amplifier was tested when a fast puls (200ns duration, rise and fall time around 100ns) was applied direcly to the Pockels cell. The pulse was simultaneously measured with a high voltage probe. From these measuremens it was calculated that the ratio between the slow and fast amplification is 1.82.

This ratio makes it possible to calibrate the total setup - primarily the capacitve coupling - with a slow, i.e. 50 Hz, HV signal that is not nececary in the same range as the transients one wishes to measure. The measured voltage of the transient is just

$$V_t = V_s \frac{V_{ot}}{V_{os}} 1.82$$

were

V_t is the transient voltage

V_s the slow calibration voltage

V_{ot} the measurement on the osciloscope of the transient

V_{os} The measurement on the oscilloscope of the calibration voltage

As have been mentioned earlier a faster Ortec amplifier was also used. The impulse response measured with the same method as above is shown in the figure below.

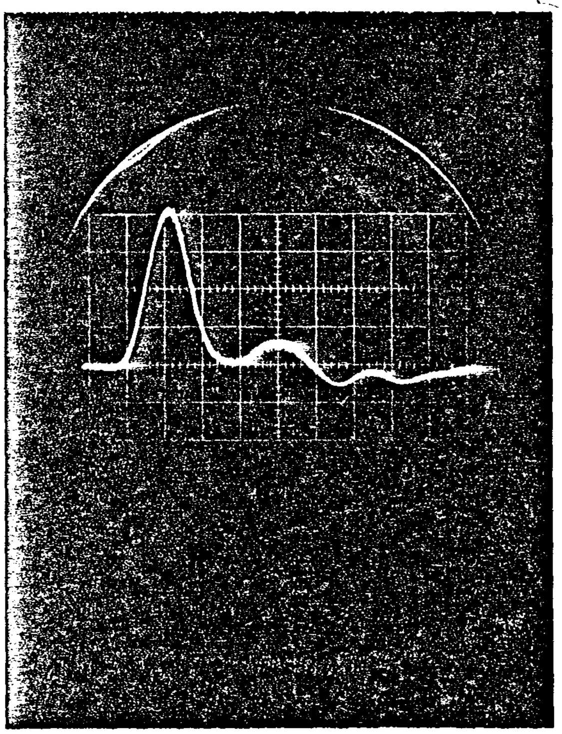


Fig. 6.4 The impulse response of the Ortec amplifier (2ns/div)

The rise and fall time are both approximately 2 ns.

6.3 The Pockels cell

A DC voltage was applied directly to the Pockels cell and the transmission of the light from the diode laser was measured.

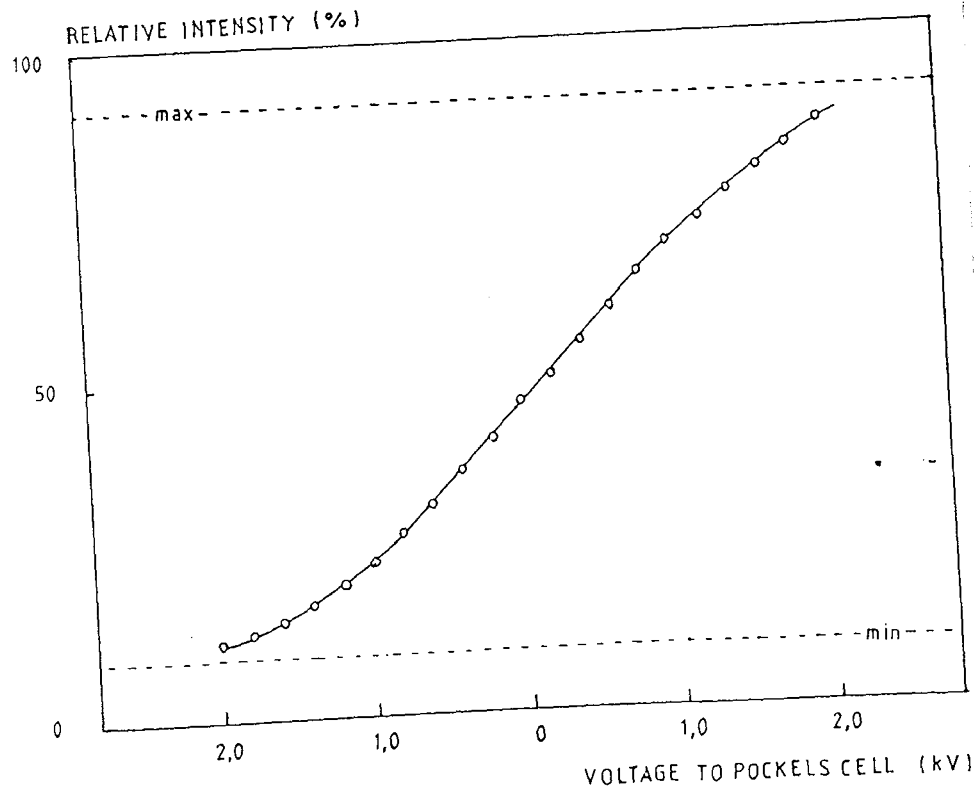


Fig. 6.5 The characteristics of the Pockels cell with the diode-laser

From this it is seen that the Pockels effect works nicely even if there is some width in wavelenght of the laser light. For a more thorough discussion see sec. 3.9.

The Pockels cell was also tested with pulses coupled direcly to it. The pulses was simultaneously measured with a high voltage probe. The fast detector was used.

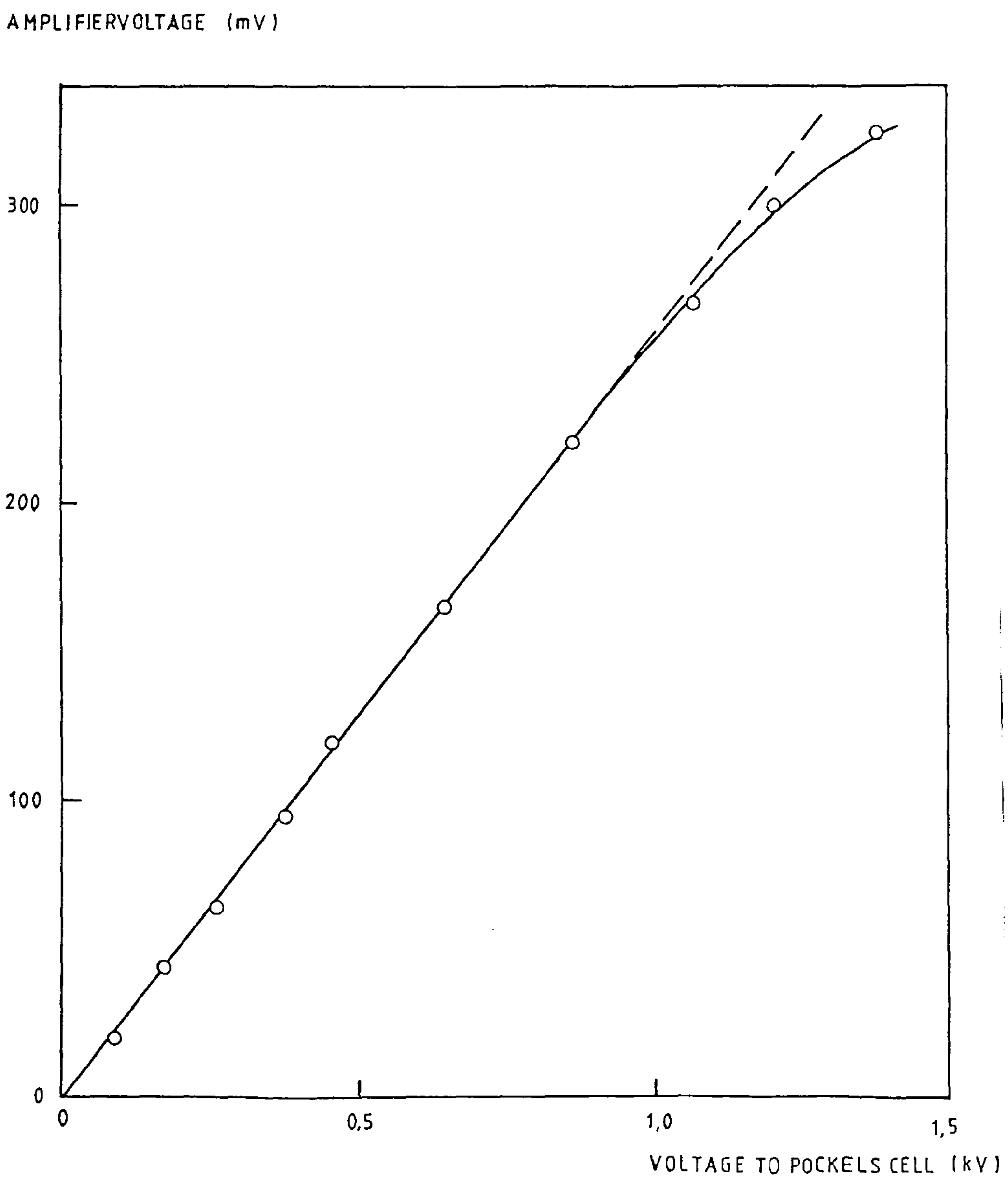


Fig. 6.6 The characteristics of the Pockels cell whith fast (200 ns long) pulses

This result should not be seen as a calibration of the fast amplifier. The output voltage depends on the transmitted light which can vary between setups. It is finally concluded that the cell has an approximatly linear region up to a voltage of 0.9 kV.

6.4 Estimation of measurement precision

In the present system it is the fast amplifier that introduces the significant errors in measurements. It has an noise of about 5 mV and this compared to a signal of say 100 mV gives an error of 5 %. This error also depends on how well one has adjusted the system - how much light that is transmitted.

Another source of error is the callibration of the setup (see Sec. 6.2). The error depends on the calibration voltage - the lower calibration voltage the greater error.

CHAPTER 7 TESTS AND MEASUREMENTS AT UPPSALA

During the period of May 5 to 7 1986 the complete system was tested and used at Institute for High Voltage Research at Uppsala.

7.1 Tests

A coaxial system that generates 1 µs long high voltage square pulses was used (1). The pulses have a rise- and falltime of less than 5 ns. (The institute hasn't been able to measure it more precisely.) The pulses are generated in the following way: a 100 m long coaxial cable is charged by a known voltage; two electrodes are pneumatically neared each other; the cable discharges. The voltage of the puls is related to the voltage that charged the cable and is thus well known. The space surroundig the electrodes was first air but later filled whith SF_6. In the later case it was possible to reach voltages of 50 kV compared to 30 kV in air. The coaxial system was terminated with a water-resistor of 50 Ω. capacitanse in this resistor was roughly 0.5 nF and one could thus expect a risetime of roughly 5 ns. Later this resistor was changed to a faster but which only worked up to 5 kV. No improvement in risetme was however seen.

The capacitive coupling between the probe and water-resistor was two electrodes - one attached to the probe and one to the resistor. First we started with small electrodes but later we tried bigger and then got stronger coupling.

The laser/detector box was put in a screened room approximately 10 m away from the sourse. The signal was recorded on a 100 MHz storage oscilloscope.

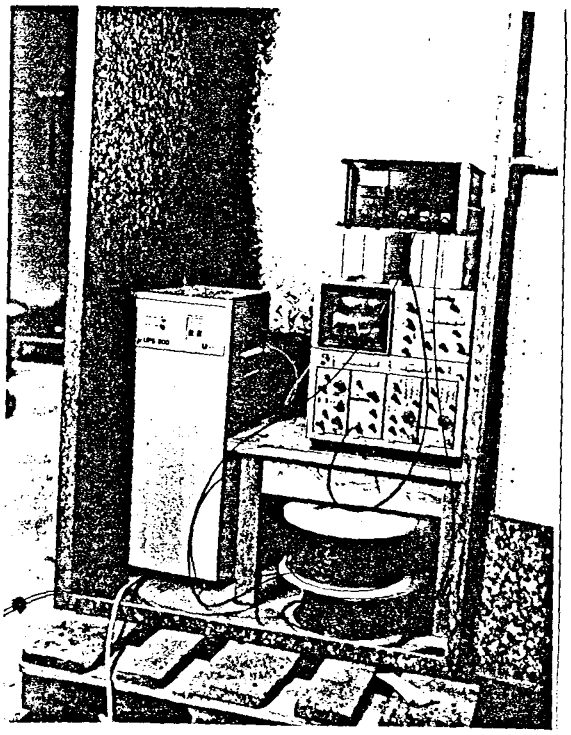


Fig. 7.1 The laser/detector box in the screened room with an oscilloscope and internal power supply

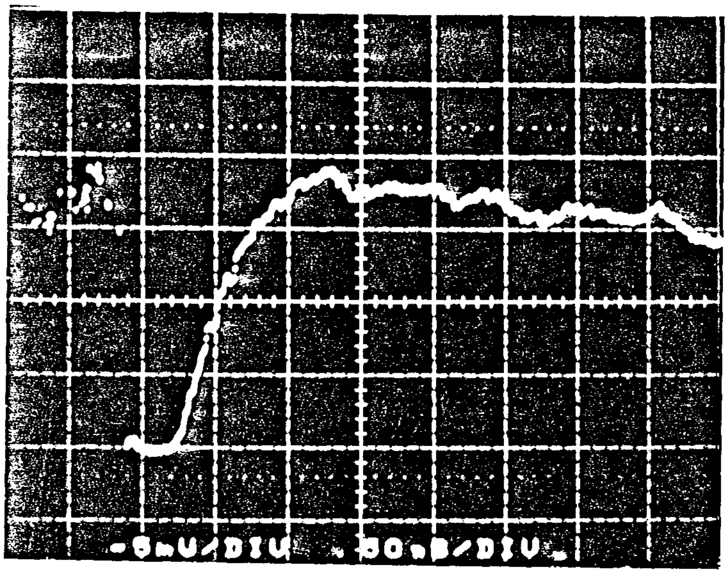


Fig. 7.4 Risetime with the same amplifier

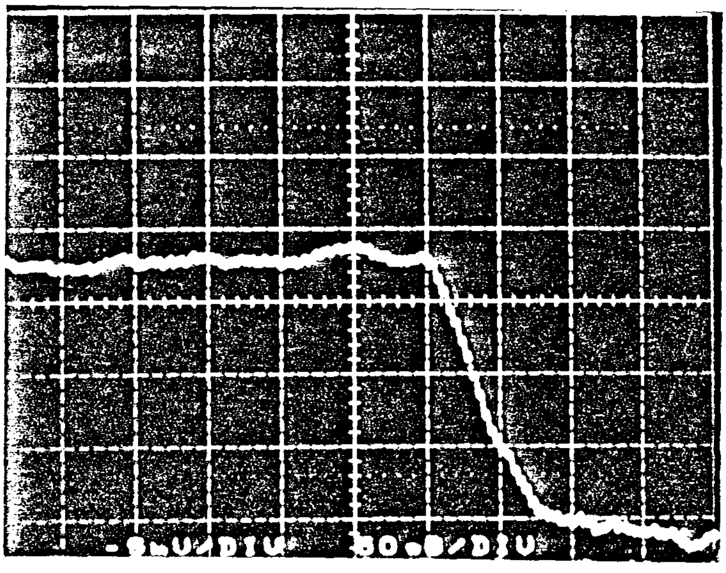


Fig. 7.5 Falltime with the same amplifier

From these figures it is seen that the rise and falltime is not better than 50 ns. It is also seen that the 1 µs long puls is not faithfully reproduced - it should be a flat-top pulse. This is due to the capasitors in the amplifier - they discharge. But this is also expected because the amplifier was built for transients faster than 1 µs.

After the conclusion of these tests the other detector based on the Ortec amplifier was used. To begin with the same set-up and voltages were used. The initial tests with this amplifier revealed that it was more sensitve to rf-noise than the one in the laser/detector box .This is most certainly due to the better box for the later. It was thus decided to use the optical fibers an put the detector in a screened room approximately 30 m away from the source. Much better results were obtained and one of the advantages of the system was thus shown, i.e. the suppresssion of rf-noise by increasing the distance between source and detector. The results are presented in Figures 7.6-8.

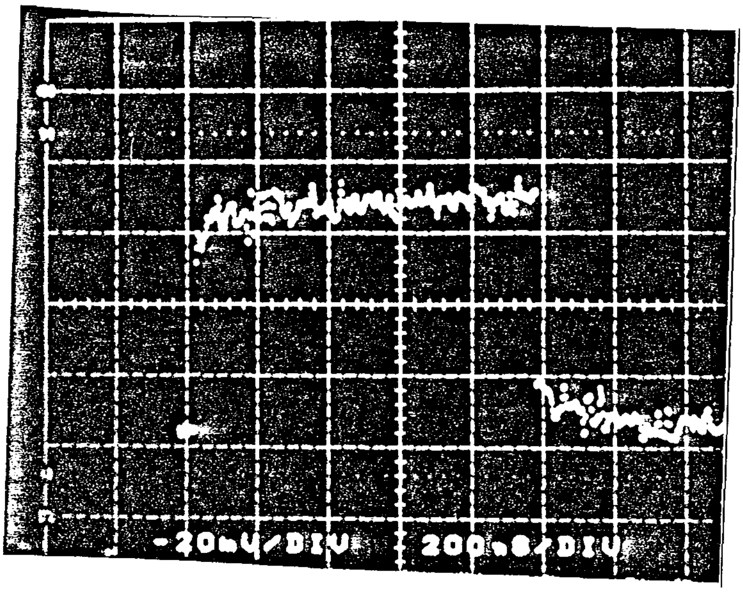


Fig. 7.6 The complete puls as seen by the Ortec amplfier

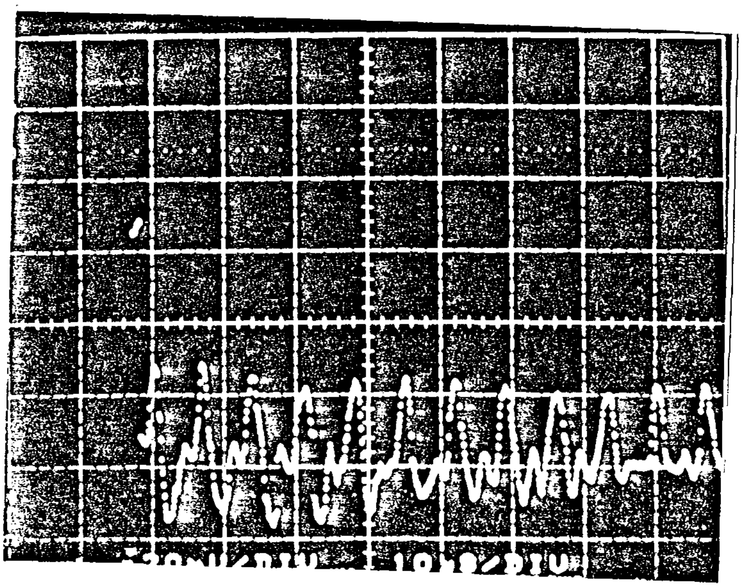


Fig. 7.7 The piezo-electrical oscillations in the pockels cell after the puls (10 µs/div)

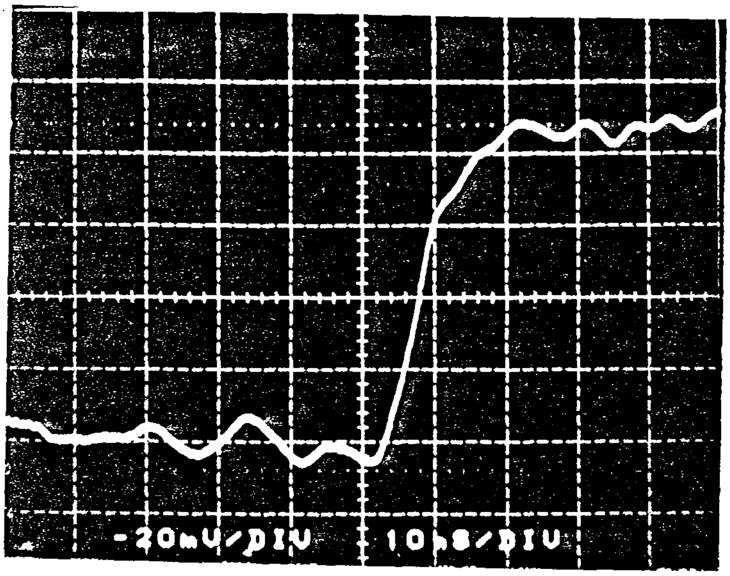


Fig. 7.8 Risetime as seen by the Ortec amplifier

To verify that the system worked for high voltages it was desided to use the SF_6 gas and voltages up to 50 kV. The rf-noise naturally increased and the voltage over the Pockels cell was held at the same level (in the linear range) as earlier. Thus the signal to noise level decresed. This is however no real problem because one can always increase the distance to the source and always improve the screening. The results are presented in Figures 7.9-10

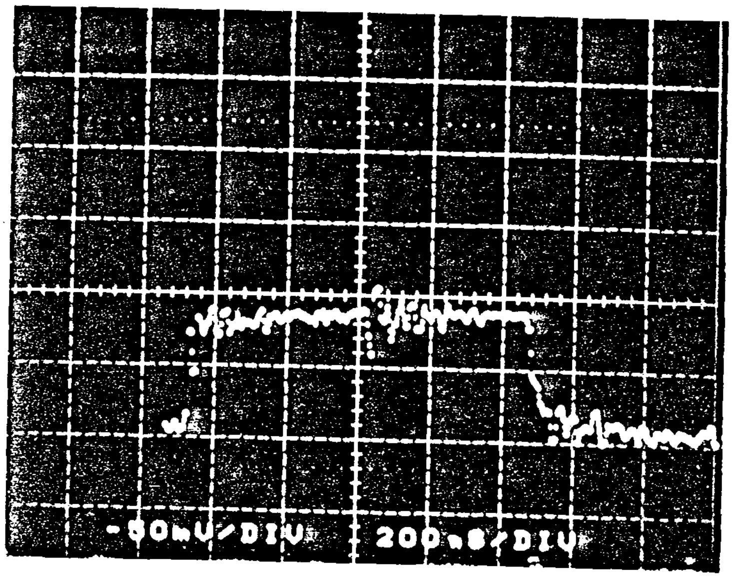


Fig. 7.9 The total puls, 50 kV, as seen with the Ortec amplifier

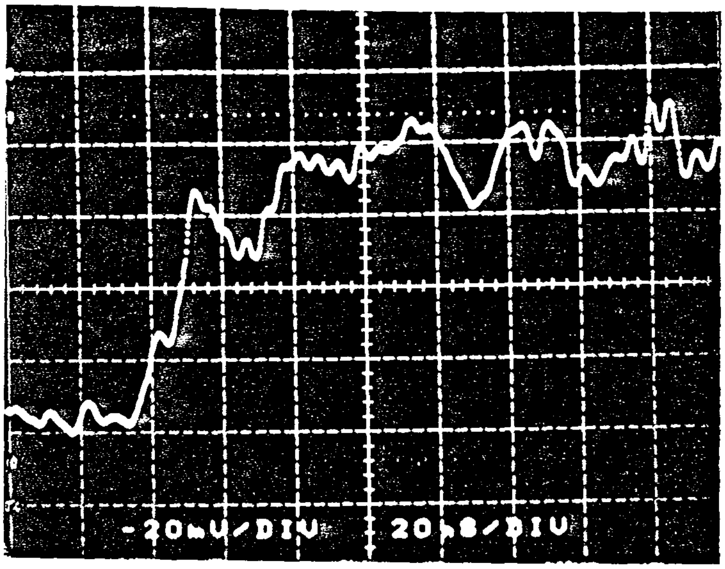


Fig. 7.10 Risetime with the same set-up

The risetime is about 10 ns but this is the risetime of the signal not the system.

7.2 Summary of results

With the fast amplifier the system has a risetime of about 50ns.

With the Ortec amplifier it is less than 10ns. In the measurements presented above the risetime was not limited by the measurement system. Further tests will be performed to check this. Theoretically, the risetime of the system should be 2 - 3 ns.

The system works for at least 50 kV and there is nothing, besides rf-noise, that implies that the voltage could not be substantially higher.

CHAPTER 8 CONCLUSIONS

As have been indicated throughout this paper there are many ways in which the system can be improved. The present system is the result of several modifications and not as elegant as it could be.

There is need of a better amplifier. A commercial one is the easiest and probably the best solution. A better amplifier might also make two seperate amplifiers unnecessary and also improve on the precision in measurements.

One other obvious modification is to discard the two XYZ-translators and thereby make the system more compact. It has been suggested in Secs. 3.3 and 4.2 how the translator at the laser could be made obsolete. Removing the translator from the probe could prove to be more difficult. A possibillity could be to glue the optical components directly onto each other. The probe would then also become much smaller and compact. And above all the system would become much more easy to use.

One should use a fiber with smaller core diameter (50 µm) because the bandwidth is greater and the divergence from the graded-index lens will be less. Instead of two separate fiber cables there is the possibillty to use a twofiber cable as described in Sec. 3.2, or one could also use just one cable. But the later would complicate the system and the losses in transmitted power would probably increase and thus make the system slower.

This paper has not dealt with the crystal material in the Pockels cell - a very complex subjet, but a field in which one can reap a rich harvest. As have been mentioned there is the problem with the piezo-electrical oscillations. With the selection of different crystals one could measure different frequency ranges up to the limit of the amplifiers.

But the most important conclusion is

IT WORKS !

HISTORY

At the end of october 1985 I started on this project and *Hans Hertz* became my supervisor. We made a visit at ASEA Research and Innovation in Västerås where the last details were outlined with *Birger Drugge*.

The rest of that year I spent trying to forsee the various problems I might encounter and selecting and order the components. On the fiberoptics I got advice from *Stig Borgström*, *Sven-Göran Petterson* and *Hans Hallstadius* all at the Department of Physics.

At the beginning of the new year I concentrated my efforts on the electronics. It was always fun to discuss with and learn from *Åke Bergquist* and *Bertil Hermansson* at the Department's electronics workshop. With great relief I was then able to succesfully run the diode laser - the only one I would have in several months - for the first time in the cold and dark days of Feburary 1986.

As the components started to arrive during the winter *John Bergin*, *Göran Werner* and *Rolf Olofsson* produced various parts of the mechanical construction in the workshop at the University.

With persistance and a fair share of luck I was able to recive good signals at first try in the beginning of April. After a visit by Birger Drugge at the end of the same month, I and later Hans Hertz set out for Uppsala.

At the Institute for High Voltage Research at Uppsala we made our final tests and measurements in this project. We recived skilled help from *Dragan Filipovic*, *Lars Liljestrand* and *Victor Scuka*. And besides the work we spent some nice and refreshing evenings of spring in Uppsala and Stockholm.

All mentioned above have my sincere thanks, but a special thanks goes to Hans Hertz and Birger Drugge who are the originators of this project.

As for the result it is a product of my skill and the time I spent on the project, but also of the economic limits and finally the need to get things finished and working on time.

This project was financed by ASEA Research.

REFERENCES

(1) Hebner Z. E. et al.,Optical methods of electrical measurement at high voltage levels, Proc. IEEE 65, 1524-1548, 1977

(2) Hertz H. M., Capacetively coupled KD^*P Pockels cell for high voltage pulse measurements, J. Phys. E. Sci. Instrum. 18, 522-525, 1985

(3) Yariv A. and Yeh P., Optical Waves in Crystals, John Wiley & Sons, 1984

(4) Cherin A. H., An Introduction to Optical Fibers, McGraw Hill, 1983

(5) Optics Guide 3, Melles Griot 1985

(6) Handbook of Optics, Ed. W. G. Driscoll, McGraw Hill, 1978

(7) Liljestrand L. and Scuka V., A 200 kV cable generator with nanoseconds risetime, UURIE 1985-86