

Development of Electrooptic Polymers for High Voltage Instrument Transformers

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ABSTRACT

This paper describes some poled electrooptic bulk polymers (EOP) of the guest/host type having a cured epoxy resin as the host. The electrooptic polymers of typical dimensions 13x13x3 mm are characterized with respect to application as Pockels materials in an optical high voltage sensor. The electrooptic coefficients obtained here are of the same order of magnitude as those which are required for high voltage applications. An optical sensor based on disperse red 1 dye and an epoxy polymer is developed. It is able to measure voltages up to 10 kV AC. It is shown that bulk EOP can be produced with relatively large physical dimensions comparable to commercially available Pockels crystals. A technique is described which compensates for the inevitable intrinsic birefringence built into most bulk polymers. The epoxy based EOP shows high orientational stability, even when compared with a polysulfone based EOP having a higher glass transition temperature.

Keywords: Electrooptic polymer, nonlinear optical dye, epoxy, fiber optic sensor, high voltage, Disperse Red 1.

2. INTRODUCTION

Over the last decade, electrooptic polymers have been the object of extensive research,^{1,2,3}. Most effort has been focused on obtaining very high electrooptic coefficients, modest optical absorptions and acceptable long-term stability of the electrooptic polymer. The electrooptic polymers have not yet found any widespread commercial use, because present materials do not meet the demands set by waveguide modulator applications. Materials having acceptable long-term stability, do in general have too low a magnitude of the electrooptic coefficient. This paper presents a high voltage sensor using an electrooptic polymer, where the demands with regard to electrooptic coefficient and maximum operational temperature are less critical as compared to waveguide applications in microelectronics.

The electric power utilities are persistently working on reducing costs, thus running a very complex electric power system in a minimum cost state. For this purpose, the power utilities want to be able to measure the voltage and current at a large number of sites. Optical sensors would be well suited for electric power systems because they provide galvanic insulation to the high voltage potential, and they are insensitive to electro magnetic induced noise^{4,5,6}. Section three in this paper describes the optical measurement principle of the prepared experimental high voltage sensor. Section four to six describe the preparation process and material properties of the EOP materials. The concept of making an optical high voltage sensor based on the EOP material was shown in 1990⁷. The EOP serves two purposes in the optical sensor. 1) It provides the electrical insulation between a high voltage electrode and ground potential, 2) The voltage is measured optically using the electrooptic effect of the polymer, with the full high voltage applied over the polymer material. For comparison, electrooptic crystals do not easily insulate for more than a few kV, thus a special voltage divider is necessary⁸. Since the voltage sensor presented here has a simple high voltage insulation system as well as a simple optical measurements system, it has the potential of becoming a low cost device for voltage measurement.

3. OPTICAL HIGH VOLTAGE INSTRUMENT TRANSFORMER

In principle, the optical voltage sensor works as an optical modulator operating in the linear range⁹, where the modulated light intensity is proportional to the applied modulating voltage, this ensures the sensor to be linear. A schematic presentation of the voltage sensor is shown in figure 1. The high voltage sensor consists of two high voltage electrodes, which are embedded into the electrooptic polymer, as seen in figure 3. One electrode is connected to ground potential and the other electrode is connected to the AC voltage which is to be measured, up to 10 kV. Light polarized in 45° relative to the z-axis is sent through the polymer through the gap between the two electrodes.

The polarization of the light is changed by the applied electric field in the polymer. The change in polarization is converted into a change in light intensity by a phase retarder $\lambda/4$, and a polarizer. The resulting change in optical light intensity is strictly proportional to the applied high voltage.

The polarization of light, sent through a material with electrooptic effect, changes as a function of the electric field inside the material between the two electrodes, because the refractive index changes in proportion to the electric field in the material, and the refractive index changes three times more in the z-direction than in the x-direction¹⁰.

Thus in principle, the voltage measurement is a determination of an electric field strength by the measurement of refractive index.

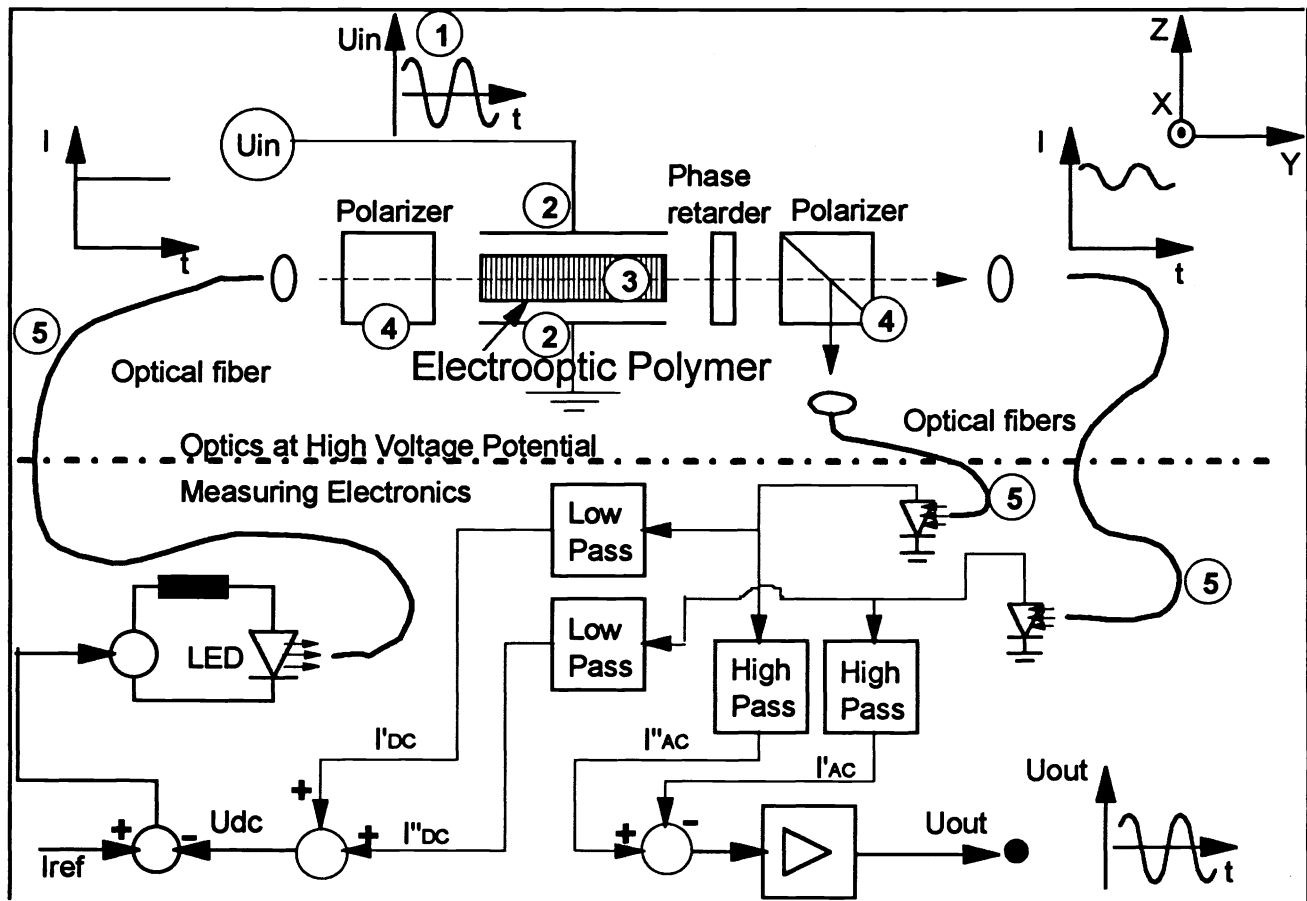


Figure 1. Diagram of high voltage sensor. The voltage to be measured (1) is applied to two electrodes (2) imbedded in the bulk electrooptic polymer (3). The voltage is measured with polarized light in a Pockels cell arrangement. The optical signal is detected with a two polarizer(4)/three fiber(5) system, which partly compensates for intrinsic birefringence built into the polymer.

3.1 Sensor design which partly compensates for intrinsic birefringence

The polymer sensor provides complete galvanic insulation between the measuring electronics and the optics at high voltage potential. As seen in figure 1, the sensor has an optical part which is placed at high voltage potential, and an electronic part placed at ground potential. The only link between the two parts are three optical fibers.

The light is provided by a 820nm LED which is regulated by a feedback loop in such a way that the sum of the light intensities, from the two output fibers, is held constant. The light intensities from the two output fibers are high pass filtered and subtracted. Since there is a phase difference of 180° between them, this is equivalent of adding the two signals. The signal is amplified, giving an output voltage proportional to the input high voltage.

The intrinsic refractive index varies in size throughout the bulk electrooptic polymer, because the polymer has built-in stresses. The stresses build up during the curing process because the polymer shrinks even after the polymer has become a solid, and also because the polymer shrinks during cooling down to room temperature after the curing process. Variation in refractive index is called intrinsic birefringence, and acts in the measurement as an additional waveplate with unknown phase retardation.

Therefore, the electric field induced phase shift of the light is analyzed in two perpendicular polarization directions, and the light intensity is detected by two photodiodes. The applied voltage is extracted from the two optical signals by taking the difference between the high pass filtered parts of the two signals, and at the same time holding the sum of the low pass filtered part of the two signals constant. This method does in part compensate for intrinsic birefringence¹¹. When the temperature is changed the built-in stresses in the polymer change, thus changing the intrinsic birefringence.

A phase shift of $\pm 57^\circ$ is observed in the experimental sensor based on material E828/[a] when the temperature is changed from 20°C to 65°C . With the three fiber technique a constant phase shift in the light traveling through the polymer of $\pm 60^\circ$ only gives a change in the detected signal of $\pm 8\%$, whereas the uncompensated signal varies $\pm 50\%$. The temperature dependent birefringence can be reduced by annealing of the sample.

4. PREPARATION OF BULK ELECTROOPTIC POLYMER

The guest/host EOP is prepared by mixing the three components, resin + hardener + accelerator with the nonlinear optical dye. The polar dye molecules are oriented by poling in an electric field, and at the same time the polymer is cured to a solid under a heating process.

4.1 Selection of materials

Disperse Red 1 (DR1) is chosen as the guest dye in the electrooptic polymers, because it is commercially available and well described in the literature¹². Since only very few nonlinear optical dyes are commercially available, two dyes from JPL/CALTECH are chosen. Dye [a] and [b] developed at JPL/CALTECH¹⁴ are chosen because they are expected to have 5-6 times larger nonlinearity than DR1, and still be chemically stable at 150°C at which temperature the epoxy is cured.

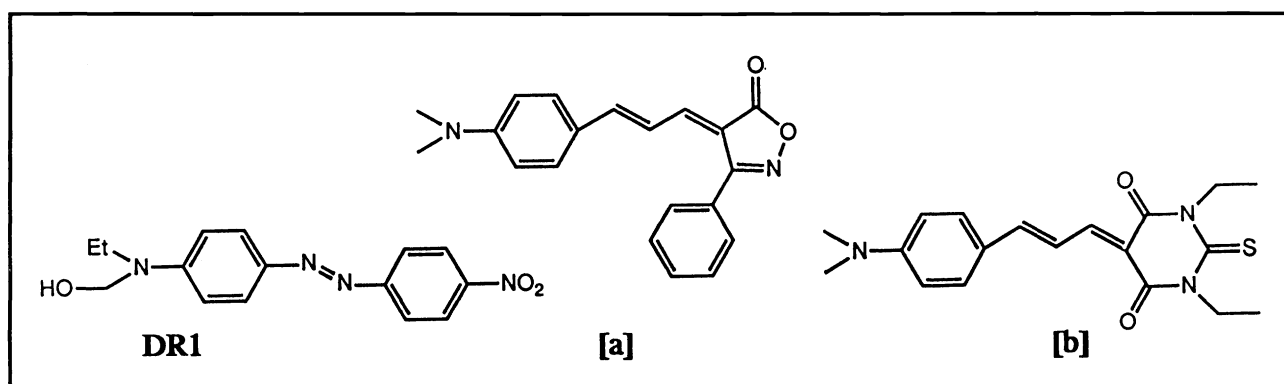


Figure 2, The three nonlinear optical dyes used in the guest/host polymers.

Epoxies are chosen as host polymers, because they can be poured into a mould and then cured in bulk form. Furthermore the chosen epoxy polymers are transparent at 820nm , and they have good high voltage insulating properties. An epoxy (E828), Epikote 828 + MNA + BDMA¹⁵, with high glass transition temperature 150°C is chosen because it is expected to have good orientational stability. For comparison another epoxy, Epofix¹⁶ is chosen; it can be cured at room temperature, thus facilitating the poling process.

4.2 Preparation of E828/DR1 electrooptic polymer

The EOP solution is made by dissolving the epoxy resin (4.25g) and the dye (0.5g) in acetone. After the epoxy, dye and acetone have been mixed carefully, the acetone is removed by evaporation, and the epoxy hardener (4.25g) and accelerator (0.09g) is added. This mixture is poured into the mould, see figure 3.

A glass cuvette 13.5x13.5x60 mm, is used as the mould. The poling/measuring electrodes are made of the same epoxy polymer as the EOP between them, in order to minimizing stresses in the EOP building up due to differences in coefficients of thermal expansion. The pre-cured electrodes are coated with a 50 μm layer of platinum and they are shaped and polished in order to maximize the electrical breakdown strength. The bottom electrode is positioned in the glass cuvette together with a rubber lead making a tight seal for the liquid epoxy. The top electrode is positioned after the epoxy has been poured into the mould. Air bubbles sticking to the surface of the electrodes and the glass cuvette are removed under vacuum. The EOP is pre-cured for 7 hours at 70°C before poling.

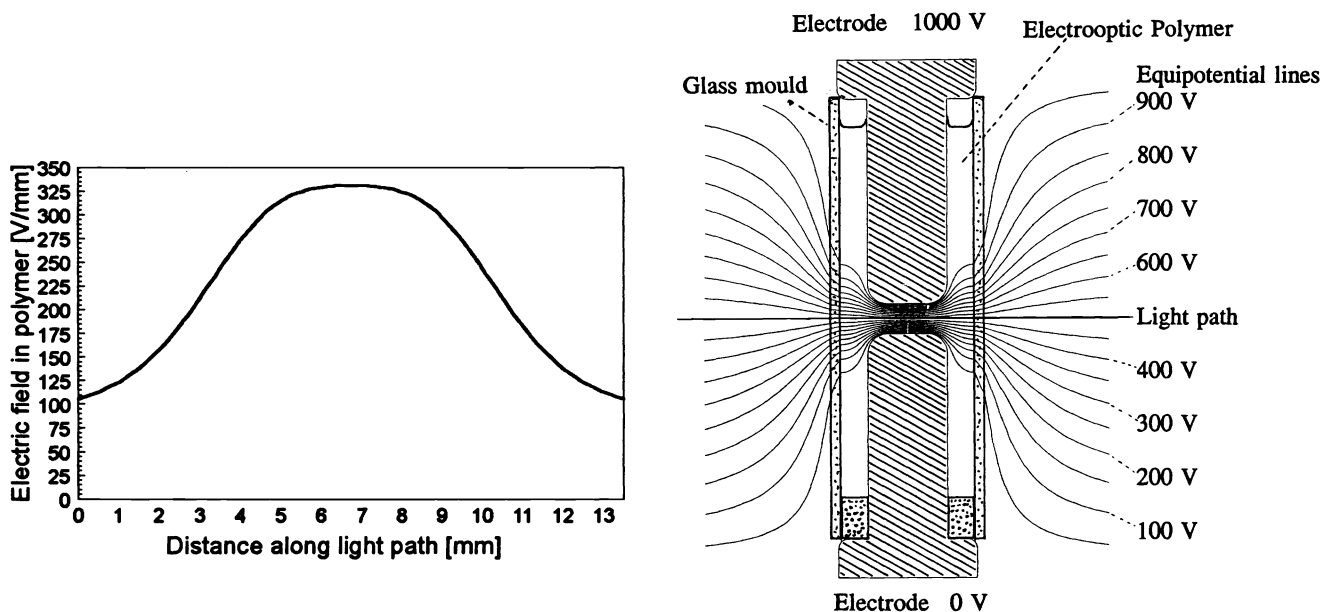


Figure 3. Left: The electric field in the poling direction along the light path between the two electrodes in the electrooptic polymer with 1000 V applied. Right: The electrooptic polymer, (the non hatched area), is cured/poled in a glass mould, with electrodes (hatched) made of metallized epoxy, positioned in the liquid EOP. Electric field calculations gave the shown equipotential lines during poling. The electrodes are rotational symmetric, whereas the cuvette is square.

4.3 Poling with high voltage DC field

The EOP is poled in a process where the sample is heated with a heat rate of 52°C/h up to 70°C and then 13°C/h up to 150°C. At the same time, a voltage of 40 kV is applied to the epoxy electrode. The poling voltage is regulated down if the current exceeds 10 μA , in order to avoid thermally induced electrical breakdown. The temperature is kept at 150°C and the voltage at 40kV for 10 hours. The sample is cooled down to 30°C slowly over 8 hours with the poling field maintained, in order to minimize intrinsic birefringence. The full poling process lasts 25 hours. The electric field distribution during poling is shown to the right of figure 3. It is seen that the electric field is more than 4 times larger in the middle of the EOP as compared to at the glass air interface, which is intentional because the air can withstand about 3 kV/mm whereas the polymer can withstand more than 15kV/mm without electrical breakdown. The electric poling field in the polymer determines the magnitude of the electrooptic coefficient, and should therefore be made as high as possible.

4.4 Failure rate

Poling with an electric field of up to 13kV/mm at up to 150°C is not an easy task, and electrical breakdown during poling does occur. Impurities in the EOP, scratches in the electrode and air or water trapped between the electrodes can cause electrical breakdown during poling. The number of failed samples were one as compared to five successful ones of the type with incorporated electrodes.

5. RESULTS, ELECTROOPTIC PROPERTIES

5.1 Electrooptic measurement

Having poled the electrooptic polymer, the glass mould is removed, and the sample is placed in the measurement setup shown in figure 1. An optical voltage sensor has been made. An AC voltage is applied to the electrodes, and light is sent through the polymer. The detected optical modulation follows equation 1. As seen from eqn. 1 the optical intensity modulation, m , is proportional to the electric field inside the EOP. The electric field distribution created in the polymer during measurement is shown at the left of figure 3. The measured average electric field \hat{E} in eqn. 1 is the line integral of the electric field in the poling direction along the light path through the EOP divided by the pathlength. In the geometry shown in figure 3, \hat{E} is 0.7 times E_{\max} , where $E_{\max} = U_{\text{in}}/d$ ($d=3\text{mm}$ = distance between electrodes).

$$m = \frac{I_{AC}^{(1)} - I_{AC}^{(2)}}{I_{DC}^{(1)} + I_{DC}^{(2)}} = \frac{2 \pi r_{33} n_o^3 l}{3 \lambda} \hat{E} \quad (1)$$

where m = light modulation ratio, $I_{AC}^{(1)}$, $I_{DC}^{(1)}$ are the high and low pass filtered optical signals from polarization state 1, where as $I_{AC}^{(2)}$, $I_{DC}^{(2)}$ come from polarization state 2, see fig.1. r_{33} is the electrooptic coefficient, $n = 1.6$ is the refractive index, $l = 13.5\text{mm}$ = light path length, $\lambda = 820\text{nm}$ = LED wavelength. \hat{E} = the average electric field in polymer in poling direction along the light path.

If the described voltage sensor were to be used in a 12kV power system, the sensor should, according to IEC 186²⁰, be able to measure voltages from 5 kV to 9 kV continuously, and it should be able to withstand a 60kV lightning impulse without electrical breakdown. The described optical sensor is able to measure voltages from 100V to 10kV, where the lower limit is set by noise in the detection electronics. With 10kV_{RMS} applied to the sensor, the light intensity from the output fibers is modulated 5½% peak-peak for sample epofix/DR1 with $r_{33} = 0.091 \text{ pm/V}$. The sensor is expected, but not shown, to be able withstand a 60kV pulse.

The electrooptic coefficients given for the different compounds in table 1 are measured by replacing the quarter wave plate in figure 1 with a tunable phase retarder (Babinet Soleil compensator) and then measure maximum and minimum of I_{AC} and I_{DC} by tuning the compensator, this procedure eliminates intrinsic birefringence effects¹⁷. The ratio of $I_{AC}^{(+)}_{\max} + I_{AC}^{(-)}_{\max}$ and $I_{DC}^{(+)}_{\max} - I_{DC}^{(-)}_{\min}$ is used as the modulation ratio in eqn. 1.

5.2 Two state model

It is considered that the electrooptic effect produced in the bulk polymer has its origin in the dye molecules asymmetrically changing polarizability under the influence of an electric field¹⁰. The electrooptic coefficient for the EOP is related to the dye's hyperpolarizability as follows:

$$r_{33} = \left[\frac{4 N f_o (f_\omega)^2}{n^4} \right] \left[\frac{3\omega_o^2 - \omega^2)(\omega_o^2 - \omega'^2)(\omega_o^2 - 4\omega'^2)}{3\omega_o^2(\omega_o^2 - \omega^2)^2} \right] \left[\frac{p}{5} - \frac{p^3}{105} \right] \beta_{\text{EFISH}} \quad (2)$$

$$p = \frac{f_o \mu E_p}{k T}$$

where μ = permanent dipole moment, β = first hyperpolarizability at 1907nm, N is the chromophore number density, f_o and f_ω are Onsager and Lorentz-Lorentz local-field factors, respectively. ω_o is the maximum absorption frequency in PMMA, ω is the electrooptic frequency, and ω' is the EFISH frequencies. p is the poling efficiency, where k is the Boltzmann constant, and E_p and T are the poling field and temperature, respectively.

The electrooptic coefficients of the poled bulk polymers are predicted using this theory from the properties of the dye molecules alone. Equation 2 has been used together with the values given in table 1 to find the theoretical electrooptic coefficients for the different samples of different geometry.

The values of μ and β for the dyes were determined by the EFISH method at 1907nm^{13,14}, and are listed in table 1.

5.3 Measured and predicted electrooptic coefficients

The results from the electrooptic measurements are shown in table 1. The epofix/DR1 and the E 828/[a] samples were made with electrodes embedded into the polymer, thus having low average electrooptic coefficient due to the inhomogeneous electric field shown in figure 3. The theoretical r_{33} for these two samples has been multiplied with 0.70x0.70 in order to compensate for the lower average poling and measuring field, because \hat{E}_{poling} equals 0.7 times E_p and $\hat{E}_{\text{measurement}}$ equals 0.7 times E_{max} .

The E828/DR1 sample is a sample size 3X14X20mm poled and measured in a homogeneous field. The remaining samples are 1 μ m thin film samples measured with a reflective ellipsometric technique¹⁷, also measured and poled in homogeneous electric fields.

$C_{\text{DYE}}=5\text{wt.}\%$ (bulk) $C_{\text{DYE}}=2\text{mol}\%$ (film) $\lambda_{\text{LED}} = 820 \text{ nm}$	E 828 - host polymer Bulk $T_g = 150^\circ\text{C}$ $\epsilon_r = 3.32$ $n = 1.555$	Epofix - host polymer Bulk $T_g = 80^\circ\text{C}$ $\epsilon_r \approx 3.3$ $n = 1.569$	PMMA - host polymer Thin film $T_g = 120^\circ\text{C}$ $\epsilon_r = 3.6$ $n = 1.6$
DR1 Guest dye $\mu = 7 \text{ (D)}$ $\beta = 49 \cdot 10^{-30} \text{ (esu)}$ $\lambda_{\text{max}} = 487 \text{ (nm)}$	$r_{33}=0.184 \text{ pm/V Meas.}$ $r_{33}=0.160 \text{ pm/V Calc.}$ $E_p = 15 \text{ kV/mm}$ $\alpha (820\text{nm})=0.093 \text{ mm}^{-1}$ $\tau_o (20^\circ\text{C}) = 55 \text{ years}$	$r_{33}=0.091 \text{ pm/V Meas.}$ $r_{33}=0.082 \text{ pm/V Calc.}$ $E_p = 13 \text{ kV/mm}$ $\alpha (820\text{nm})=0.075 \text{ mm}^{-1}$ $\tau_o (20^\circ\text{C}) = 1.5 \text{ years}$	$r_{33} = 0,8 \text{ pm/V Meas.}$ $r_{33}=1.2 \text{ pm/V Calc.}$ $E_p = 100 \text{ kV/mm}$
[a] Guest dye $\mu = 9.7 \text{ (D)}$ $\beta=124 \cdot 10^{-30} \text{ (esu)}$ $\lambda_{\text{max}} = 516 \text{ (nm)}$	$r_{33} = 0.044 \text{ pm/V Meas.}$ $r_{33} = 0.121 \text{ pm/V Calc.}$ $E_p = 6.7 \text{ kV/mm}$ $\alpha (820\text{nm})=0.096 \text{ mm}^{-1}$	Dye is decomposed by epoxy hardener.	$r_{33}=5.0 \text{ pm/V Meas.}$ $r_{33}=5.4 \text{ pm/V Calc.}$ $E_p = 100 \text{ kV/mm}$
[b] Guest dye $\mu = 5.9 \text{ (D)}$ $\beta=248 \cdot 10^{-30} \text{ (esu)}$ $\lambda_{\text{max}} = 558 \text{ (nm)}$	Polysulfone (thin film) $r_{33}=4.2 \text{ pm/V Meas.}$ $r_{33}=4.5 \text{ pm/V Calc.}$ $E_p=100 \text{ kV/mm}$ $\tau_o (20^\circ\text{C}) = 49 \text{ years}$	Polycarbonate (thin film) $r_{33}=2.8 \text{ pm/V Meas.}$ $r_{33}=2.2 \text{ pm/V Calc.}$ $E_p=30\text{kV/mm}$ $\tau_o (20^\circ\text{C}) = 8.4 \text{ years}$	PMMA (thin film) $r_{33}=6,0 \text{ pm/V Meas.}$ $r_{33}=7.7 \text{ pm/V Calc.}$ $E_p=100 \text{ kV/mm}$ $\tau_o (20^\circ\text{C}) = 0.8 \text{ years}$

Table 1, Electrooptic results, measured and calculated values of electrooptic coefficient for three bulk samples and five thin film samples. τ_o = relaxation time constant from best fit to eqn. 3. α = optical absorption coefficient, λ_{max} measured in PMMA, $\mu\beta$ measured by EFISH at 1907nm, E_p = maximum poling field.

5.4 Discussion

The electrooptic coefficients measured on bulk electrooptic polymers compare well with the values predicted by the two state model, the average deviation is 17%. This indicates that the electrooptic effect of the EOP is closely linked to the nonlinear optical properties of the dopant dye. For the thin film samples the measured values are in general slightly smaller than the predicted values (the average of 25 samples: 1.1 times smaller), whereas for the bulk samples with DR1 dye the measured values are higher than the predicted values, which can be explained by the very good poling efficiency obtained when the dye is oriented in the polymer before the polymer is fully polymerized.

The electrooptic coefficient of the bulk sample E828/DR1 is 7 times smaller than that of the thin film sample PMMA/DR1, because the poling field of the bulk sample is 7 times smaller. It is not possible to pole bulk samples with 3 mm electrode gap with as high poling fields as 100kV/mm without electrical breakdown; this is only possible in very thin films with a few μm electrode gap.

E828/DR1 has an electrooptic coefficient of 0.2 pm/V, this value is sufficiently high for the high voltage device, but unfortunately the disperse red 1 molecule is not stable with regard to trans-cis isomerization¹⁸. When the environmental temperature is changed during measurement, the electrooptic coefficient also changes, but it does not find a new stable value until after 24 hours, and the swing in r_{33} can be up to 50% of the original value.

Dye [a] and [b] were examined as guest dyes, with higher β than DR1, in the epoxy polymer. Dye [b] reacted with the amine epoxy curing agent. Dye [b] is therefore not suitable as guest dye in an epoxy EOP. Dye [a] reacted slightly with the epoxy E828 during curing/poling, thus giving a very low electrooptic coefficient of 0.044pm/V which is insufficient for the high voltage sensor.

A stable dye, which shows no cis-trans transitions, which does not react with the epoxy system, and which has higher β than DR1, still remains to be found.

The [a] dye, however, is stable with regard to temperature changes, the temperature coefficient of the optical output is 0.1 % per degree celsius, ($0^\circ\text{C} - 80^\circ\text{C}$). The temperature dependence is mainly due to the temperature dependent electrooptic coefficient and refractive index, and the thermal expansion of the polymer. In practical devices this linear temperature dependence must be compensated for either optically or electronically. The temperature compensation could be made by measuring the temperature in the polymer with a passive fiber optic temperature sensor, based on a $\lambda/4$ plate²¹.

6. RESULTS, ORIENTATIONAL STABILITY

The power utilities expect high voltage instrument transformers to last for 30 years, it is therefore important that the EOP material is long-term stable. According to IEC 186²⁰ the device should be able to operate in the temperature range -25°C to $+40^\circ\text{C}$ with an average temperature not exceeding 30°C .

The orientational stability of the produced guest-host electrooptic polymers is examined by measuring the electrooptic coefficient a number of times within the first year after poling, and at all time storing the samples at room temperature ($15-25^\circ\text{C}$). The decay curves are described well by the Williams-Watts-Kohlrausch function¹⁹, eqn. 3.

$$r_{33}(t) = r_{33}(0) * \exp\left[\left(\frac{t}{\tau_0}\right)^\beta\right] \quad (3)$$

Williams-Watts-Kohlrausch function, $0 < \beta < 1$ is an order parameter, τ_0 is the relaxation time constant.

As seen in figure 4, the epoxy based bulk polymer has relatively good stability properties. For the E828/DR1 sample, the electrooptic coefficient has decreased less than 6% within the first 1 1/2 year after poling. The E828 does apparently have superior long-time stability over the polysulfone thin film sample despite the high glass transition temperature of the polysulfone/[b] samples, 165°C , as compared to around 150°C for E828/DR1. Probably because the slow quenching process after poling (8 hours) for the E828 material reducing excess free volume, and because the E828 material is crosslinked where as the polysulfone is a linear polymer. The decay in r_{33} for Epofix, and PMMA samples is a fast process, less than 40% of the original r_{33} is left after 1 year which can be explained by the low glass transition temperatures of these samples.

For the guest/host materials described here, the Williams-Watts-Kohlrausch function gives a good prediction of the decay in r_{33} with time at a fixed temperature. From six measurements over one month on each sample it was possible to predict the size of r_{33} after 10 months for PMMA and Polysulfone with good accuracy. On the average (based on measurements on 5 different samples made of polysulfone, polycarbonate and polyimide) this procedure gave a prediction of r_{33} after 10 months, which was lower than the actual value measured 9 months later. This makes eqn.3 very suitable for predicting the long-time stability of guest/host electrooptic polymers. The stability of E828/[a] was also examined at higher temperatures. After some annealing, this material showed no detectable (less than 0.4%) decay in r_{33} after 13 days at 60°C .

The most stable material examined here, E828/[DR1] is according to eqn. 3 predicted to have only 50% of its original value of r_{33} remaining after 30 years of lifetime even at room temperature. It is therefore not able to meet the demand of 30 year lifetime at an maximum average temperature of 30°C. The more long-term stable co-polymer systems may be able to meet these requirements, but temperature cycles of a large number of samples over at least one year is necessary in order to prove such long-term stability.

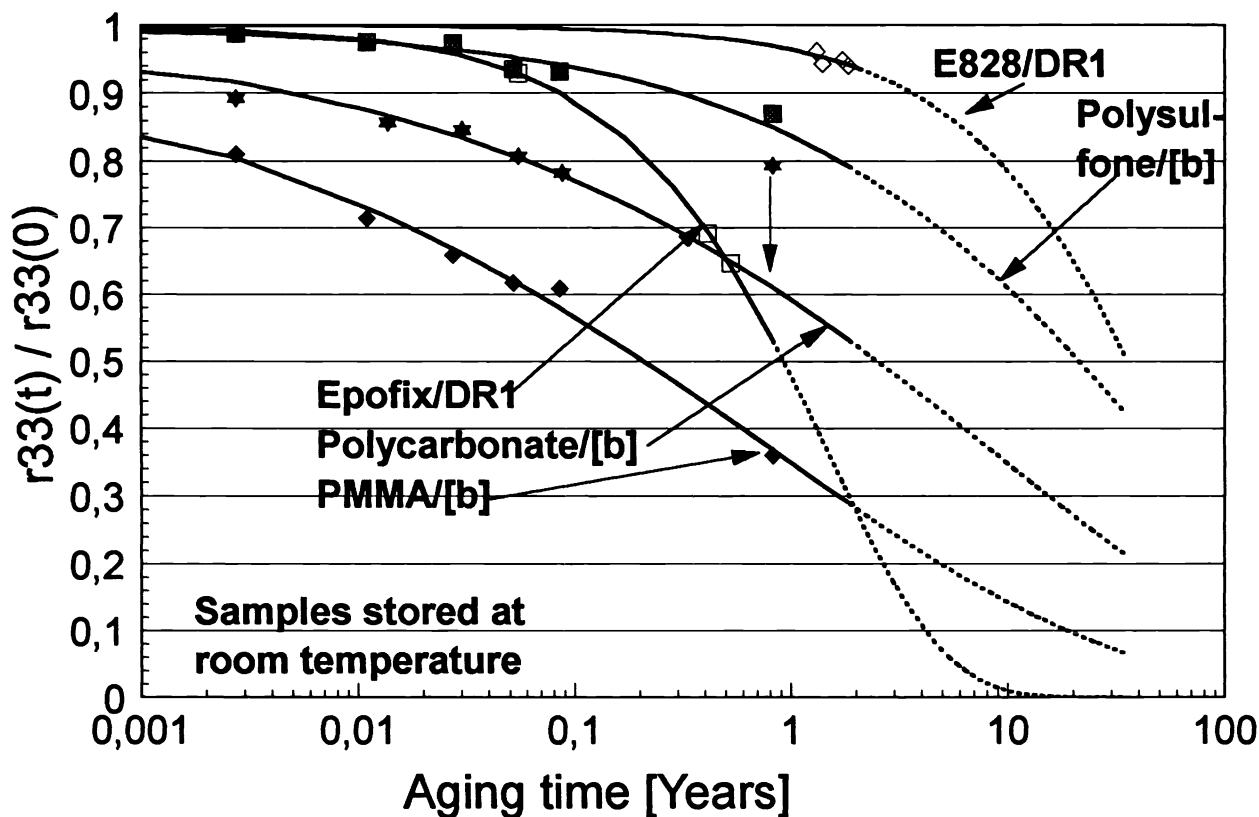


Figure 4. The decay in electrooptic coefficient as a function of aging time for samples stored at room temperature. E828 and Epofix samples with DR1 dye and Tg of 150°C and 80 °C (value for polymer), Polysulfone, polycarbonate and PMMA samples with [b] dye with Tg of 165°C, 131 °C and 106 °C (values with dye incorporated). The dotted line is an extrapolation made using eqn.3.

7. CONCLUSION

Electrooptic polymers are a promising new type of material for use in high voltage applications. They have the inherent ability of being manufactured into sensors of very small size at a low cost. It was shown in this work that it is possible to make a voltage sensor using electrooptic polymers. The described experimental voltage sensor, can measure voltages up to 10 kV rms, with voltage/signal proportionality.

The produced electrooptic effect in the described guest/host materials compare well with values calculated from the nonlinear optical properties of the guest dye molecule. The epoxy polymer used for producing bulk sensors was shown able to maintain 94% of the induced orientation of the chromophores within the first 1½ year at room temperature. There are, however, still very serious problems to be addressed with regard to stabilizing the optical output when the temperature is altered for short or long periods of time. This work does also point out the need for commercially available and stable nonlinear materials.

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Jørgen Skindhøj was born in Denmark in 1966. In 1991 he graduated from the technical university of Denmark, receiving a M.Sc. degree in electrical engineering. From october 1991 he is working on his Ph.D. about fiber optic sensors for power applications, utilizing electrooptic polymers. In 1993 he visited Jet Propulsion Laboratory, California Institute of Technology for 7 months, where he worked with characterization of electrooptic polymers.