Quantum Electronics Letters

Measurement of High-Voltage Pulses Employing a Quartz Pockels Cell

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Abstract—A high-voltage measuring system, employing a quartz Pockels cell, is described. The system is capable of a large voltage range, a fast response time (ns), a high SNR, an excellent accuracy, a good linearity, and high reliability. Furthermore, the Pockels cell can be isolated from ground potential. Equally important, the detection system can be isolated from sources of electrical noise present in, for example, fast discharges.

Introduction

PROPOSED studies of the discharge kinetics of a small XeCl laser system (~1 ns pulse duration with ~1 mJ output energy) [1] require accurate measurements of the current and voltage waveforms (~15 ns duration). The latter waveform has falltime components in the nanosecond (or subnanosecond) range. Furthermore, the voltage measurements cannot be carried out with reference to ground potential. Voltage probes having adequately fast response, together with the ability for isolation (i.e., to float above ground) were not readily available. Therefore, it was essential to develop suitable "probes."

KDP has been employed as a Pockels cell for voltage measurements of a TE N_2 laser [2]. However, this material is expensive in large sizes, is hydroscopic, and has too high an electrooptic coefficient for convenient use at high voltages (>10 kV). Initially, a voltage-measuring system employing a Kerr cell was investigated because the technique appeared to be suitable for fast high-voltage pulses [3]. It was anticipated that the large nonlinearity inherent in the Kerr effect could be corrected for. Preliminary work, using prepurified nitrobenzene in a simple Kerr cell arrangement, indicated that considerable further effort would be necessary in order to achieve a suitably fast response, as required for the laser measurements [4].

This paper describes a system employing an inexpensive quartz crystal as a Pockels cell which provides the necessary electrical isolation and fast response (from dc to the ns range). Furthermore, the measuring system has excellent linearity, is reliable, and is easy to construct and use. An important advantage, common to all optically based techniques, is the high SNR possible because the measuring instrumentation can be isolated from the large electrical noise signals which are always present in high-voltage, high-current discharges. Peak-to-peak voltages from less than 1 kV to substantially more than 100 kV can be measured accurately by choice of the appropriate crystal dimensions. The capability for subnanosecond response times has already been demonstrated for quartz [5].

Manuscript received November 5, 1982. This research was supported in part by the National Science and Engineering Research Council, Ottawa, Ont., Canada.

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Experimental Method

Briefly, the technique relies on voltage-induced polarization changes in the optical radiation passing through an appropriate crystal. Inexpensive, oriented, ground-finish quartz bars, of the type used for electronic oscillators, were employed for the measurements [6]. These were rectangular in cross section, with dimensions ~1.0 cm (between the x surfaces) and ~2.1 cm (between the y surfaces). The bars were cut (perpendicular to the z axis) to a length of ~14 cm. The ends were then polished by hand, with the aid of a jig to support the bars.

Voltage is applied across the x surface of the bar by means of copper-foil electrodes held in position by pressure pads. Linearly polarized laser radiation is incident on the crystal in the direction of the z axis, but at 45° to both the x and y axes. The output from the crystal passes through a linear polarizer (the transmission plane is usually at 90° relative to the input polarization), and is then made incident on a photomultiplier tube (PMT). For a reasonable quality crystal, the PMT output current varies as

$$I/I_{\max} = \sin^2 [(\pi V/2V_{1/2}) + \theta] \tag{1}$$

where V is the voltage applied across the crystal, and $V_{1/2}$ is the applied voltage necessary to rotate the plane of polarization by 90°. This voltage can be calculated from [7]

$$V_{1/2} = t\lambda/2ln_0^3\gamma_{11} \tag{2}$$

where t and l are the thickness and active length, respectively, of the quartz crystal, and γ_{11} is the appropriate electrooptic coefficient. A curve representing (1), for an ideal crystal having $\theta = 0$, is given in Fig. 1. In practice, the curve will be

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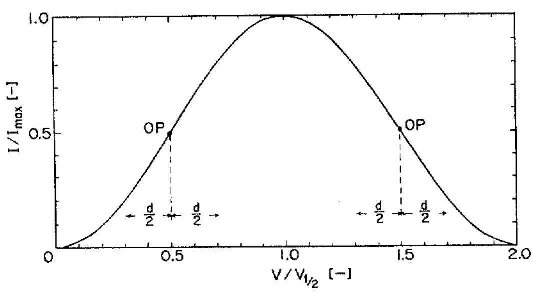

Fig. 1. Normalized PMT output current as a function of the normalized applied crystal voltage. This curve is calculated from (1), with $\theta = 0$. The operating point (OP) is the value of $V/V_{1/2}$ which gives the best linearity. The total change in $V/V_{1/2}(d)$ represents the normalized peak-to-peak voltage of a pulse being measured.

displaced ($\theta \neq 0$) due to factors such as imperfections and stress in the material. The angle θ can also be changed by using, for example, a compensating plate.

In Fig. 1, optimum signal linearity occurs for the applied voltage peaks located symmetrically about the operating point (OP). For this condition, it can be shown that the ratio of the measured voltage (V_m) to the actual voltage (V_a) is

$$V_m/V_a = [\sin(\pi d/2)]/(\pi d/2) \tag{3}$$

where d refers to the total normalized voltage swing indicated in Fig. 1. The corresponding percentage error is given in Fig. 2. The error is acceptably small for relatively large values of d. Furthermore, corrections can be made easily.

The quartz bar used in the experimental studies was not of optical quality. A strip of seed crystal ~1 mm thick was located in the center of the bar. In addition, crystal imperfections and stresses were also present. However, it was relatively easy to find portions of the cross section which were suitable for measurements. The results of calibration, employing a He-Ne laser, are presented in Fig. 3, for a portion in which θ is near zero. Relatively low voltages were employed for the measurements in order to avoid air breakdown between the electrodes. A simple fit to the data results in $V_{1/2} = 28.6$ kV and $\theta = -0.8°$. These values were used to calculate the curve shown in Fig. 3. The value of γ_{11}, calculated using (2), is 2.22×10^{-13} m/V.

A cross-sectional view of the XeCl laser, the Pockels cell, and the mounting assembly, are shown in Fig. 4. The circuit board provides the capacitors for the Blumlein discharge circuit used to excite the laser [1]. Both the laser circuit and the Pockels cell circuit have very low inductance. Air breakdown (in unavoidable air spaces between the crystal and the assembly) is not a problem because the voltage-pulse durations are small (~15 ns). Higher dc and pulse voltage capability can be achieved by using, for example, a dielectric fluid in the air spaces.

The experimental measurements were carried out using the arrangement shown schematically in Fig. 5. Apertures 1 and 2 (~1 mm diameter) define the beam passing through the Pockels cell. A beam switch is used to pulse the He-Ne laser output in order to prevent damage to the PMT. In general, a PMT will tolerate much higher peak intensities in a short duration pulse compared to a long duration pulse. A high intensity is necessary to achieve a good SNR with a wide electronic band-

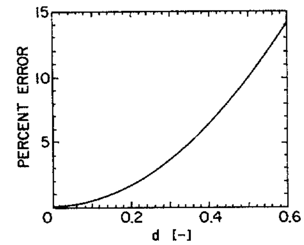

Fig. 2. The maximum percentage error as a function of the normalized peak-to-peak applied voltage.

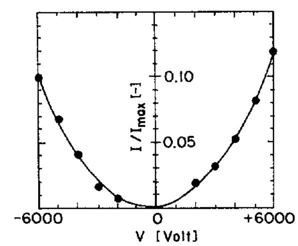

Fig. 3. Normalized PMT output current as a function of the applied crystal voltage. The plotted points are experimental measurements. The curve is calculated using (1).

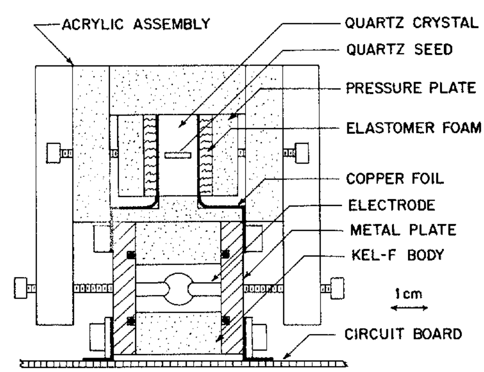

Fig. 4. Simplified cross section of the laser and Pockels cell. The copper foil electrodes are on the x surfaces of the quartz crystal. For clarity, the laser preionization system is not shown.

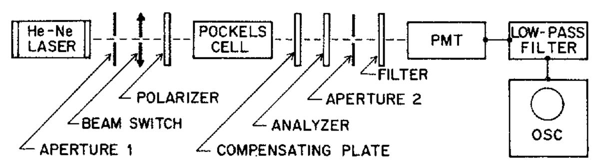

Fig. 5. Experimental arrangement for voltage measurements. The Pockels cell is connected as shown in Fig. 4.

width. The beam switch consists of an aperture (~1 mm diameter) mounted on the armature of a fast relay. When the relay is activated, the aperture passes quickly through the laser beam (~1 ms). At the time of maximum beam transmission, the relay contacts close to trigger the XeCl laser.

The axes of the polarizer and analyzer are perpendicular to each other, and at 45° to the quartz crystal x and y axes. The compensating plate makes it possible to vary θ in (1), and, consequently, to operate the Pockels cell in a linear region. A thin sheet of mica was employed for this purpose. Rotation about an appropriate axis provided the necessary compensation. The filter (narrow passband at 633 nm) allows system operation in a normal laboratory environment.

An available 10 stage PMT (RCA C7151W) was operated under conditions providing the fastest response time. The number of active dynode stages was reduced (to 5), and operation was at high PMT divider voltage (~1.2 kV). The voltage between the cathode and dynode 1, between successive dynodes, and between dynode 5 and ground, were in the ratios 1.7, 1.2, 1.2, 1.0, 1.4, and 2.0, respectively. Dynodes 6-10 and the anode were connected together to form a resultant anode.

The output of the PMT contained a strong 380 MHz component resulting from modes in the high-stability He-Ne laser (Spectra Physics 120). This signal component was minimized using a single-section *m*-derived ($m = 0.6$) low-pass filter, with maximum attenuation at 380 MHz, and a bandwidth of 300 MHz. The data were recorded using a 450 MHz bandwidth storage oscilloscope (Tektronix 7834 with 7A19 preamps), providing a resultant filter-oscilloscope risetime of 1 ns.

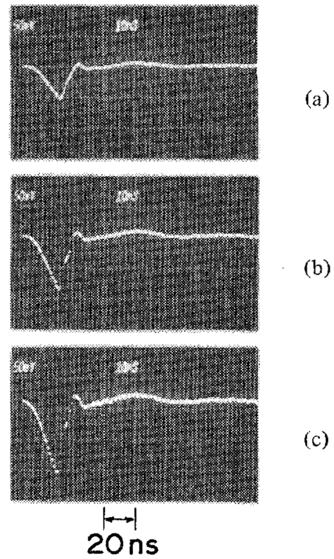

Fig. 6. Waveforms using the quartz Pockels cell. Essentially identical voltage pulses are shown in each photograph. The PMT gain was increased from (a) to (b) to (c) in order to provide additional detail.

Results and Discussion

Initial voltage measurements have been carried out on the small XeCl laser system [1] using a total gas pressure of ~3300 torr. An example of these measurements is shown in Fig. 6, where the peak-to-peak is ~11 kV, which corresponds to the discharge breakdown voltage. The PMT peak output current was increased [from ~2 mA in Fig. 6(a) to ~5 mA in Fig. 6(c)] by increasing the PMT voltage. A small amount of residual mode-beating (380 MHz) can be seen in the figures. This can be reduced by additional signal filtering.

Immediately after breakdown, the falltime is ~3 ns, which is probably limited by the PMT. The short duration "oscillation" is in the laser-discharge and capacitor circuit; the long duration "oscillation" is in the spark-gap and capacitor circuit.

Fig. 6, together with the previous section, demonstrates that a system employing a quartz Pockels cell is very suitable for high-voltage measurements. Quartz is an ideal material for this purpose because of relatively low cost, easy fabrication, and excellent mechanical and chemical stability. Furthermore, the low electrooptic coefficient makes the material particularly suitable for high-voltage applications. By the appropriate choice of material dimensions (and dielectric fluids, etc., if necessary), peak-to-peak voltages ranging from less than 1 kV to substantially more than 100 kV can readily be measured. The measuring system is also capable of high SNR, high accuracy, good linearity, and high reliability. This type of system should have wide application in the measurement of high voltages, particularly for lasers employing fast discharges.

Further research will be carried out to determine the full potential of the measuring system. The major anticipated improvements, in response time and signal-noise levels, will result from the use of a single-mode pulsed output from a He-Ne laser, and a fast channel plate PMT.

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