Simultaneous High Intensity Ultrashort Pulsed Electric Field and Temperature Measurements Using a Unique Electro-Optic Probe

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***Abstract*—High intensity nanosecond pulsed electric fields and temperature were simultaneously measured using a unique electro-optic (EO) probe. The measurements were performed in an electroporation cuvette with 4 mm electrode gap and filled with a buffered salt solution. High voltage generators delivering 2.6 and 10 ns duration pulses with different pulses shape and intensity were investigated. The EO probe linearity was characterized up to 2 MV/m. The temperature measurement uncertainty was found to be less than 22 mK. Excellent measurement abilities were achieved with this EO probe showing its suitability for bioelectromagnetic experiments and particularly for wideband high intensity field applications.**

***Index Terms*—Electro-optic (EO) probe, finite difference time domain (FDTD), temperature measurement, vectorial electromagnetic field measurements.**

I. Introduction

PULSED electric fields (PEF) have gained considerable attention in the recent years due to their great potential applications in medicine, biotechnology and environment [1]. Recently, nanosecond pulsed electric fields (nsPEF) have been the subject of intense investigation. These high intensity (0.5–30 MV/m) pulses in the tens-of-nanoseconds range (4–300 ns) have been shown to impact both cell functions and structure [2]. The knowledge of the physical parameters, such as electric field (E-field) and temperature, is of great importance when PEF are applied to biological samples. Indeed, significant Joule heating can arise and damage the biological cells or tissues under critical exposure conditions of E-field strength and repetition rate [3], [4]. For this reason, the simultaneous measurement of the E-field and temperature can be highly advantageous to monitor bioexperiments protocol.

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Bioelectromagnetic investigations are challenging because they are typically conducted in very small volume. They require the development of specific probes such as for *in-vivo* permittivity measurements of biological tissues [5]. Compared to the standard diode-loaded dipole sensors, electro-optic (EO) probes are good candidates because they are fully dielectric, not invasive and effective around metal-based devices [6].

A millimeter-sized pigtailed wideband EO probe was developed for simultaneous measurement of one component of the E-field and the temperature variation using a single EO crystal [7]. Both measurements are based on the determination of the Pockels-effect-induced polarization state modulation of a laser beam after a round trip across the EO crystal. The short-term polarization changes in the optical signal from the probe yield the voltage measurement while longer-term changes yield changes in temperature. The EO probe crystal properties permit wideband transient measurements (up to 10 GHz).

In this work, we characterized the ability of the EO probe to perform E-field and temperature measurements in terms of E-field linearity and intensities as well as temperature uncertainty. To our knowledge, this is one of the first successful reports of simultaneous measurements of wideband high intensity E-field and temperature. In order to achieve the E-field distribution inside the sample, a numerical characterization was also performed using an 3-D finite difference-time domain (FDTD) tool.

II. Measurement Setup Configuration

The developed measurement setup is shown in Fig. 1. In order to characterize the EO probe measurement capabilities, two 50-Ω high voltage pulse generators were used. The first one, switched by laser (HLX-I, Horus Laser, France), delivered 2.6 ns duration pulses, up to 1.6 kV amplitude and 800 ps rise and fall times [8]. A second one delivered 10 ns duration pulses, up to 10 kV amplitude and 1 ns rise and fall times (FPG 10-1SM10, FID Technology, Germany). The pulse delivery system comprised a $44 \times 12 \times 12$ mm classical electroporation cuvette [9], with two integrated 10×21 mm aluminum electrodes separated by a gap of 4 mm. The cuvette was filled with a 1-ml buffered salt solution or biological growth medium whose dielectric properties ($\varepsilon_r = 78$ and $\sigma = 0.31$ S/m) were experimentally acquired with a dielectric probe (85070E, Agilent, USA). These properties ensured a 50 Ω equivalent electrical impedance [10]. The EO probe was vertically inserted into the cuvette and centered with respect to the electrodes. It was connected through an optical fiber to the associated

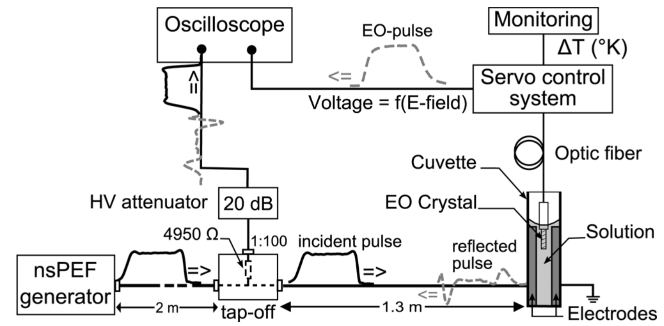


Fig. 1. Schematic of the experimental setup for the exposure and measurement of high-intensity nsPEF. Two transmission lines, RG214 coaxial cable (2-m and 1.3-m long), are used to connect the generator, the tap-off and the cuvette.

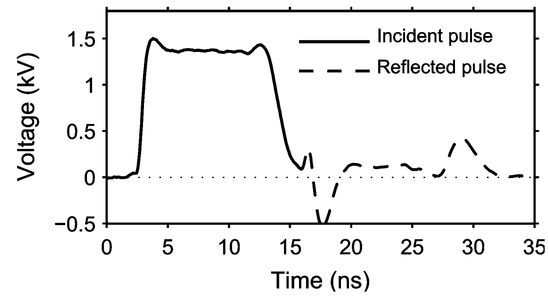


Fig. 2. Pulse delivered by the 10 ns generator. The high voltage incident and reflected pulses are measured with the tap-off. A 1.3-m long cable is inserted between the tap-off and the electroporation cuvette.

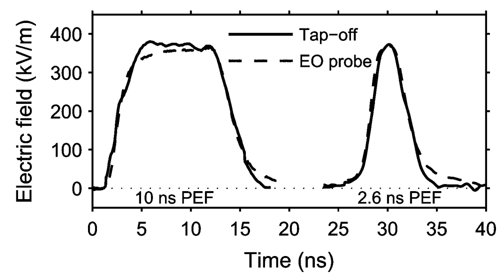


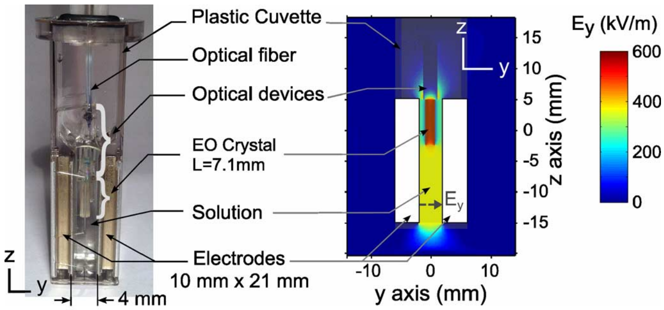
Fig. 3. EO probe measured electric field compared with the electric field obtained from 1.6 kV applied voltage measured with the tap-off. The applied voltage is determined from the incident and the reflected pulses, once the electrical delay suppressed for the 10 ns and 2.6 ns generators.

servo control system whose development was detailed in [7]. A 12 GHz bandwidth oscilloscope was used for the real-time display of the pulses. The EO probe output voltage was compared with the incident-reflected pulses voltage using a three-port tap-off (245 NMFFP-100, Barth Electronics, USA). The backward pulse is due to the frequency variation of the cuvette impedance [10]. The tap-off is a three-port device whose main-line impedance is 50 Ω. The measurement port impedance is 4950 Ω, allowing the voltage measurement on the oscilloscope with a 1:100 ratio. For the measurement of the propagating signals in the exposure setup, two transmission lines were introduced to dissociate the incident-reflected pulses. Indeed, considering the propagation theory, an electrical delay (T) is obtained using $L = T \cdot v$, depending on the transmission lines lengths (L) and the wave propagation velocity ($v = c/\sqrt{\varepsilon_r}$, c represents the speed of light in vacuum and $\varepsilon_r = 2.2$ corresponds to the transmission line relative dielectric permittivity). Due to the distance between the tap-off and the cuvette, an electrical delay of 13 ns was obtained. This value represents the time duration of the forward-backward pulse propagation in the 1.3 m line, i.e., a total of 2.6 m electrical length. The losses in the transmission line have been evaluated and considered as constant over the frequency range. The temperature variation acquired through the EO probe was recorded by the associated servo control system. The probe calibration is reported in [7] for the temperature and in [11] for the E-field.

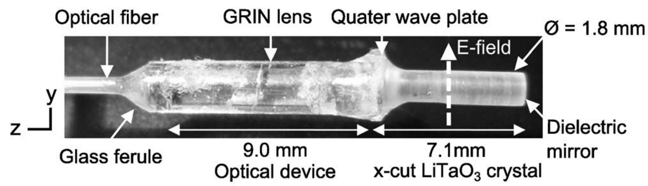
III. Results and Analysis

Fig. 2 presents the pulse voltage measured with the tap-off for the 10 ns generator. From the applied voltage, the E-field between the cuvette electrodes was obtained and further compared with the one measured by the EO probe using its calibration factor. The comparison is illustrated in Fig. 3 for both 2.6 ns and 10 ns generators. A very good level of consistency between these measurements was observed, showing the ability of the EO probe to measure high intensity nanosecond electric fields. In order to characterize the EO probe behavior, linearity measurements were carried out. Using the 10 ns generator, the applied voltage varies from 20 V to 8 kV. This corresponds to an E-field between the electrodes varying from 5 kV/m to 2 MV/m. The linearity is defined as the standard deviation between the data measured by the EO probe and the best linear fit. The linear fit of the measurement data yielded a slope of 0.097 ± 0.008 mV/(kV/m), demonstrating the constant linear ratio of the EO probe measurements up to at least 2 MV/m. A similar behavior was obtained with the 2.6 ns generator. For a complementary characterization of the E-field between the electrodes, a numerical study using 3-D FDTD method was performed [Fig. 4(a)]. The cuvette was modeled as filled with a medium whose dielectric properties are $\varepsilon_{\mathrm{r}} = 78$ and $\sigma = 0.31$ S/m. The EO probe crystal with a relative dielectric permittivity $\varepsilon_{\mathrm{r}} = 42$ was also modeled. A picture of the EO probe is given in Fig. 4(b). The active part of the probe corresponds to a crystal of congruent x-cut Lithium Tantalate of 7.1 mm long and 1.8 mm diameter large. The EO crystal is preceded by optical components mounted at the output of the optical fiber. Fig. 4(a) shows the E-field distribution considered along the transverse cut to the EO probe. As observed, the E-field was homogenous in the solution medium and in the EO probe crystal. Thus, the insertion of the EO probe does not modify the E-field distribution in the solution. Moreover, the EO probe calibration factor takes into account the permittivity mismatch between the EO crystal and the outer medium.

As previously mentioned, simultaneously to the E-field, temperature measurements were acquired with this EO probe. 120000 pulses were applied with a duration of 2.6 ns, an E-field strength of 450 kV/m and a 1 kHz repetition rate. As observed in Fig. 5, the generator was turn on 40 s after the beginning of the temperature recording. Four points per second were recorded. A temperature rise of 0.3 K was obtained after 120 s of nsPEF exposure. This low temperature rise revealed minor thermal effects induced by the nsPEFs even for a high number of pulses applied with a high repetition rate. The temperature curve was fitted using a sum of two exponentials that represents



(a)



(b)

Fig. 4. (a) EO probe inserted in the 4 mm gap width electroporation cuvette and FDTD-simulated E-field distribution along the transverse cut to the EO probe and the cuvette. A uniform spatial grid (FDTD mesh size: 0.2 mm) was used to mesh the structure. The E-field distribution was computed considering a 10 ns pulse duration and displayed at half pulse duration. (b) Photography of the used EO probe (optical components and dimensions). The EO probe crystal and a 3 mm part of the EO optical devices section are immersed in the solution. X-cut crystal corresponds to Z-axis of propagation.

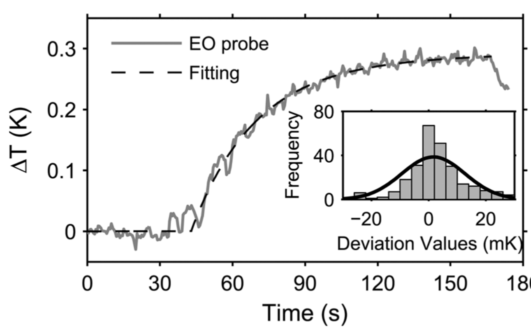


Fig. 5. Temperature measurement and fit. In the inset, the distribution of the deviation and the normal probability density function.

the temperature variation of the biological medium towards its new equilibrium, and the heat transfer between the biological medium and the EO crystal. The probability density function of the deviation between the measurements and the fit was assumed to be Gaussian. The temperature measurement noise floor was found to be 22 mK with a confidence level of 95%. Compared to the common temperature EO probes used for bioelectromagnetic experiments, this probe presents also a low noise floor.

IV. Conclusion

In conclusion, the ability of the EO probe to simultaneously measure high intensity nsPEF and temperature variations was demonstrated. Excellent time-domain measurement performance was observed in terms of E-field strength up to 2 MV/m. Moreover, a temperature measurement noise floor as low as 22 mK was achieved. Thus, this EO probe is suitable for bioelectromagnetic experiments and particularly for wideband high intensity electric fields, such as those used in radar or plasma applications.

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