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Capacitively coupled KD*P Pockels cell for high voltage pulse measurements

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Abstract. A device for high voltage measurements of fast spark transients in electrically noisy environments is presented. The design utilises a KD*P Pockels cell and a capacitive coupling between the Pockels cell electrode and the high voltage spark electrode. Due to this capacitive voltage divider, the device can be adjusted so that maximum response within the linear range can be obtained for a wide range of voltages. Further characteristics of the device are its fast response time (ns), simplicity of set-up and excellent RF noise suppression because of the electrical isolation of the detector.

1. Introduction

The development of powerful laser techniques has provided new tools for studies of fast electrical discharges. The work of our laboratory in this field is aimed at investigations of intrinsic spark parameters and ignition properties of sparks (Aldén *et al* 1983).

One important parameter characterising a spark is the voltage waveform at the spark gap. Since our work is concerned with sparks having risetimes of a few ns and peak voltages of 5–30 kV, no commercial probes were readily available. Furthermore, the intense electrical RF noise from the spark requires total electrical isolation of the detection system. This is hard to achieve with a conventional high voltage (HV) probe connected to an oscilloscope.

This paper describes a HV measuring device, which employs a commercially available KD*P Pockels cell. The device is insensitive to electrical noise, has a fast response time (ns), is simple to assemble and easy to adjust for maximum response within the limits of linearity for a wide range of voltages.

2. Design and experiments

2.1. Principles of operation

The device described in this paper combines two well known HV measuring techniques: the capacitive voltage divider and the electro-optic Pockels effect. These will be briefly described in the following.

The principle of the capacitive divider for measurements of HV pulses with an oscilloscope is well known (e.g. Schwab 1972). The method relies on the fact that two pure capacitances in series, which are connected between a HV source and a reference potential (e.g. ground), divide a voltage pulse at the HV source independent of frequency according to

$$V=\frac{C_2}{C_1+C_2}V_0.$$

Here V_0 and V are the input high voltage and the divided voltage respectively and C_1 and C_2 are the two capacitances. A capacitive divider system is simple and, if properly designed, is also fast (ns). It has, however, a few disadvantages. It is not electrically isolated from the spark source, which often results in severe noise problems. Furthermore, in order to avoid cable reflections, the oscilloscope input impedance (R) must match the cable impedance. This results in a rather short time constant C_1R (often only a few 100 ns), making it possible to accurately measure only the high frequency content of the signal. The last problem can be solved with the insertion of a high impedance voltage follower between the capacitive divider and the oscilloscope (cf Benjamin 1982). This electronic device has then to be very carefully shielded from the electrical noise. Further, one has to consider that the inherent inductances in the leads form a series resonance circuit with the capacitances of the divider which might distort the highest frequency components of the voltage pulse to be measured.

The Pockels effect, or the linear electro-optic effect, is described in any optics textbook. Its use as a HV probe has been described earlier (Mitani and Nakaya 1978, Ballik and Liu 1983). However, for practical applications the voltage range of Pockels cell devices is often limited.

Briefly, the method relies on a voltage-induced birefringence in certain crystals, e.g. quartz or KDP. If light of proper polarisation is transmitted through the crystal, the Pockels effect yields an optical phase delay proportional to the voltage according to

$$\Gamma=\pi V/V_{\lambda/2}$$

where Γ is the phase delay in radians, V is the voltage applied over the crystal and $V_{\lambda/2}$ is the half-wave voltage of the crystal. $V_{\lambda/2}$ is specific for each crystal, being inversely proportional to the electro-optic coefficient of the crystal material. The common commercial Pockels cells used in the device described in this paper are of the longitudinal type, i.e. the voltage V is applied in the same direction as the light path.

In order to detect the voltage-induced optical phase delay the set-up of figure 1 is usually used. Here a Pockels cell is placed between crossed polarisers and a beam of light is transmitted through the optical components to the detector. A voltage-induced change of the birefringence results in an intensity variation at the detector according to

$$\frac{I}{I_0}=\sin^2\left(\frac{\pi}{2}\frac{V}{V_{\lambda/2}}+\theta\right)$$

where I is the intensity at the detector and I_0 is the input intensity.

This function is shown in figure 2 for $\theta=0$. The insertion of a quarter-wave plate in the system, as shown in figure 1, is optically equivalent to the connection of a DC bias voltage of $V=\frac{1}{2}V_{\lambda/2}$, i.e. $\theta=\pi/4$. The output intensity I will then be a nearly linear function of the voltage V around the $I=I_0/2$ point. In the $I=I_0/2\pm I_0/4$ interval the deviation from linearity is less

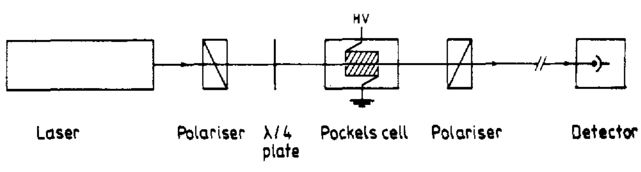

Figure 1. Usual set-up for electro-optic Pockels cell measurements of high voltages.

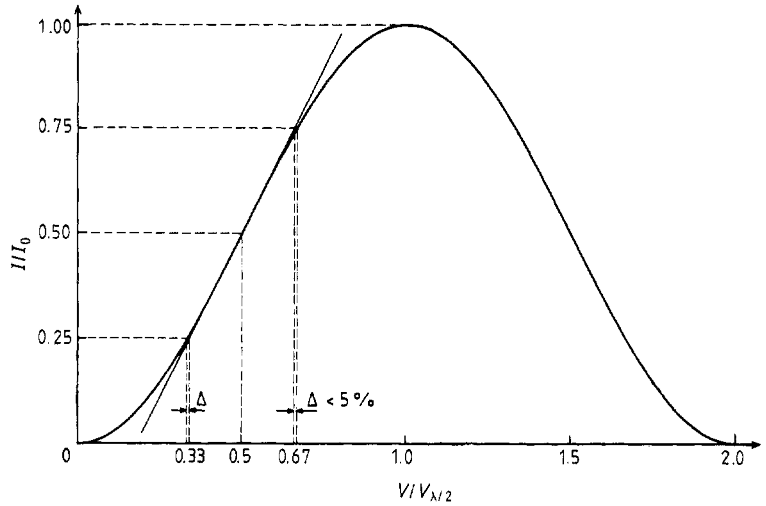

Figure 2. The intensity variation at the detector as a function of an applied voltage V over a Pockels cell in the set-up of figure 1. With a quarter-wave plate bias the intensity varies linearly with the voltage in the interval $I=I_0/2 \pm I_0/4$ with less than 5% error (Δ). This intensity interval corresponds to a voltage interval of $V=\pm 0.17 V_{\lambda/2}$.

than 5%, as indicated by Δ in figure 2. For our purposes the intensity in this interval can be considered linearly dependent on the voltage. Thus, as shown in figure 2, the useful linear range for a voltage measurement with a Pockels cell directly connected to the HV source is limited to $V=\pm 0.17\ V_{\lambda/2}$. A more thorough discussion of these arguments, including the problems of linearity, is presented by Ballik and Liu (1983).

The Pockels effect method for HV pulse measurements has a number of advantages. The basic set-up is simple, the device is fast (ns) and excellent suppression of electrical noise is provided by moving the electrically isolated detector as far away from the noise sources as is necessary for total noise reduction. The disadvantages include the nonlinear I/I_0 response at voltages above a certain fraction of $V_{\lambda/2}$. This problem is especially pronounced when using commercially available KD*P Pockels cells, which have half-wave voltages of around 3.4 kV. The remedy is either to linearise the measurement afterwards or to use another crystal with a lower electro-optic coefficient, for example quartz (Ballik and Liu 1983) or KDP. However, in order to achieve maximum response within the limits of linearity for a wide range of voltages, a number of types of crystals must be used. Alternatively, if the crystal is transversely coupled (Ballik and Liu 1983), the voltage range can be adjusted for by a suitable selection of crystal length. However, with directly coupled Pockels cell devices the voltage range is always ultimately limited by sparking between the electrodes along the crystal surface.

2.2. Experimental arrangement

The present device uses a Pockels cell in combination with a capacitive divider. This combines the advantages of both systems and increases the useful voltage range practically without limits. Also, by proper selection of the capacitive division, the linear range of the device can be adjusted to suit the voltage range to be measured in order to obtain maximum response. By using a KD*P Pockels cell, with its high electro-optic coefficient, voltages from approximately 100 V to infinity can be covered. Further, the system uses only commercially available components, which greatly simplifies the construction.

The present set-up uses a commercial Nd : YAG-laser KD*P Q-switch in the same principal arrangement as that of figure 1 with one important difference: the positive electrode of the KD*P crystal is not directly connected to the HV spark electrode. The electro-optic design is schematically depicted in figure 3. The unknown voltage V_0 is coupled into the Pockels cell through the capacitance C_s between the HV electrode and an 'antenna' A, which is connected to the positive Pockels cell electrode. This capacitance depends on the geometry between the HV electrode and the 'antenna' A. The other Pockels cell electrode is connected to ground via a shielded cable. As the Pockels cell itself is an almost pure capacitance C_p (approximately 6 pF), the two capacitances C_s and C_p form a capacitive divider. Thus, the system in figure 3 can be considered to work as a capacitive divider with a high impedance KD*P crystal detector. Other capacitances than C_s in the system, e.g. the stray capacitance between the antenna and ground, affect the voltage division only with a constant, frequency independent factor, which is determined by the calibration procedure described below.

The voltage probe sensitivity is easily adjusted for maximum response within the linear range through changes of the capacitance C_s using differently shaped antennae connected to the KD*P electrode. In the current set-up the full scale reading

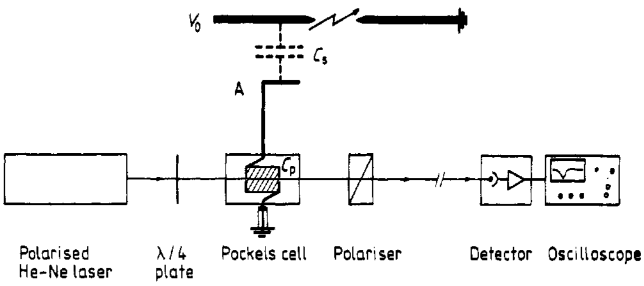

Figure 3. Schematic diagram of the electro-optic design of the capacitively coupled Pockels cell device. The 'antenna' A connects the Pockels cell electrode and the HV electrode via the capacitance C_s. The voltage V_0 is divided capacitively between C_s and the Pockels cell capacitance C_p.

($I = 0.25I_0$ or $0.75I_0$) can be obtained from $V_0 = 600$ V with direct coupling to $V_0 = 50$ kV with a minimum capacitive coupling.

The laser used in the system is a 10 mW He–Ne laser (Hughes). Its intensity varies less than 0.5% for all frequencies of interest, which is important in this application. The detector comprises a biased fast pin-diode (Hamamatsu). Its output is amplified 36 times by an amplifier constructed of discrete components. The total risetime of the detector is 4 ns, presently being the slowest part of the system. Alternatively, a photomultiplier tube could be used in order to improve response time. However, in that case a light chopper has to be inserted in the system to avoid damage of the photomultiplier caused by the DC light level.

2.3. Results

In order to create sparks a thyratron is used to generate 200 ns long HV pulses, which are transmitted to the spark electrodes through a 75 m coaxial cable. This long cable is chosen to avoid the influence of reflections in the timescale of interest. An oscilloscope track of such a spark is shown in figure 4. In this case the detector was placed in another room some 20 m away from the spark source in order to avoid the RF interference. As the intensity $I_0/4$ corresponded to 150 mV at the oscilloscope screen, the measured voltage pulse was well within the $I = I_0/2 \pm I_0/4$ linear domain. This waveform would not have been observable with a conventional HV oscilloscope probe due to the intense RF background generated by the spark.

For each new experimental set-up the HV measuring system should be calibrated because C_s and the other capacitances, and thus the voltage division, may have changed. This is done with a conventional HV probe using lower voltage pulses which do not create sparks and electrical noise.

In figure 5 the linearity of the Pockels cell device was tested against a calibrated HV probe. In this case $I_0/4$ corresponded to 176 mV on the oscilloscope. The figure shows that the Pockels cell behaviour agrees well with theory, including the deviation from linearity at higher voltages. Thus, as long as the intensity modulation is within the $I = I_0/2 \pm I_0/4$ linearity limits, the oscilloscope trace of the Pockels cell response is easily calibrated with one reading.

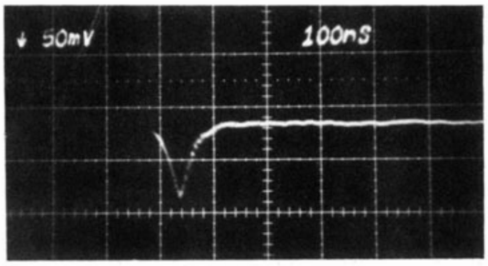

Figure 4. Spark voltage waveform recorded with the Pockels cell system. The vertical scale is 50 mV/div and the horizontal scale is 100 ns/div.

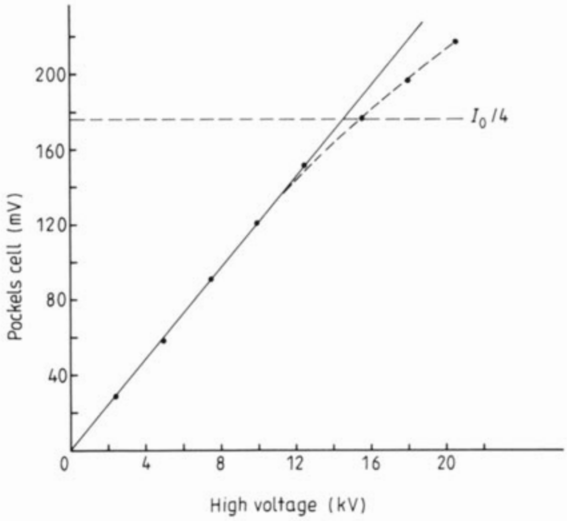

Figure 5. Test of linearity of the capacitively coupled Pockels cell device. The deviation from linearity at higher voltages is due to the intrinsic nonlinear response of the system as illustrated in figure 2.

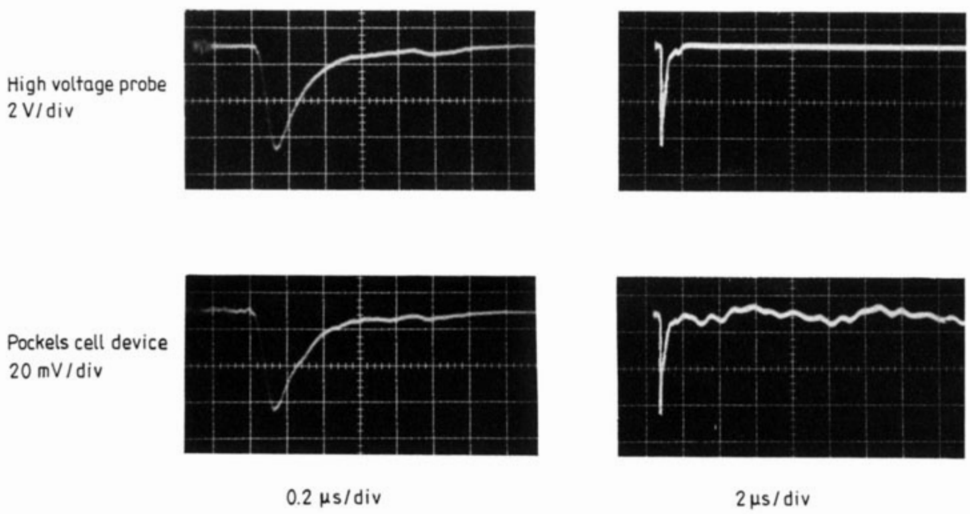

Figure 6. Comparison of the Pockels cell device with a conventional probe (1:1000 voltage division) under non-sparking conditions. In order to avoid cable reflections, the spark electrodes were connected with a 50 Ω resistance. The 200 ns HV pulse excites acoustic resonances in the crystal. The influence of the acoustic oscillations is negligible on the short timescale displayed (0.2 μs/div) but distorts the waveform of the longer timescale (2 μs/div).

As mentioned above, the Pockels cell is nearly a pure capacitance. The parallel resistance (R_p) between the Pockels cell electrodes was found to be $7 \times 10^{10}\ \Omega$. This results in a $R_p C_p$ time constant of about 0.4 s. This long time constant has been experimentally observed with slowly varying HV pulses. For fast HV pulses, however, oscillations at acoustic crystal resonance frequencies may develop in the system. The crystal has acoustic oscillations of the order of μs, which may cause distortion if measurements are to be performed in this time domain. However, for measurements as fast as that of figure 4, the intensity variation due to the acoustical vibration is negligible in the short time of interest. For slowly varying voltage pulses with no frequency component above the acoustic resonance frequency, the acoustical oscillation will not be excited and thus will not interfere with the measurement.

Figure 6 shows a comparison in the μs time domain of voltage pulses recorded with a conventional probe (Tektronix PE6015, 1 : 1000 voltage division) and the Pockels cell device. Here, a 50 Ω resistance was connected between the spark electrodes to minimise reflections of the 200 ns voltage pulse. A small residual reflection can be observed approximately 700 ns after the pulse. Sparking was avoided using low voltages (5 kV peak voltage). In the fast recording (0.2 μs/div) practically no difference between the conventional probe and the Pockels cell device can be observed, i.e. the acoustical oscillations have a very small influence on the waveform. However, in the recording with 2 μs/div the effect of the acoustical vibrations is evident, making detection of small voltage pulses following the big one difficult with the Pockels cell device. In the Pockels cell used here the acoustic oscillation continues to vibrate for 0.1–1 ms. This time can be shortened if the crystal is damped in a similar way as is done in the field of transducers for ultrasound echo methods (Kossoff 1966).

The resonance behaviour of the Pockels cell device at frequencies above 1 MHz was investigated with a Hewlett Packard 4191A RF impedance analyser (1–1000 MHz). At these frequencies the inductances of the leads form series resonances with the capacitance of the Pockels cell (C_p). If no external leads were connected to the Pockels cell the resonance occurred at 550 MHz, corresponding to a minimum risetime of < 700 ps. With the leads used in the actual system the risetime of the Pockels cell system was found to be slightly longer, still indicating a risetime of < 1 ns.

3. Conclusions

This paper has shown that a KD*P Pockels cell capacitively coupled to a HV electrode is a versatile tool for HV pulse measurements over a wide range of voltages. The advantages include excellent suppression of electrical noise, fast response (ns), rapid set-up including calibration and simple adjustment for maximum response within the linear range for a wide range of voltages. Furthermore, the probe can be totally isolated from ground potential. For fast voltage waveforms ($< \mu$s) the measurement accuracy is comparable to that of commercial probes. However, these are slower than the Pockels cell device and sensitive to RF interference. In the μs time domain acoustical oscillations in the Pockels cell crystal limit the accuracy somewhat.

Acknowledgments

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