Detection of light distribution in a package

Diploma work by Peter Lindskog

performed
during the spring 1994

at Tetra Pak Research & Development AB
in collaboration with
department of physics LTH

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Presentation of the problem

At Tetra Pak Research & Development AB a project is going on to sterilize packages by an ultraviolet lamp. In this project it is interesting to get as homogeneous radiation distribution all over the inside of a package as possible. Producing UV-lamps with new geometries is very expensive and handling with UV-radiation is unpleasant. As the reflectance for visible light impinging on the packaging material is almost the same as the reflectance for UV-radiation, the intensity distribution in the package also ought to be the same. The distribution might as well be measured using visible light.

The task of this diploma work was to build a model of the real arrangement and to measure the distribution. The geometry of the light source and its spatial distribution of radiation should look like these of the planned UV-lamp. The measuring method was free. The diploma work included choosing, buying, construction of and test of the equipment.

Choice of equipment

Light source

Demands

The light source in the model arrangement should have the same geometry as the ultraviolet lamp and its spatial distribution of radiation should be close to that of the UV-lamp. It should be relatively cheap and it should be continuous. The reflectance for the packaging material is approximately independent of wavelength in the ultraviolet and in the whole visible range, and hence the only restriction of wavelength of the lamp is that it should be in the visible range.

As the plasma of the ultraviolet lamp is a partially transparent volume emitter, the lamp throws somewhat more light at higher angles than a Lambertian source does, but the latter would work rather well as an approximation.

Frosted glass tubes

Frosted glass tubes were discussed. It is possible that a tube with suitable size and shape could be formed, light guided into it and the requirements of spatial distribution fulfilled. Another thinkable solution would be putting a kind of Christmas tree lighting into a glass tube. None of these methods were chosen.

Neon lamps with and without luminescent powder

In the branch of illuminated advertising devices there are companies, that make lamps on requests from customers, and a neon lamp with luminescent powder was ordered from such a company. The reason, why one with luminescent powder was bought, was the demand that the light source should be diffuse. However, nowadays the powder is moist when it is put into the glass tube and this means that powder is accumulated at the bottom of the tube before it becomes dry. Normally, when the lamp is used as a sign, this string of powder is put towards the wall, and nobody will see it. This accumulation drastically reduced the intensity of light from that side of the lamp, and the lamp could not be used as a model of the ultraviolet one.

One way to circumvent this problem is using an older method to put luminescent powder into neon lamps. In this method dry powder is used. The lifetime of the lamp will be much shorter and that is the main reason why this method is not used today. In these applications, where the lamp is held indoors and where the required lifetime is the time for some measurements, this should not cause any problems. However, such a lamp could not be produced in the wanted dimensions by the company, from which the first lamp was bought. Another company may be able to do it.

An observer, looking at a neon lamp without luminescent powder, feels that it sends out light with a somewhat higher intensity from the centre of the lamp than from points closer to the edge. Nevertheless such a lamp as a model of the ultraviolet one was considered to be good enough and in the experiments such lamps were used.

The purchase

Two identical neon lamps without luminescent powder were bought and the figure below shows their dimensions.

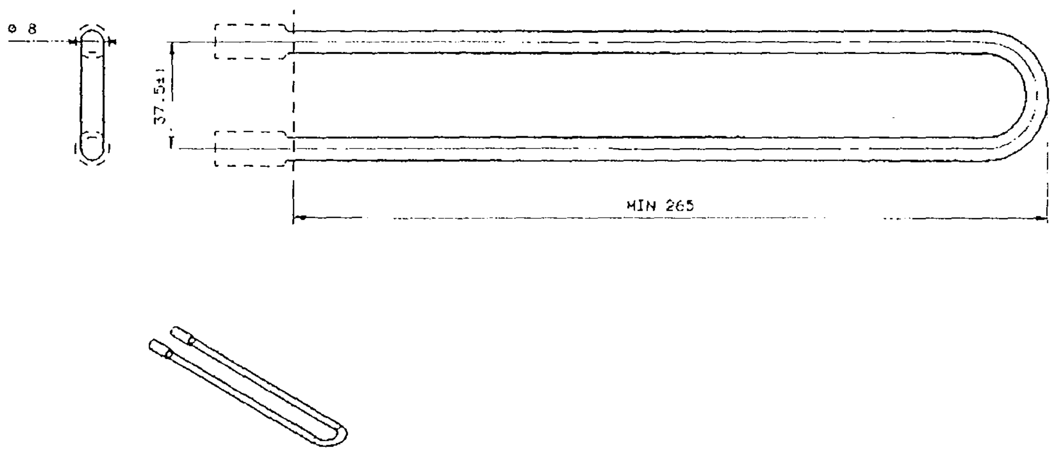


Figure 1. As a model of the ultraviolet lamp, a neon lamp shaped like this is used.

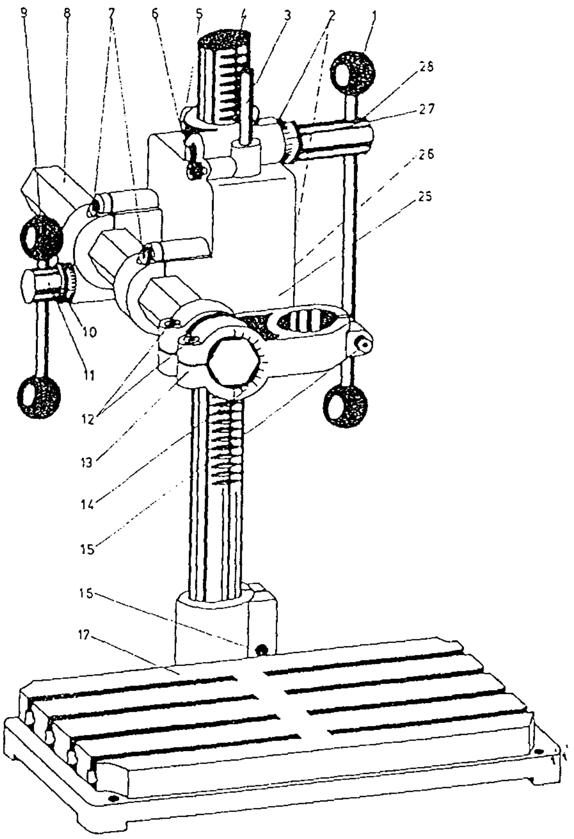
The left wider parts of the lamp contain the electrodes, and the rest of the lamp shines with a red colour.

To drive them a transformer is needed and one, whose output voltage is about 3 kV, was bought. That voltage can drive one lamp alone or two lamps connected in series.

Meter frame

The meter frame should position the lamp in a fix position relative to the package. This position should be possible to retrieve after dismantling and it should be adjustable in three dimensions. The lamp should also be rotary around an axis parallel to its branches.

A stand, actually intended for drilling and milling, was ordered and after some arrangements it fulfils all these requirements. On the base plate of the stand, No. 17 in figure 2, a cross table is mounted. On the cross table the lamp together with two blocks, see figure 3, are fastened. By the cross table the position of the lamp can be adjusted in an horizontal plane. By a bolt, through the little hole of the bigger block and through the hole of the smaller one, the blocks are fastened on the cross table and this means of attachment allow rotation around the bolt.



Legend

1 feed lever
2 eccentric with nut
3 depth stop
4 column
5 clamping bolt
6 lock bolt
7 clamping bolts
8 extension rail
9 feed lever
10 graduated ring
11 feed-rack pinion
12 clamping bolts
13 drill gun's holder
14 scale
15 clamping bolt
16 clamping bolt
17 base plate
25 housing
26 lock bolt
27 graduated ring
28 feed-rack pinion

Figure 2. A stand fixes the lamp relative to the package. The lamp is fastened on a cross table mounted on the base plate No. 17 and the carrier of the package on the extension rail No. 8.

The bigger block can keep one or two lamps. Its bigger holes are adequate to hold the wider part of the lamp's legs.

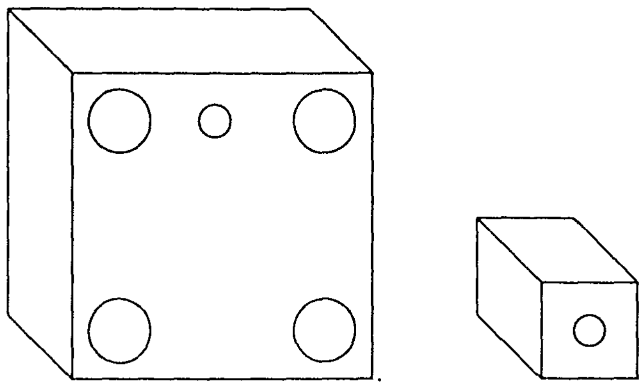


Figure 3. The two branches of the lamp are stuck into two of the bigger holes of the bigger block. A bolt through the smaller hole of the bigger block and through the hole of the smaller block fastens the lamp on the cross table.

The drill gun's holder of the stand, No. 13 in figure 2, is removed, and a carrier of a package is by a clamp fastened directly on the extension rail, No. 8 in the same figure. One carrier has been made for each type of package, on which measurements have been performed. They are just a piece of plexiglass with a hole adequate to hold the package, which is fastened by tape.

The package together with the whole housing, No. 25 in figure 2, can with the feed lever, No. 1 in the same picture, be moved along a vertical axis.

Detection system

Demands

The detection system should give the relative intensity distribution all over the inside of a package from the neon lamp. Since some areas of the inside of the package mainly receive light impinging almost perpendicularly on the surface and other areas get light from other angles of incidence, the detection system must not favour any direction of incidence.

Discussed courses of action

Before being acquainted with the measuring problem, some ideas about how to tackle it were discussed. The inside of the package could be covered with a photosensitive layer or photographic papers, exposed and then the blackening could be measured. Another proposal was making small holes in the package, inserting one optical fibre into each of them and comparing the intensities at the other ends of the fibre. Searches in data bases were also made to see whether anyone had worked with similar measuring problems.

Earlier solutions to similar measuring problems?

To get to know if anyone had any solution to a similar problem, that could be modified, searches were done in some data bases. Search words as *light, measurement, measuring, distribution, device, intensity, detection, surface* and *radiation* and data bases as *Inspec, Pira, E.I* and *Dialog* were used. Nothing really interesting was found. There were some articles about measurements of light distributions, but they dealt with measurements of angular light distribution around a light source and that measuring problem differs to much from this one.

Photosensitive layer

One potential method was covering the inside of the package with a photosensitive layer. This could then be exposed with the lamp and the intensity could be obtained by densitometry. This method should give an excellent spatial resolution and it should work even if the package includes plastic caps with complicated geometries.

However, to be able to make densitometric measuring, the layer must be absolutely homogenous. It is possible to create such layers on plates, because plates can be held horizontally and then the law of gravitation smoothes the layer. Nevertheless after having consulted researchers with experience in nuclear emulsions it seems to be no idea trying to cover the inside of a package with a photosensitive layer, at least not with gelatines of silver halides.

Photographic paper or film

One idea was pasting photographic papers or films on the packaging material or even producing a package made of photographic paper, expose it and develop it. It would not be possible to cover the whole inside of a package if the package has a plastic cap with a complex shape, but where useful it would give a splendid spatial resolution.

The reflectance of the paper or film should not differ to much from the reflectance of the packaging material. As a result of that, photographic films could not be used.

In these applications the photographic paper would be placed only one or two centimetres from a big lamp and not to overexpose it a very short exposure time would be needed. In order to estimate how short this had to be, the illumination was measured by a luxmeter at relevant distance from the lamp, and it was found to be about 3000 lux. *Appendix A* shows diagrams, that are received from a company of photographic papers and that show the blackening of their black-and-white papers versus the logarithm of the exposure. The least sensitive of these papers needs an exposure of about 25 luxseconds to reach half of its maximum blackening level, and this means the exposure time would need to be in the order of 1/100 of a second.

The transformer of the lamp is driven by a voltage, whose period is 1/50 of a second. This transformer could be connected to a timer, and short controlled exposures could be accomplished, but that would be hard when the required exposure time is shorter than the period of the supply voltage. There exists equipment that can trig on a certain part of the voltage cycle, but they are expensive.

It was checked whether the intensity of the lamp is lowered if the voltage over it is reduced and it turned out that there is no big difference. Perhaps the lamp could just be covered with a homogeneous layer of paint. No attempts were made.

On inquiries about photographic papers with a substantially lower sensitivity than normal photographic papers, representatives from three of the leading companies of photographic papers all answered that they did not have. Obviously there is no commercial interest in such papers.

The ignition process of the neon lamp is very short, and would not cause any problem even if the exposure time would be as short as 1/100 of a second.

Optical fibres or light guides

Small holes could be made in the package, one end of an optical fibre or a light guide could be put into each of them and there could be a detector in the other end. This method should give a worse spatial resolution than the methods with photographic papers or photosensitive layers, but the dynamics of the intensity estimation would probably be better.

Each fibre would have to be terminated with something that eliminates its acceptance cone, that is the cone within which light must impinge to be collected into the fibre. This fibre termination should also achieve that the measuring surface is plane and that it can be located to the same position as the spot, on which the sterilization effect from the UV-lamp is going to be estimated. It should also accomplish that the measuring surface has the same orientation as the spot on the package. The fibre termination should collect a light flow proportional to the cosine of the incidence angle, since the projected area of a plane surface varies in that way.

At the other end of the fibre there should be a detector whose output signal is linearly related to the incoming light. There should also be an arrangement that compares the signals from the different fibres and clearly presents the result.

This method to register the intensity distribution was chosen.

Summary about the choice of equipment

Light source

As light source a neon lamp without luminescent powder was bought. The lack of powder implies that it does not really radiate as a Lambertian source, but it was considered to be good enough.

Meter frame

To be able to adjust the lamp relative to the package, a stand designed for drilling and milling was bought. The lamp is also rotary, since it is fastened by a bolt through two blocks on the cross table.

Detection system

To find out the best way to measure the intensity distribution, data bases were utilized but no solution to any similar problem was found. Probably it is not possible to cover the inside of a package with a photosensitive layer smoothly enough to be able to make densitometric measurements. Commercially available photographic papers are that sensitive to light that a well-controlled exposure cannot be made short enough.

It was chosen to use optical fibres that should be put into holes in the package. At the other ends of the fibres photodiodes should be placed, whose output signals would be compared and displayed on a screen. It turned later out that the main problem with this method is to achieve that the fibre termination collects light according to the expected cosine dependence, without suppressing large angles of incidence. The rest of the construction worked rather well.

Design

Fibre type

General aspects

There are some potential fibre types, that could be used to guide light from the package to a detector. The smaller light guiding area the fibre has, the better spatial resolution is possible, but a small light guiding area also implies difficulties in getting a well-controlled signal. The numerical aperture, defined as

$$NA = \sin\alpha ,$$

where α is half the angle of the acceptance cone of the fibre, indicates how well the fibre collects light, and it should in these applications be as big as possible. Transmittance spectrum, price and time of delivery should also be taken into account.

Different types of optical fibres

In the smallest fibres, *the single mode fibres,* as they are called, the diameter of the light guiding area is about five or ten μm. They are very expensive, and they only accept light from one angle. Such a well-defined position of measuring should not be needed.

The multimode fibres have a light guiding diameter in the range of 50 μm or bigger. They can be divided into *stepindex fibres* and *gradientindex fibres.* The former consist of a core with one index of refraction covered by a cladding with a lower index of refraction and the light remains in the core, as a result of total internal reflection in the interface.

In *the gradient index fibres* the index of refraction is gradually lowered from the centre, and this is necessary in transmission of signals. In the *stepindex fibre* rays traverse with different speeds along the fibre, if they have different angles between the direction of propagation and the symmetric line of the fibre.

The larger *multimode fibres* are normally called *light guides*, after their normal field of application.

There are also fibre bundles and they consist of a large number of fibres packed together and are mostly used for light guiding.

Optical fibres and fibre bundles are usually made of glass or quartz, and glass has a higher numerical aperture than quartz. Light guides can also be made of plastics or nylon. Besides there are light guides that are a liquid. All of these materials are suitable in the visible range.

Parameters that influence on the signal

The signal from a connected detector depends on some parameters; the intensity from the lamp, the light guiding area of the fibre, the numerical aperture, the surface structure of the fibre end, that is close to the lamp, and the sensitivity of the detector at appropriate wavelength. If it would be necessary to use a detector, where the end of the fibre cannot be placed quite close to the detector, then the size of the detector and the distance, between the end of the fibre and the detector, also would influence on the result.

The choice

Because of all these parameters the most simple way, to find out which fibre that is most suitable, should probably be by proceeding by trial and error. Measurements were made on some fibres, i.e. one end of the fibres was put close to a lamp, the other end was fastened close to a photoconductively connected photodiode and the signal-to-noise ratio was studied. The conclusion was that a plastic light guide with a core diameter of 1.0 mm and a very thin cladding worked well.

It is likely that fibre bundles or light guides made of other materials could have been used as well, but this was available in a proper size and it could be delivered relatively quickly. There also was a detector that was designed for fastening on this light guide.

Conclusions from the measurements about the chosen fibre type

The lack of a jacket of black nylon turned out to be a disadvantage. When choosing fibres the lack of a jacket were thought not to introduce losses, as total internal reflection, in the interface between core and cladding, should keep the light within the fibre. Stray light should not be caught into the fibre and light scattering in it should not cause problems. However it was found that light that enters the fibre close to the detector and whose direction of propagation is nearly towards the detector can remain within the fibre a distance long enough for the light to be registered by the detector. Its deflections in the interfaces are small.

Because of this a 15 cm long part of the fibre close to the detector had to be covered with a black tape.

Fixing the fibre end in the wanted direction relative to the package

The packages may have threads or other complicated geometries and the light collecting area should be placed, so that its orientation is close to the orientation of the studied spot on the package. This means that it must be possible to fix the light guide in a well-defined direction relative to the package.

To be able to do that, the end of the fibre was considered to need a termination made of a not to soft material. This shield should also prevent the end of the fibre from being damaged, when putting it into the hole of the package. It should not be too wide, since a big hole in the package makes adhering in a specified direction difficult.

Fibre optic connectors were studied, but their diameters are rather big. There are optical transmitters intended for reaching small nooks, but they are bendable. Diffusers, designed for spreading light on for example plants, exist but no diffuser with a diameter smaller than 16 mm were found.

The conclusion was that a tube with an inner diameter somewhat bigger than the cladding diameter of the light guide should work as cover. The simplest way of getting such tubes, was buying cannulae and stoning away the point.

At the experiments tape and tapemass were used to fasten the cannulae on the package and to fix the direction relative to it. The aim was always to attach the fibre perpendicular to the measured spot.

Collecting light

Demands

An optical fibre or a light guide with a polished end only accepts light impinging from directions within the acceptance cone. One of the conditions on the detection system was that it should not suppress any direction of incidence. The amount of light that is collected should be proportional to the cosine of the incidence's angle, as it holds for a plane surface that the projected area perpendicular to the ray varies in that way. The outermost part of the fibre termination should be plane. It should be possible to use one and the same fibre termination for measurements on spots at different locations, and everywhere have a moderate agreement between the shape of the measuring surface and the shape of the viewed spot.

Discussed alternatives and my choices

The problem to collect light was not easily solved and these constructions need to be further developed.

Some potential solutions to the problem were discussed. A sheet of ground glass could be glued in front of the fibre end, the fibre end itself could be ground frosted, a transparent substance mixed with reflecting or scattering shivers could be placed on the fibre end or holographic films could be used.

In the calibrations and in the measurements fibres with frosted ends were used, but the attempts to produce these fibre terminations without any dependence of incidence direction failed. The technique with reflecting particles is the most promising, but it needs to be developed for some weeks.

Some general comments on the technics of measurement

In all these fibre terminations the aim was that the direction of the ray when it leaves the diffusing medium should be completely independent of incidence direction. The amount of light received within the acceptance cone should on that account be a measure of light intensity impinging on the fibre termination. These constructions would cause losses, but only the relative intensities between different points of measure are interesting. Absolute intensities from the neon lamp are irrelevant. The computer should compensate for differences between these fibre terminations in how well they collect light.

For all these fibre terminations also holds that if the outermost part of the fibre termination is not of a hard material, it could be given a thin transparent coating of a hard substance to avoid getting mechanical damages, that destroy earlier calibrations.

A sheet of ground glass in front of the fibre end

The first idea was cutting out small sheets of ground glass and adhering one sheet in front of each fibre. Figure 4 shows how that could look like. In this case the sheet is inserted into the cannula, but the sheet could possibly also be glued on the end of it.

However it is hard to cut out such small pieces of ground glass, and because of that no fibre terminations including ground glass were produced.

Figure 4. One technique to achieve that light is collected from a whole half sphere was gluing a sheet of ground glass in front of the light guide in the cannula.

Making the fibre ends frosted by grinding

Another potential method was making the end of the fibre frosted. In *appendix B* it is explained exactly how these fibre terminations were produced, but the basic idea was gluing the light guide in the cannula and then sandpapering it until it has a plane and frosted end that is situated edge to edge with the end of the cannula, see figure 5.

Figure 5. In the calibrations and in the verifications light guides, glued in cannulae and with ends frosted by grinding, were used.

To find out whether this technique was practicable and if so which abrasive to use, five fibre terminations with different grindings were produced. The cannulae with light guides were placed in different angles relative to a parallel and rather wide beam of light. A photoconductively connected photodiode was in the other end of the light guide. By this method the current through the detector as a function of incidence angle was investigated. To avoid shadows and reflections from other objects, the cannula was fastened on a stand and below it on the table a graduated arc was placed.

The results of these measurements are shown in *appendix C*. If the ends of the fibres were highly polished, there should be a cosine dependence for angles in the range between -30 ° and 30 ° and there should only be dark current for other angles. On the other hand if the ends of the fibres were perfectly frosted, there ought to be a cosine dependence in the range between -90 ° and 90 °.

The five fibre terminations were unequally successful. Nevertheless all of them have in common that the signal for angles within the acceptance cone decreases more than it should according to the cosine dependence and for bigger angles there is a current but it decreases rapidly when the angle increases. The interpretation of these results ought to be that there is a high likelihood that the light's change of direction is rather small, when passing through this frosted surface. Most of the light is only refracted once. Light impinging within the acceptance cone but near the border has a rather high probability to be refracted out of the cone and light impinging not within it can be refracted into it.

It could have been checked if this method could be improved by other grindings, but because of the fact that light only is refracted once, it can probably not be made satisfactory. In case there is any relation between direction of propagation before and after passing the interface, then this method to make measurements of intensity cannot be used.

Despite these weaknesses fibre terminations, prepared according to this method, were used in the calibrations and in the verifications. The reason for this is that the rest of the equipment needed to be tested and this was the best available fairly well developed technique.

Diffusing by a transparent medium mixed with shivers

To accomplish that light changes direction many times without too large losses, some techniques were discussed. Instead of sticking the light guide the whole way through the cannula, the fibre could be glued so that its end becomes recessed a small distance relative to the end of the cannula. The rest of the interior of the cannula could be filled with a transparent substance mixed with shivers of another substance. These shivers could either be transparent but have an index of refraction that differs from the surrounding material's, or have a high reflectance. In the first case the light should be diffused by refractions in all interfaces and in the second case by scattering. Schematically drawn the construction could look like this:

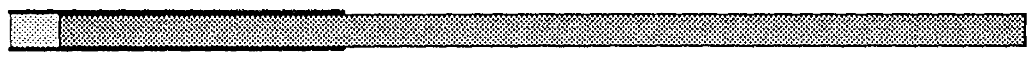


Figure 6. The best way to collect light without favouring certain angles of incidence is probably by putting a transparent substance mixed with shivers in front of the fibre end in the cannula.

This measuring method needs to be developed for some weeks before having a satisfactorily working fibre termination. Suitable substances have to be chosen and the thickness of the layer and the concentration of shivers must be optimized.

As transparent medium two available substances, PMMA and epoxy, were tested. When using PMMA, a piece of the light guide was dissolved, the solution was mixed with shivers and the end of the cannula was filled with this mixture.

It appeared that acetone did not work as solvent, probably due to occurrence of fluoric polymers in the cladding. Almost the whole piece of fibre could be dissolved in hot toluole, but that was after 12 hours and with solvent in abundance. Because of that the cannula had to be refilled repeatedly, as the toluole evaporated. This method is not recommended.

When using epoxy, it was just mixed with shivers. As epoxy has a rather high viscosity, it did not flow into the hole of all cannulae, but solidified outside it. The viscosity also implied difficulties in mixing.

The conclusion was that it is advisable to take the following into consideration when deciding which transparent medium to use. It should be a mobile substance and it should dry relatively quickly. It should further have a density close to the shivers', to slow down the accumulation of shivers at the bottom or at the surface. Otherwise it would need to be stirred intensely and problems with bubbles of air would arise.

If it is chosen to use transparent shivers, then these should have an index of refraction that differs as much as possible from the corresponding index of the surrounding material. Since most transparent substances have indices of refraction in the same magnitude and since light only is deflected a small angle in each interface, then it is likely that a larger thickness is needed than in the case of reflecting shivers.

Polyethylene's index of refraction is 1.3, and attempts to grind up that as well as PMMA were made. Emery clothes were used. Small amounts of potential contaminations of particles from the cloth, should not prevent light from being collected from all directions. This method requires time but works. As these substances consist of large molecules, they can be pulverized in a beating vat only if they are frozen.

Substances suitable to be reflecting particles are zinc oxide, zinc sulphide and barium sulphate. These are used as diffusing pigments in light fixtures, to conceal the filament or the fluorescent tube, and the diameters of their particles are in the order of 1 - 4 μm.

Titanium dioxide is the most widely used white pigment for plastics and its particle size is 0.25-0.3 μm. To improve its ease of dispersion it can be coated with aluminium or silica, but as mentioned before, its concentration and the thickness of the layer need to be optimized.

Diffusing by holographic films

A quite different method to collect light is using holographic films. A frosted surface could be exposed by a coherent light source, e.g. a laser, and the reflected light could impinge on a holographic film. The film could then be developed and a plate of suitable size could be punched out. This could be placed in front of the light guide at the end of the cannula.

The detectors

Demands

The detector should have a relevant wavelength dependence, a sufficient sensitivity and it should be possible to fix the light guide at least close to it. Rise times and fall times are not important but there should be a linear dependence between signal and intensity of light. The prices of detectors vary very much.

Different types of detectors

The phototransistor works as a normal transistor, but the excess charge of the base is created by light and not by a current. The main advantage is the low price, but the phototransistor is not linear.

Photodiodes are p-n junctions and they can be made of silicon, indium arsenide, germanium, lead sulphide or lead selenide. Indium arsenide detectors are designed for IR - radiation, as are lead sulphide and lead selenide detectors. Germanium detectors are sensitive in the visible range, but also they have their peak in the infrared range. Silicon photodiodes are probably the most suitable photodiodes, and they have a high responsivity and linearity. Photodiodes can have built-in preamplifiers for even better linearity, but this facility drastically increases the price.

There are pin-diodes, i.e. diodes with a low-doped region between the positively and the negatively doped one. This region lowers the junction capacitance and makes the detector quicker.

Avalanche photodiodes are diodes, over which a much higher voltage is put. This gives a higher gain.

To be able fasten a detector solidly on the light guide, most detectors require an extern means of attachment. There exist fibre holders, that can be fastened into detector heads, which contain the detectors and necessary electronics. These detector heads are very versatile and by appropriately setting the internal switches they can accept inputs from a large number of detector types. However, this would be very expensive.

There are detectors designed to be fastened directly on fibres. Most of them are intended for data communication and have built-in circuits that optimize the detectors to receive digital signals. These circuits destroy the linearity, but one photodiode without these circuits was found and this type of detector was chosen.

The choice

A sketch of and data about the chosen detector, a photodiode designed for attaching directly on the light guide, are shown in *appendix D*. A clip is put into the hole and it holds the light guide. The clip is shown there too.

The detector consists of a diode with connectors included in transparent plastic. This means that light could reach the diode from other directions than from the fibre and it was later necessary to cover the detector with black tape.

Electronics

Photovoltaic or photoconductive connection?

A photodiode can be connected either photovoltaicly or photoconductively. Figure 7 shows a typical photovoltaic connection. When light impinges on the diode, electron-hole pairs migrate to the opposite side and a voltage over it is produced and measured. This construction has low noise and is above all used in low to medium frequency applications.

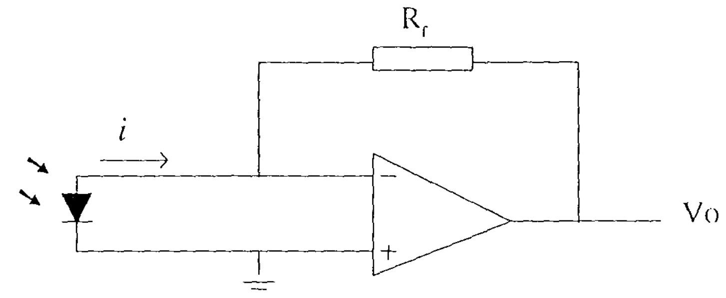


Figure 7. A photovoltaic connection implies a low noise.

The second connection is the photoconductive one and it is shown in figure 8. The photodiode is reverse biased and the current through it measured. This construction exhibits better linearity and is mainly used in high frequency applications. As the linearity properties are important the photoconductive connection was chosen.

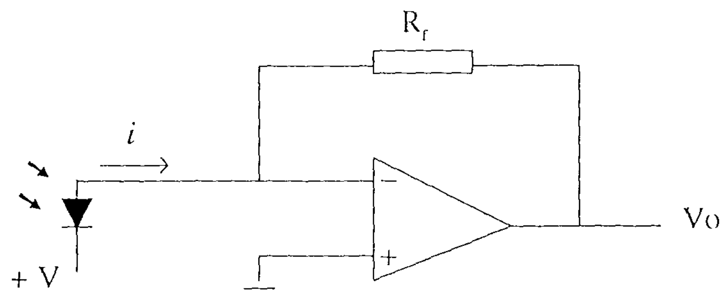


Figure 8. A photoconductive connection exhibits a good linearity between intensity and output voltage.

Determining the feedback resistance

To find out which feedback resistance to use the components were connected on a laboratory plate. To save space operational amplifiers fitted four and four in capsules had been bought. Their notation are *TL064CN*.

The output voltage is proportional to the feedback resistance and as resistor a potentiometer was used. Since the supply voltages of the operational amplifier are -15 V and +15 V the output voltage should be in the range between -13 V and +13 V. The cannula in the other end of the fibre were put into a hole in a package, the neon lamp lighted and the potentiometer adjusted until a suitable output voltage was obtained. The investigation made it plain that the resistance needs to be over 1 MΩ. Using such a high feedback resistance is risky, since it can cause oscillations, but in this connection the noninverting input is grounded, so probably this would still work. Later 5.6 MΩ-resistors were used as feedback resistors in the permanent circuit and that worked well.

Determining the reverse bias over the photodiode

The maximum allowed reverse voltage is 32 V. To get to know, which reverse voltage to use, a cannula was fastened on the extension rail of the meter frame. For different reverse voltages it was then investigated how the output voltage varies with distance between cannula and lamp. *Appendix E* shows the result.

As the absolute intensities impinging on the cannulae were unknown, the only drawn conclusion from the measurement is that all the reverse voltages almost gave the same result. In the permanent circuit a 10 V reverse bias is used.

The permanent printed circuit card

There were totally 20 photodiodes. This means that the final permanent circuit should contain 20 equivalent circuits. It should have 20 light intensities as input and 20 voltages as output. A permanent printed circuit card has been produced by soldering. It is designed for fitting in a rack and the photodiodes are glued in holes in the front panel of the card. By a multipool connector the output voltages are transmitted to the rack bottom card. A schematic sketch of the printed circuit card is shown in figure 9.

The ground and the two supply voltages, +15 V and -15 V, are through the multipool connector transmitted to the three horizontal and parallel conductors, from where they are conducted to the operational amplifiers.

The vertical conductor to the right should have the potential +10 V and this is accomplished by voltage dividing between the +15 V conductor and the ground. The 7.5 kΩ - resistor and the 15 kΩ - resistor are to achieve this. The cathodes of the photodiodes are by this conductor supplied with +10 V.

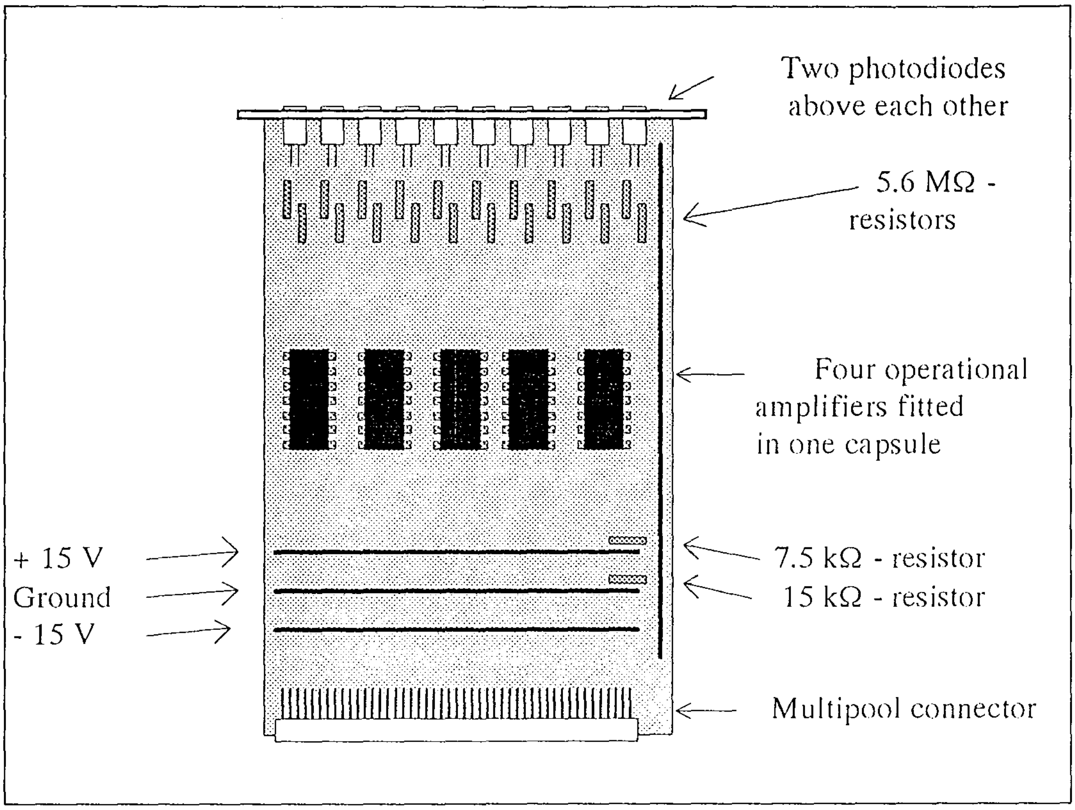


Figure 9. A permanent printed circuit card has been produced by soldering. This should be placed in a rack.

According to the circuit diagram, for photoconductive connection on page 18, the current through a photodiode is conducted to the inverting input of an operational amplifier and to a 5.6 MΩ-feedback resistor. The output voltages are transmitted to the multipool connector.

The circuit needs an external power supply. The two supply voltages and the ground should be connected to the rack bottom card, from where they are conducted to the multipool connector. 15 V should be fastened by screw No. 15 on the rack bottom card, -15 V by screw No. 16, and the ground by screw No. 32.

The 20 output voltages from the rack bottom card are through a multiconductor cable transmitted to a multiplexer that is inserted into a computer.

Displaying the result

Calibration coefficients

In the calibration it is assumed that the signal from each diode can be written

$$V_i = A_i + B_i \cdot I$$

where A_i and B_i are constants, i is an index for each diode and I is the intensity of light. To compensate for the different constants calibration coefficients according to

$$K(i) = \frac{V_{light}(1) - V_{dark}(1)}{V_{light}(i) - V_{dark}(i)}$$

are calculated. The vector $V_{dark}(i)$ contains voltages measured with the cannulae in darkness and the vector $V_{light}(i)$ contains voltages with cannulae in light.

The computer program

A calibration program for the computer has been written. Its name is *exjobb.ibw* and it is in the dictionary *ibasic/silvio* on the hard disc of the computer *dator # 1* at *Sterilization & Filling*. Before it can be driven the multiplexer must be put into slot No. *7* at the back of the computer, the voltmeter *HP 44701-A* into slot No. *5* and *excel* started.

The program consists of three parts named *calibration1*, *calibration2* and *measurement*. The subprogram *calibration1* reads the voltages in $V_{dark}(i)$ and puts the values into the file *ibasic/silvio/calibr1.dat*. The subprogram *calibration2* reads the voltages of $V_{light}(i)$, calculates the calibration coefficients $K(i)$ and saves these in the file *ibasic/silvio/calibr2.dat*. It presupposes that all cannulae can be placed in the same radiation at the same time, e.g. in daylight. If this is not possible the voltages of $V_{light}(i)$ can manually be measured one by one. Calibration coefficients can then be calculated and from *DOS* directly written on the file.

The subprogram *measurement* five times reads the 20 voltages one by one. Each reading lasts 80 μs. The voltages are multiplied with their respective calibration coefficients and written on an *excel* file. A graph also shows the 20 calibrated voltages.

Alternative ways to compare the intensities

The fibre ends, which are not stuck into the packages, could be fitted in a plane. A lens could then image this plane on a diodarray, i.e. an array of closely packed diodes, which are produced on the same substrate. Usually a diodarray contains 256, 512 or 1024 pixels.

The diodarray could be connected to an analogous oscilloscope and a curve with one top for each fibre would be obtained. The area under a top should be proportional to the light-flow. A plotter could be connected to the oscilloscope.

Alternatively the signal from the diodarray could be digitized in a digital storage oscilloscope and the intensities could be written in a table on the screen.

The plane of fibre ends could also be imaged on a CCD-camera. To convert the signal from the CCD to the format of the screen a video card would be required.

The distribution of intensity on the CCD would be shown on the screen and there it could be marked how much light that should belong to each fibre end. This could then be integrated to get the light flow through the light guide.

Summary of the design

As optical fibre a plastic light guide was chosen. Its core diameter and cladding diameter are close to *1.0* mm. The fibre is glued in a cannula without point to make fixing of orientation easier.

The best way to achieve that light is satisfactorily collected from all directions is probably by having a layer of a transparent substance mixed with reflecting particles on the end of the fibre. This technique requires however developing for some weeks, to choose suitable substances and to optimize the thickness of the layer and the concentration of shivers.

In the measurements and the verifications fibres with one end frosted by grinding were used.

In the other ends there are photodiodes designed for fitting directly on the light guide. The photodiodes are connected photoconductively as the property of linearity is the most important.

A printed circuit card, containing 20 equivalent circuits, has been produced by soldering. The circuits have the light intensity on the detector as input and the output voltage as output. The latter are transmitted to a computer that graphically displays the result on the screen and that saves the result.

Verifications

Generally

Some measurements were done to estimate the reliability of this measuring system. Fibres with ends ground with an emery paste *Carborundum "Coapse"* were used. Terminations of this type have inevitably an unmistakable dependence of incidence's direction, but they were the best available. This dependence of direction introduced a source of errors, since the angular intensity distribution around the fibre end had been changed between calibration and measuring.

Calibrations

The calibrations were first made in daylight. All cannulae were fastened parallel to each other on a plate and placed close to a window. The subprogram *Calibration 2* of the earlier mentioned head program *Exjobb.ibw* was used. If the sun shines with a suitable intensity this is the best way to calibrate.

If its intensity is too low, numerical errors can be too large and because of this the cannulae were later calibrated one by one in a well-defined position in front of a desk lamp. The voltages were read manually by a voltmeter and the calibration coefficients calculated and written on the file from *DOS*.

Errors caused at the fastening of cannulae on packages

To check the size of the errors introduced by the fastening of cannulae on packages, repeated measurements with one and the same cannula in the same hole were performed. Cannulae were inserted at three measuring points, the measurements made and the cannulae removed. With the same cannulae this was then repeated some times. The first part of *appendix F* shows the results.

At these tests the package *Concept 3*'s smaller version was used. The first and the second measuring points were on the envelope surface of the package's cylindrical part. The first was half-way between bottom and top of the package and the second close to the plastic cap. At these measuring points only tapemass was used to fasten the cannula on the package. The third point was on the plastic cap and here both tapemass and tape were used to fasten and fix the direction of the cannula.

Measuring results for different cannulae at the same measuring point

At these measurements the measuring point 1 in the previous chapter was used, to minimize errors introduced by the fastening. Some cannulae were put one by one into the same hole and measurements done. The second part of *appendix F* shows the results.

Conclusions from the verifications

The fastening

A cannula can fairly be fastened by tapemass at measuring point 1. The uncertainty at points 2 and 3 is unacceptable. The difference between the accuracies at the measuring points 1 and 2 is probably a result of a higher consistency of the packaging material at point 2.

A suggestion to improve the fastening of cannulae on a package is mounting a stand around the package. On the cannula a small plate could be fastened by gluing or soldering. This plate could then work as a stopper, i.e. the cannula could be stuck that far into the package that the plate touches the packaging material. The other end could then be fastened on the stand for example with tape. By attaching the cannula in this way the fixing of the cannula in the wanted direction relative to the package would be considerably improved.

The comparability of the measuring test results from the different fibres

At the measurements with different cannulae some sources of errors can occur. There is a moderate agreement between the values from the cannulae marked *17, 21, 22, 23, 24, 25* and from the first measurement of cannula No. *19* and this shows that the measuring method ought to be practicable.

Probably the values from cannula No. *26* and the second from cannula No. *19* deviate as a consequence of changes of the fibre ends' surface structure after calibration. These changes are easily got, since the ends are ground, i.e. shivers on the surfaces can get loose. There is also a risk that the fibre ends get a layer of perspiration from the hands when handling with the cannulae.

By reasons mentioned in the chapter *collecting light* fibre terminations with ground ends are not recommended and this is another disadvantage. If someone wants to continue this work it would be advisable to achieve that the outermost part of the construction is hard and at least fairly smooth. If the diffusing medium not itself fulfils this, it could be covered with a hard, thin and transparent layer. It would be advantageous if the outermost part of the fibre termination could be wiped clean with a cloth before calibration and before measurements.

The cannulae No. *18* and *20* also gave deviating measurement test results, but in these cases it likely is by other reasons. At the calibration these two had much lower output voltages and hence their calculated calibration coefficients are large numbers. Their values in the *K(i)*-vector, shown in *appendix F* and the definition of the vector in the chapter *displaying the result*, were as much 2.75 and 5.06 respectively. If all fibre terminations, fibres, detectors, etc. were equal then these values would have been 1. Calibrating with such high coefficients implies uncertainty.

The differences in the output voltages when different cannulae is held in similar radiation are caused by some sources of errors. The detectors and the fibre cables are not equal, but above all the fibre ends in the package and the fibre ends at the detector differ from corresponding ends on the other fibres. All the fibre ends in the cannulae are ground with the same abrasive materials and for equally long times, but they are made by hand and thus with different pressures on the abrasive. Local differences in the grinding material influence too. A possible accumulation of grindings on the fibre end causes losses.

The fibre end that is at the detector should be plane and highly polished. The normal procedure to polish a fibre end is by first gluing it in a fibre optic connector. Since this is not possible here, the fibre end was put into a hole through a block and polished with gradually more fine-grained abrasives. A block, with one surface perpendicular to the direction of boring, was used. This grinding method allows movement of the fibre within the hole to some extent.

Possible unevennesses of the surface also imply a somewhat larger distance between the fibre end and the diode. The smallest distance that can be obtained is 0.7 mm, since the plastic layer in front of the diode is that thick. A rough estimate, see *appendix G*, gives that if the fibre end is perfectly smooth and attached quite close to the plastic in front of the diode, then only 57 % of the by the fibre incoming light reaches the photodiode. The rest ends beside it, since the light is spread over an area that is bigger than the diode's. An uneven end of the fibre means that an even smaller part of the light is collected by the photodiode.

In the other end of the fibre there can be local irregularities in the grindings or, if that is chosen, in the diffusing medium. For short optical fibres holds that the output angular intensity distribution depends very much on the angular distribution at the input. Irregularities at the input end of the fibre can cause light to be sent out in higher or lower intensities at certain angles. These lighter or darker areas in the output beam can hit different spots on the diode or miss it. On the other hand if the problem with collecting light from all directions could be satisfactorily solved, then there would not be any light or dark spots at the output and this problem would be solved automatically.

Summary of the most important required improvements

The developing of this technique to detect the light distribution in a package has not been fully completed, as a result of lack of time. Here is a summary of the most essential improvements, that must be done before having a well working measuring system.

The most difficult and important problem to solve is that of collecting light without suppressing any angles of incidence. The technique with white reflecting pigments in a transparent medium is the most promising. It needs development for some weeks to select the most suitable substances and to optimize concentration of shivers and thickness of layer.

Light guides and detectors of that types, that were chosen, work after some arrangements. The light guide should have a jacket and stray light must not reach the photodiode, but the latter problem could be solved by painting the plastic around the photodiode black.

Conclusion

Measurements on the light distribution in a package were not performed, as a consequence of problems to collect light without suppressing certain angles of incidence. This dependence of incidence direction was considered to be so large that such measurements would not be purposeful.

Instead some measurements were done to estimate the reliability of the detection system. The inference was that if the problems mentioned in the previous chapter could be solved, then measurements of intensity distribution on the inside of a package could likely be performed satisfactorily.

The intensity would not be got everywhere in the package, but just in some selected spots. Nevertheless, since each measurement only lasts the time for inserting the cannulae into the package and then for just a minute, it is possible to get intensities relatively quickly in quite a large number of measuring points. Estimating a range, within which the intensities for all spots are, would be quite easy and by fitting a polynomial to the measurement test results an estimate of the intensities on other spots would be obtained.

Inserting small photodiodes directly into the package is another idea that has arisen. They would need a shield to avoid mechanical damages and something that fix their orientation relative to the package. The problem with favouring certain angles of incidences would not occur and whether the spatial resolution would be suffering depends on the available sizes of diodes.

If it is possible to cover the lamp with a completely homogeneous layer of for example paint, then the technique with photographic papers may work. The same would hold if a lamp with equal shape and spatial distribution but a much lower intensity could be found. But the densitometric measuring and the repeatability of the exposures would cause problems.

Acknowledgement

I want to thank my two tutors Håkan Mellbin and Sven-Göran Pettersson for having been of great assistance the whole way through this diploma work. I also want to thank Peter Blomqvist, head of the section *Sterilization & Filling*, for letting me make my diploma work here. Thanks also to all persons mentioned under the heading *Contacts with:*.

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- *Silicon Detector Corporation*, form no 400-44-002, 400-44-003 and 400-44-004.

Tutors:

- Håkan Mellbin, Tetra Pak R&D AB, 046 - 36 19 45.
- Sven-Göran Pettersson, department of physics LTH, 046 - 10 76 56.

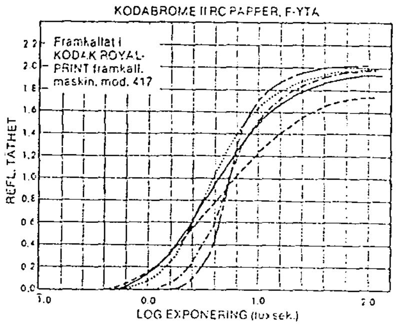
Contacts with:

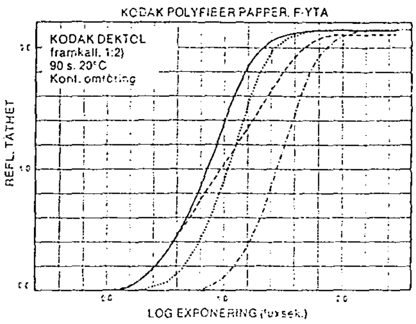
- Jan Ohlsson, department of physics LTH, 046 - 10 77 39. He has produced all fibre terminations.

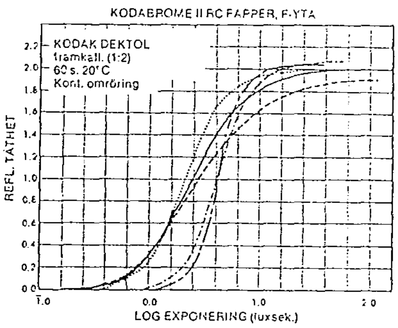
- Kaj Söderström, department of nuclear physics, 046 - 10 77 04. He has experience in nuclear emulsions and by that in photosensitive layers.
- Representatives from Kodak AB, Agfa-Gevaert AB and Ilford Anitec AB about light sensitivity of photographic papers and films.
- Silvio Matei, Tetra Pak R&D AB, has made the program that reads the voltages and displays the result on the screen.
- Claes Ingvert, Tetra Pak R&D AB, about the electronics.
- Gert Holmström, Tetra Pak R&D AB, about the electronics.
- Istvan Ulvros, Tetra Pak R&D AB, about the electronics.
- Torbjörn Andersson, Tetra Pak R&D, AB about diffusing light by shivers of reflecting or transmitting substances.
- Per Ragnarsson, department of physics LTH, 046 - 10 76 58 about optical fibres.

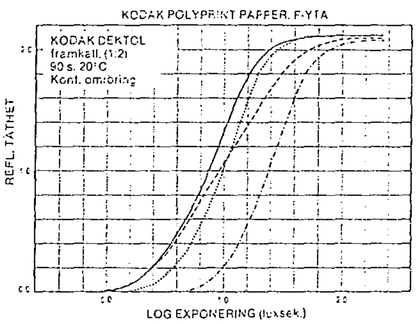
Appendix A

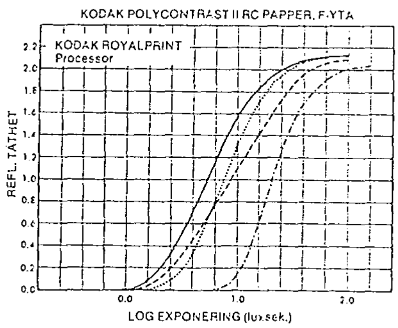
The blackening of black-and-white papers

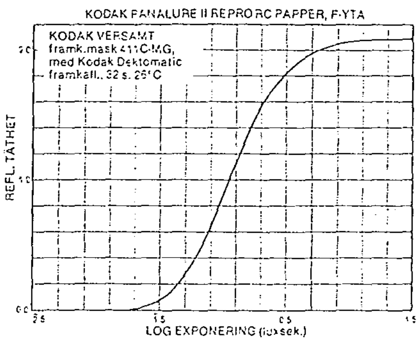


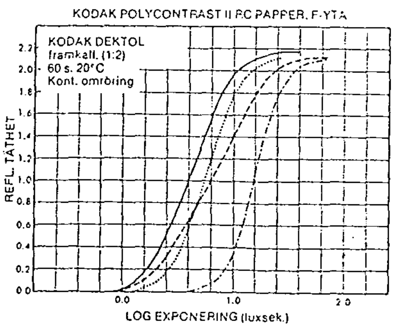


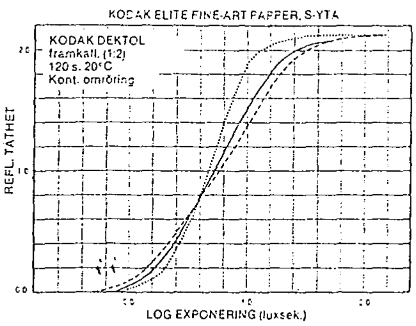












Appendix B

<u>How to produce fibre terminations with cannulae</u>

Fibres with frosted ends

1. Stone away the point of the cannula and take off the burrs.
2. Clean the fibre with alcohol.
3. Give a thin coating of glue on the light guide and stick it into the cannula. Draw it backwards and forwards. On the plastic light guide a cyanoacrylate adhesive called *loctite* was used. On glass or quartz fibres a glue called *EPO-TEK 353 ND* offered by *MPE Microtech AB* could be chosen.
4. Let the fibre protrude 2-3 mm from the end of the cannula.
5. Let the glue dry.
6. Produce a block with a drilled hole somewhat bigger than the full diameter of the cannula. One of its surfaces should be perpendicular to the direction of drilling.
7. Place an emery cloth on a smooth surface, e.g. a plate of glass. Put the cannula into the hole and grind the fibre by moving the block along a path shaped as the numeral *8*. The fibres, that were used in the calibrations, were ground with a cloth called *P220*.
8. Place a piece of emery paste on the plate of glass and proceed similarly. The fibre terminations used at the verifications were ground for two minutes with a paste called *Carborundum, Coapse.*

Fibres with a transparent medium with shivers

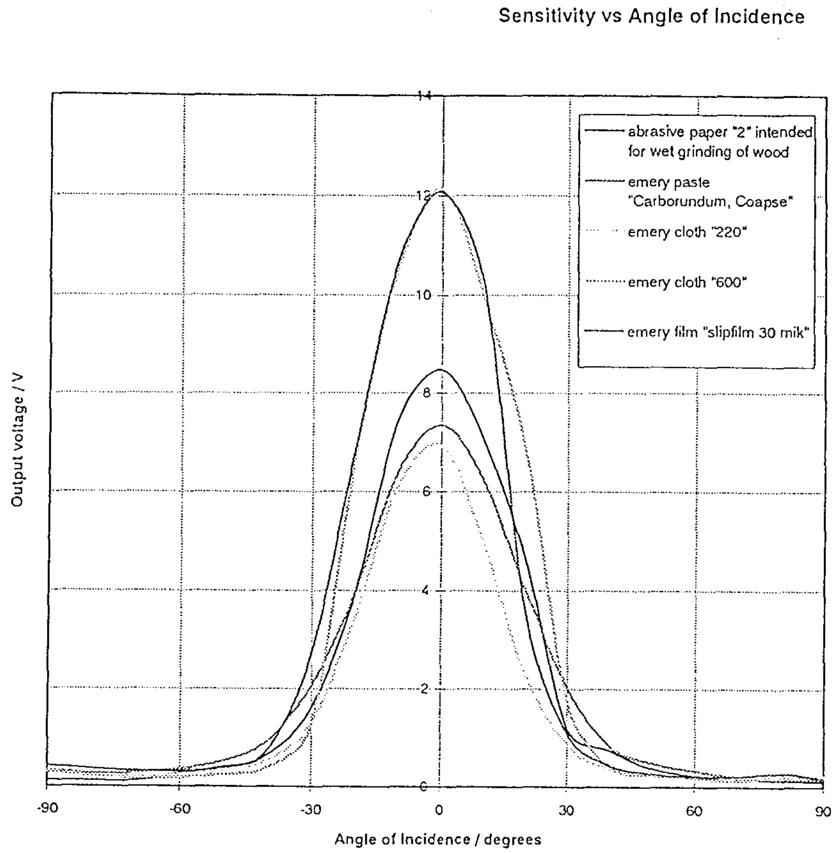
1. Make a stopper for example by fastening a boring bit so that it protrudes a small distance, equal to the wanted thickness of the transparent medium, from a surface.
2. Cut the light guide with a razor blade and proceed then according to items 1-3 in the chapter above. When drawing the light guide backwards and forwards, try to avoid getting glue on the fibre end.
3. Put the stopper into the cannula and the light guide close to the stopper.
4. Remove the stopper and let the glue dry.
5. Fill the ensued empty space in front of the fibre end with the wanted mixture.

Comments

If the fibre ends are to be polished with fine-grained emery cloths or with emery films, then water first ought to be put on the cloth. If fibre optic connectors are preferred instead of cannulae, the gluing will be easier. The connectors have small holes, through which the glue can penetrate.

Appendix C

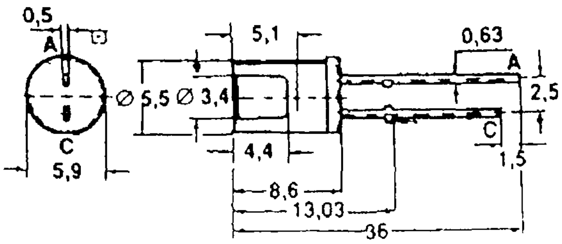
The connection between output signal and angle of incidence for some grindings of the fibre end



Five fibre terminations were produced and in the small square it is written which grinding material that was used in their last grindings. The emery film *slipfilm 30 mik* is the roughest one in a series that are commonly used for fibre polishing.

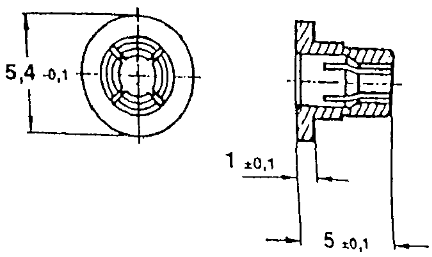
Appendix D

The photodiode



Notation: TEYD5500
Wavelength: 600 - 1200 nm
Maximum reverse voltage: 32 V
Dark current: 10 nA max.

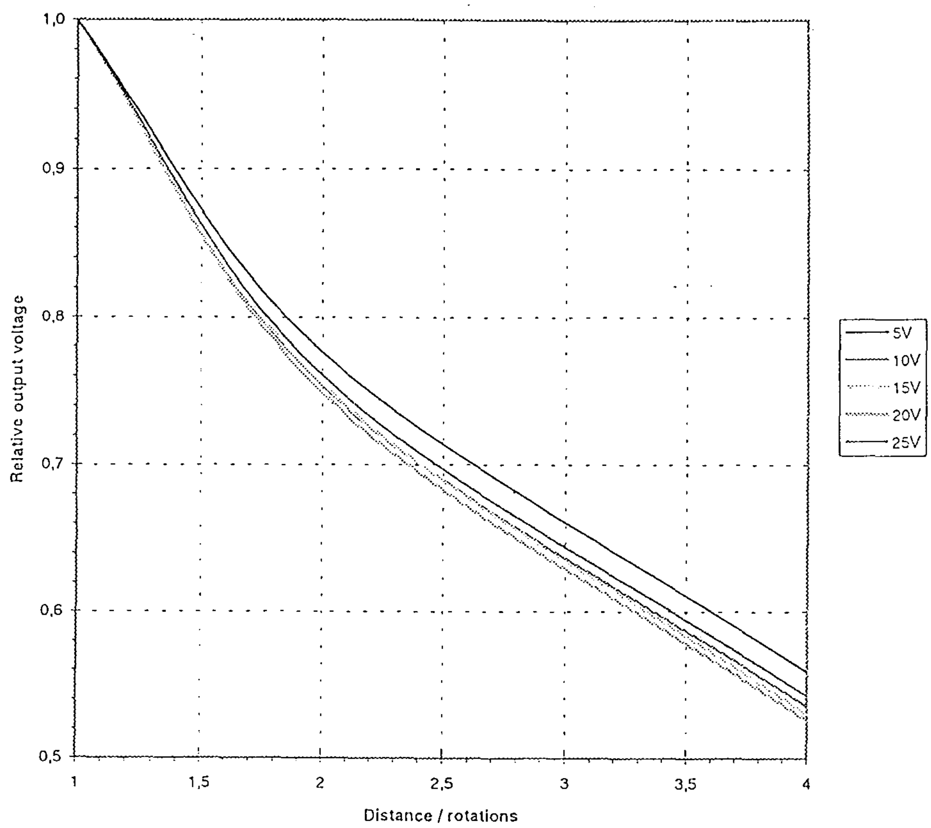
The clip



Notation: YC10

Appendix E

The connection between output signal and distance for some reverse voltages over the photodiode



The small square contains the reverse voltages over the photodiode. On the x-axis the unit is number of rotations that the handle was turned when moving the neon lamp away from the cannula.

On the y-axis there is a relative output voltage. For each reverse bias the output voltages, that corresponded to some distances, were in rapid succession measured. This was done three or four times, but as it was found that the lamp does not radiate with constant intensity, then slightly different results were obtained.

To circumvent this it has been assumed that the intensity of the lamp remained constant during each sequence of measurements. Each output voltage has been divided with the corresponding voltage from the measure at the shortest distance in the same sequence.

These in this way calculated relative voltages agree quite well with the corresponding relative voltages from other sequences and the diagram has averages of these voltages on the y-axis.

Appendix F

Repeated fastenings and measurements with one cannula
(output voltage / V)

Measurement point 1	Measurement point 2	Measurement point 3
7.58	7.31	5.79
7.60	7.39	5.87
7.63	7.62	4.61
7.57	7.60	4.99
7.70	7.67	4.22
	7.97	4.66
	7.46	4.42

Repeated measurements with different cannulae in the same point
(output voltage / V)

Cannula No.	Measurement 1	Measurement 2
17	6.09	5.87
18	5.26	4.51
19	5.83	5.04
20	5.24	5.44
21	6.04	5.74
22	6.12	6.10
23	5.78	5.76
24	5.97	5.72
25	5.92	5.93
26	5.13	4.52

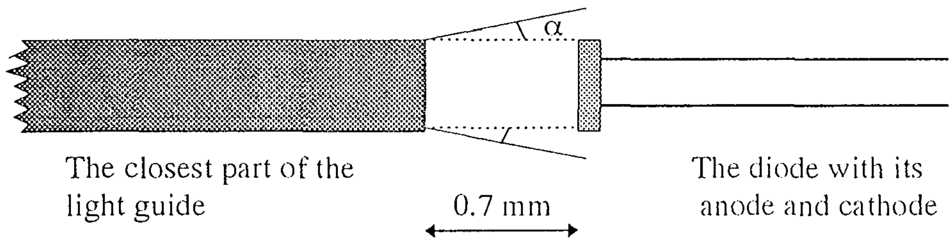
Data for calibration

The table contains output voltages measured with cannulae in darkness and calibration coefficients K(i), see page 21.

Cannula No.	Output voltage / V	K(i)	Cannula No.	Output voltage / V	K(i)
1	0.01	1.00	17	0.00	1.31
2	0.01	0.96	18	0.01	2.75
3	0.01	1.12	19	0.00	1.54
4	0.01	0.98	20	0.01	5.06
5	0.00	1.22	21	0.01	1.06
6	0.00	0.76	22	0.00	1.09
7	0.01	2.11	23	0.00	1.02
8	0.01	0.96	24	0.00	0.93
9	0.01	0.88	25	0.01	1.01
10	0.01	1.34	26	0.01	1.19

Appendix G

Share of the guided light that hits the diode



To get the share of the guided light that hits the diode the area of the diode is compared with the area over which the light is spread at that distance from the fibre end. The diode is a square, whose edge is 1.0 mm, so its area A_D is 1.0 mm^2.

To determine the area of the beam at the diode the angle α is first calculated. The numerical aperture NA of the light guide is 0.5. The index of refraction n for the plastics between the end of the fibre and the diode is unknown, but in this estimate it is assumed to be 1.5. This gives

$$NA = n \cdot \sin\alpha \qquad \Rightarrow$$
$$\alpha = \arcsin(NA/n) + m \cdot 360° \qquad \text{or} \qquad \alpha = 180° - \arcsin(NA/n) + m \cdot 360°$$

where m is an integer. The angle α should be in the range between $0°$ and $90°$, and consequently it holds that

$$\alpha = \arcsin(NA/n) = 19.5° \,.$$

The radius r_b of the beam at the diode should be the radius r_f of the fibre end plus the increment due to divergence of the output beam, that is

$$r_b = r_f + d \cdot \tan(\alpha) = (0.5 + 0.7 \cdot \tan(19.5°))\ mm = 0.75\ mm.$$

This gives that the area A_B of the beam is

$$A_B = \pi \cdot r_b{}^2 = 1.76\ mm^2$$

and the share S of the incoming light that hits the diode should be

$$S = A_D/A_B = 57\ \%$$

Appendix H

Purchases

Product	Supplier
Neon lamps + Transformer	Roos Neon Hammarvägen 17 232 37 Arlöv 040 / 43 72 00
Cannulae	Viggo Spectramed AB Gåsebäcksvägen 36 252 27 Helsingborg 042/17 88 00
Light guides 55-953-27 Photodiodes 75-458-41 Clips 75-458-66 Multiconductor cable Operational amplifiers TL064CN Resistors	ELFA 171 17 Solna
Combined stand for drilling and milling 24400	Clas Ohlson AB 790 85 Insjön
Barium Sulphate	The Pharmacy