LLNL-TR-414129

LAWRENCE LIVERMORE NATIONAL LABORATORY

Report on Non-Contact DC Electric Field Sensors

R. Miles, T. Bond, and G. Meyer

June 23, 2009

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Report on Non-Contact DC Electric Field Sensors

Robin Miles, Tiziana Bond, Glenn Meyer

Lawrence Livermore National Laboratory; miles7@lllnl.gov

Introduction:

This document reports on methods used to measure DC electrostatic fields in the range of 100 to 4000 V/m using a non-contact method. The project for which this report is written requires this capability. Non-contact measurements of DC fields is complicated by the effect of the accumulation of random space-charges near the sensors which interfere with the measurement of the field-of-interest and consequently, many forms of field measurements are either limited to AC measurements or use oscillating devices to create pseudo-AC fields. The intent of this document is to report on methods discussed in the literature for non-contact measurement of DC fields.

Electric field meters report either the electric field expressed in volts per distance or the voltage measured with respect to a ground reference. Common commercial applications for measuring static (DC) electric fields include measurement of surface charge on materials near electronic equipment to prevent arcing which can destroy sensitive electronic components, measurement of the potential for lightning to strike buildings or other exposed assets, measurement of the electric fields under power lines to investigate potential health risks from exposure to EM fields and measurement of fields emanating from the brain for brain diagnostic purposes. Companies that make electric field sensors include Trek (Medina, NY), MKS Instruments, Boltek, Campbell Systems, Mission Instruments, Monroe Electronics, AlphaLab, Inc. and others. In addition to commercial vendors, there are research activities continuing in the MEMS and optical arenas to make compact devices using the principles applied to the larger commercial sensors.

Types of electric field sensors:

There are three primary mechanisms for measuring DC electric field strength (or potential relative to a ground plane). These are induction probes, field mills and optical sensors. The induction probe measures the potential of a conductive plate that has been equilibrated to the local ambient potential with respect to a reference ground plane. The field-mill is similar to the induction probe except that the DC signal is converted into an AC signal by either alternately shielding and unshielding a conductive plate exposed to the local field or by oscillating the top plate of a parallel-plate capacitor. The third method induces a physical change in an optical fiber thereby changing its optical properties which are then analyzed.

Induction probes

The fundamental principle of operation for measuring an electric field using an induction probe is to allow a conductive plate or antenna to equilibrate with the local field then to measure the voltage in the plate as shown in Figure 1a. Electrometers are very high-input impedance electrical meters which can be used to measure the voltage or charge on the induction plate. A typical circuit for the measurement of the voltage of the induction plate is shown in Figure 2. Induction probes are often used in surface charge meters such as the ones produced by AlphaLab or MKS Instruments to detect the presence of charges on surfaces. In this case, they use the plate as one side of a capacitor and the surface under test as the other side as shown in Figure 1b. Since $C=Q/(V_{plate}-V_{surface})$ where the capacitance, C, is known. For a give distance to the surface, the charge, Q, and the plate voltage, V_{plate}, are measured. From these measurements the surface voltage, $V_{surface}$, can be deduced. In principle, surface probes can be used to measure fields at larger distances by adjusting the readings for distance, d, since the capacitance C is roughly $C= \varepsilon A/d$ where ε is the permittivity of air, A in the area of the plate and d is the distance to the object under test. The probe is calibrated for a certain distance and can be adjusted according to the new distance.

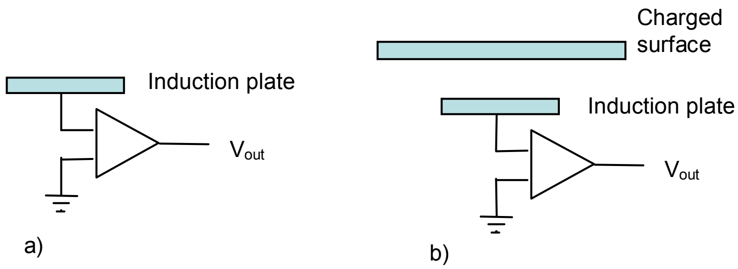


Figure 1. a) Schematic of induction plate field measurement b) surface charge meter.

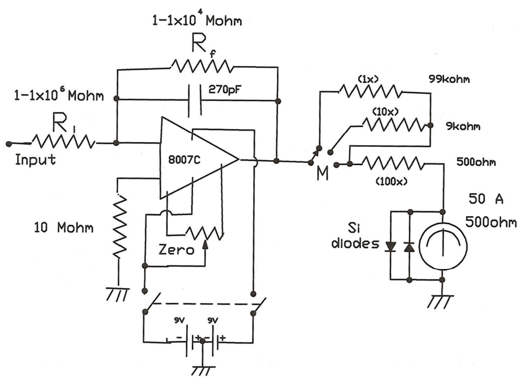


Figure 2. Schematic of an electrometer [1].

Unfortunately, surface probes and other induction probes, are not recommended for field measurements. They require frequent re-zeroing in shielded conditions and consequently cannot be used for measurements over extended periods of time. They are highly susceptible to ambient space charges. Their form factor as shown in Figure 3 is not conducive to measurement through small opening in boxes and therefore not of significant use for this project in the long term. We purchased the AlphaLab "Surface DC Voltmeter" and found that it did, in fact, require frequent re-zeroing, every few minutes. We used the meter to indicate charging of dielectric boxes. Typical measured voltages ere 200 V for wood surfaces and 400-3000 V for acrylic surfaces. A deliberately brushed acrylic box measured as high as 14000 V. Some researchers have been using the induction probe technique to make very sensitive measurements µV range using an ultrahigh input impedance detector at room-temperature. They do not measure DC signals but have measured AC signals at >8 Hz. [2].

Figure 3. AlphaLabs surface probe [3].

Field Mills and other oscillating plates

A common technique for measuring DC electric fields is to create a pseudo AC field by spinning a shutter over a measuring capacitor or by oscillating one plate of a parallel plate capacitor. A schematic of a shuttered capacitor or field mill is shown in Figure 4. Conversion of the electric field measurement from a DC field to an AC signal helps to minimize the effects of spurious offsets, drifts and space charge effects. Field mills are more complex and therefore more expensive than induction plate systems but exhibit higher sensitivity without the need for frequent re-zeroing. The AC signal resulting from the milling action is amplified. The electric field is gleaned from $I = \varepsilon E\,[dA/dt]$; where I is the time dependant current, ε is the permittivity of the air, and A is the time-dependant exposed plate area.

Several field mills are commercially available. However, they are typically used in systems which measure lightning or fields emanating from electric power lines and can be quite large (4" or more in diameter). A typical commercial field mill is shown in Figure 4. A description of a typical research version of a field-mill can be found in reference [4]. Because of the large size of these mills, they were thought to be unsuitable for this project and none were purchased.

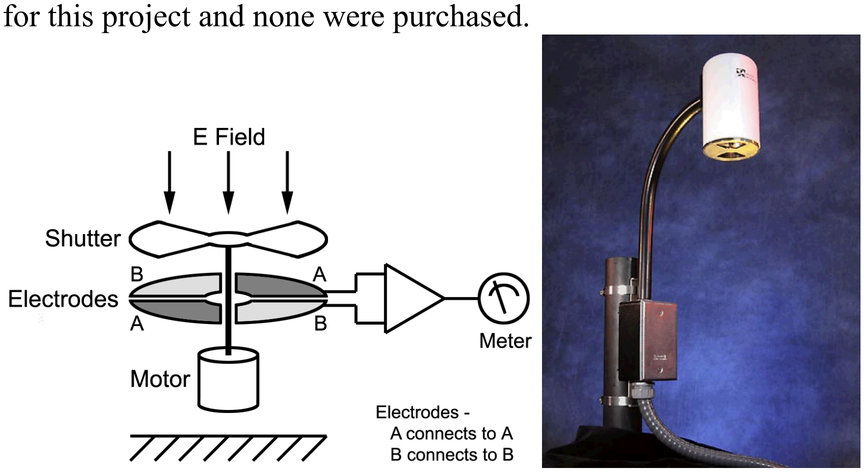


Figure 4. Schematic of a field mill for measuring electric fields [5].

A second type of field mill is the cylindrical mill shown in Figure 5. This mill rotates about the axis perpendicular to the imposed field. The resulting AC current is related to the electric field from via the equation, $I = 4\varepsilon_0 rLE\cos(\omega t)$ where r is now the radius of the cylinder and L is the length of the cylinder rotating at an angular frequency ω.

Cylindrical devices have the advantage of being insensitive to small leakage paths and can measure fields accurately away from ground planes. Additionally, these probes are directional as they are unable to sense fields parallel to their axis such that three orthogonal probes can be used to discern the orientation of the field. JPL and the Army have used cylindrical electric field sensors for atmospheric studies but there are no known commercial vendors for these devices [6]. However researchers a the University of Michigan have recently built small field mills for NASA applications and are interested in commercializing them. The current rendition is 22 mm in diameter and 150 mm long and has measured fields down to 0.05 KV/m and up to 100 KV/m [7]. A picture of the latest cylindrical field-mill sensor and associated data is shown in Figure 6.

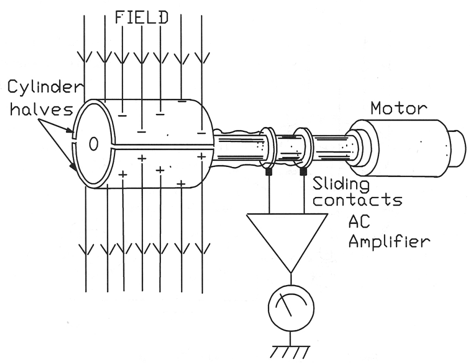


Figure 5. Schematic of a cylindrical field mill sensor [1].

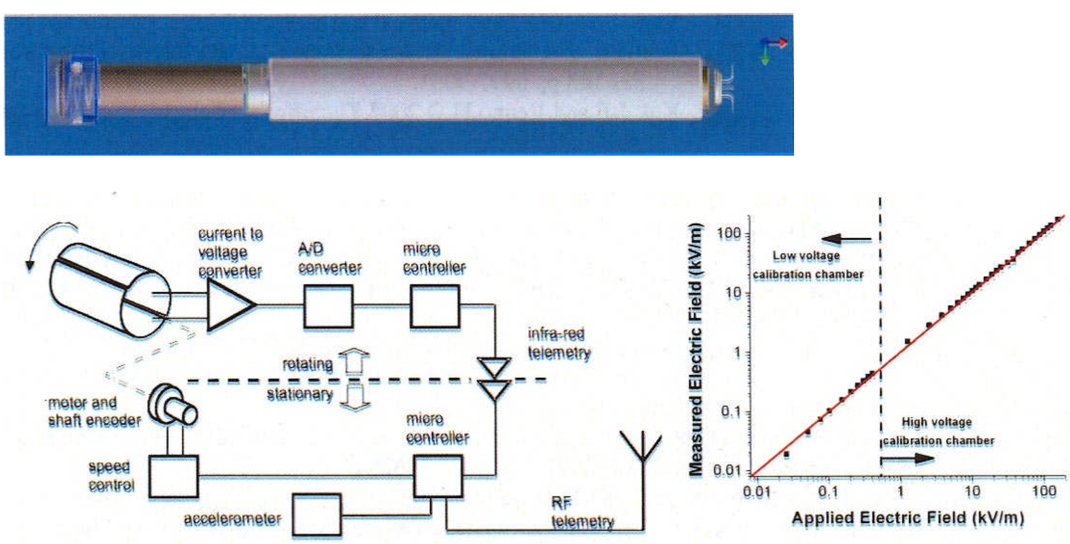
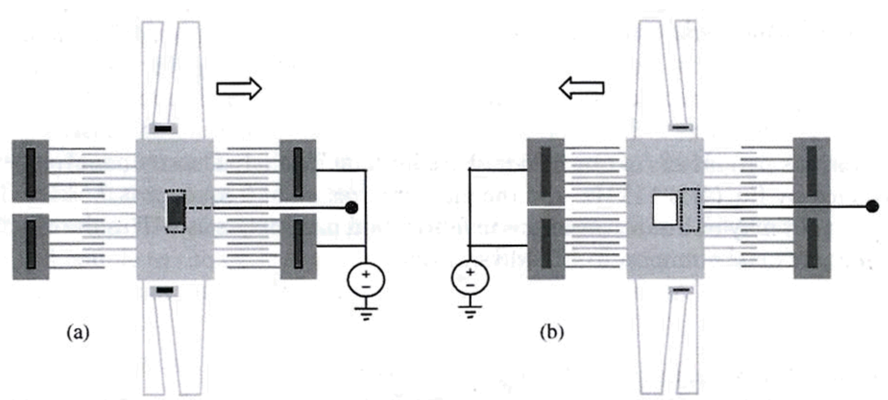


Figure 6. Cylindrical field-mill and associated data [7].

MEMS field-mills

MEMS versions of the field mill can be manufactured using microfabrication techniques wherein a comb-drive is usually use to open and close a shuttered capacitor. The device discussed in reference 8 describes a miniature electrostatic field mill constructed using a silicon surface micromachining MEMS fabrication process. A moving shuttle with a viewing aperture of 10 um periodically exposes and covers a charge sensing electrode. The signal output is on the order of 40 nV per V/m [8]. This device is shown in Figure 7. A similar device is discussed in reference 9. The sensor combines a vibrating MEMS structure with synchronous-detection electronics. The sensor architecture has three major blocks: a MEMS shutter, a sense interface, and a self-resonant drive loop that feeds back to the MEMS shutter. The noise floor is 4.0 V/m/ √ Hz and the integral nonlinearity is 20 V/m over a range of ±700 kV/m [9]. Yet another version is presented in reference 10. The design, fabrication and characterization testing of a high-performance micromechanical resonant electrostatic field sensor at low driving voltages is presented. These electrostatic field sensors have a resolution of 200 V/m. A nonlinearity of 1.8% (end-point-straight-line) in a measurement range of 0–10 kV/m is reported [10].



Transverse motion of the shuttle alternately: (a) covers and (b) exposes the sense electrode.

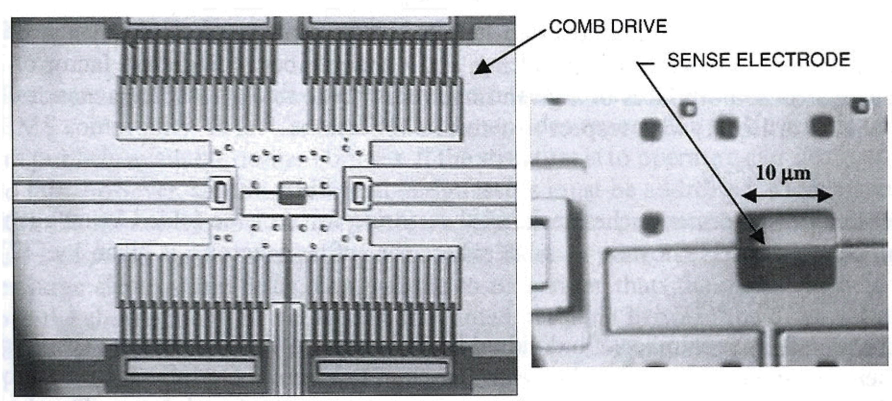


Figure 7. MEMS field-mill configuration.

Oscillating parallel plate sensors

Another method for creating an AC response from a DC electric field is to use a time-variable parallel-plate capacitor technique. The surface charged at the unknown voltage constitutes one electrode plane of the parallel-plate capacitor and a vibrating plate constitutes the other electrode as shown in the schematic of Figure 8. The current, I, to the capacitor plate is proportional to the voltage across the capacitor, V, and the temporal change in the capacitor, C;

$$I = V\ dC/dt$$

Which can be re-written as:

$$I = -V\ \varepsilon A\ (D_1 \omega \cos(\omega t))/(D_0 + D_1 \sin(\omega t))^2$$

Where A is the capacitor electrode area, D_0 is the nominal distance between the tested surface and the electrode, D_1 is the vibration amplitude of the vibrating electrode, ω is the vibrating frequency and ε is the electric permittivity of the medium between the electrodes. The vibrating electrode can be placed in a circuit shown in Figure 8 such that either the field is measured or the voltage can be measured with reference to ground.

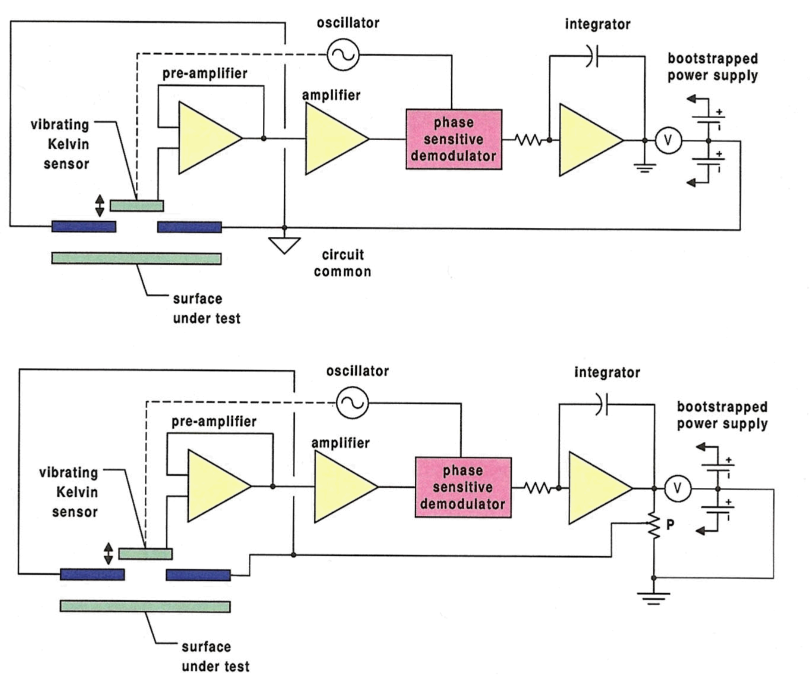


Figure 8. Schematics of variable-plate capacitor for voltage(top) and field(bottom) measurements [11].

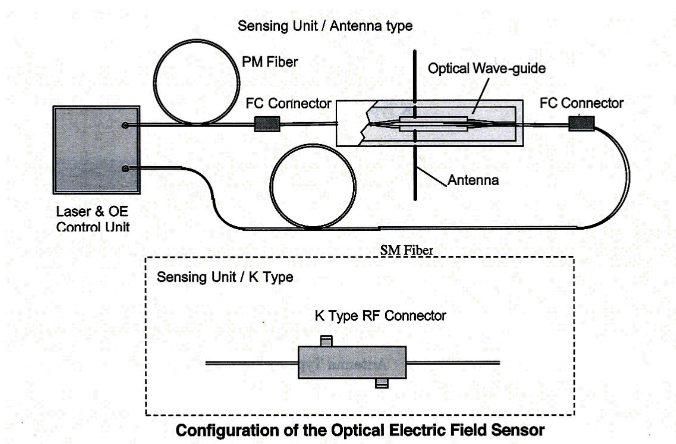
We have purchased sensors of this variety. We have purchased a Trek voltmeter and a Monroe electric field meter. These sensors can measure fields at standoff distances although they are most accurate near the object of interest. Because of the feedback loop used to null the exposed plate to the environment, they can be subject to drift at low signal levels away form the source. We have used the Trek sensors for the majority of our measurements. The measurements corresponded well with theory. They are less sensitive to space charge effects but accumulation of charged particles on the surface adversely affects the performance of the sensor.

Differential voltage measurements

Since the electric field is proportional to dV/dx, the electric field can be measured by measuring the voltage at two locations in space and calculating the differential. A probe based on this concept is presented in reference 12 wherein an electrode is made to vibrate and the voltage change is measured at the travel limits of the vibrating probe. The device is used to detect ionic currents in biological samples. In a grosser dimension, we have used this technique to measure the electric field using the Trek voltage probes.

Optical Methods

A disadvantage to the sensor methods described previously is that the very presence of the metallic sensors disturbs the electric field being measured. Optical sensors do not affect the field being measured. These sensors are typically based on Pockel's effect wherein an electric field changes the birefringent properties of a crystal subjected to that field and the resulting change in polarization of laser light traversing the crystal is measured using a variety of optical system architectures. Lithium niobate ($LiNbO_3$) and bismuth germanate ($Bi_4Ge_3O_{12}$) crystals have been used to measure DC electric fields down to about 10 kV/m with resolutions of 100 V/m [13,14]. AC sensors have measured to 10 V/m [15]. It is possible that a custom device could be built to measure DC fields at the lower field strengths. Kyosemi sells a Mach-Zehnder version of an optical electrical field probe for RF frequencies [16]. A schematic of the optical configuration and picture of the packaged sensor are shown in Figure 9.



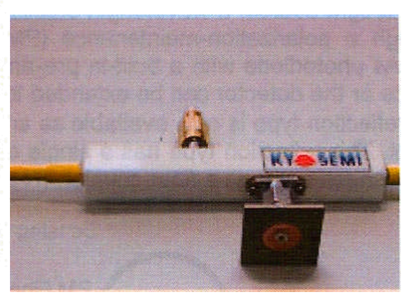


Figure 9. Commercial optical electric field sensor for RF measurements [16].

The use of an asymmetric Mach Zehnder interferometric amplitude modulator to measure a relatively low frequency electric field strength is described in reference 17. Measurements were performed in the range 0.1 V/cm to 60 V/cm at 60 Hz through 100 kHz, using a probe antenna of 10mm X 10 mm. By increasing the effective area of the probe antenna, better sensitivity was obtained over the measured range [17]. Another electromagnetic field sensor uses a $LiNbO_3$ electro-optical crystal and an optical-fiber link in a Mach Zehnder interferometer with a YAG laser pumped by a laser diode whose output power is 25 mW. The resulting frequency response is almost flat from 100 Hz to 300 MHz, and the minimum detectable electric field strengths are 0.22 mV/m at 50 MHz and 0.079 mV/m at 750 MHz. [18].

As an alternative to using Mach Zehnder electro-optic devices, electric fields can be sensed using electro-optical retarders as described in reference 19. In this case, the electric field modulates an optical delay, instead of the optical intensity as in the Mach Zehnder interferometers. The wideband 0–20 kHz sensing scheme was successfully tested by detecting high-intensity electric fields, ranging from 20 to 350 kV/m using two $LiNbO_3$ crystals, each one 13 mm long [19].

Another configuration is to incorporate the birefringent medium into a fiber ring resonator as discussed in reference 20. A laser can control the oscillation frequency difference between two counter-propagating lights through the birefringent medium of the ring resonator. Since the frequency difference is proportional to the birefringence, it can be measured to detect the beat frequency generated by combining two counter-propagating lights and the laser can be applied to an optical fiber sensor whose detecting signal is in frequency domain. Electric field sensor was demonstrated with a lithium niobate crystal as a sensing probe [20].

Conclusion:

A variety of non-contact sensors for measuring DC electrical fields are available. Most are either large in configuration (> 1 cm) or measure best when measuring AC fields. Commercially available probes such as those sold by TREK and others are adequate for measurements where the measurement space is not restricted. Small MEMS field probes look promising for measuring in confined spaces but are not yet commercially available. Optical techniques are attractive for removing the influence of the probe on the measured signal but the resolution may not be adequate if small probes are needed in confined areas.

References:

1. http://www.missioninstruments.com/
2. Harland, C.J., Clark. T.D., Prance, R.J., *App. Phys. Lett*., 81, (17) 21 (2002) .
3. http://www.trifield.com
4. Daviest, A. J., Turri, I. , *Meas. Sci. Technol.,* 1 (1990) 869-874.
5. http://a-tech.net/ElectricFieldMill/index.html
6. Johnston, A.R., Kirkham, H., *IEEE Transactions on Power Delivery*, 4 (2) (1989)

1253-1255.
7. Renno, N. O., Kok, J.F., Krkham, H., Rogacki, S. J. of Physics: Conference Series 142 (2008) 012075
8. Horenstein, M.N., Stone, P.R., *Journal of Electrostatics,* 51 (2001) 515-521.
9. Lundberg, K.H, Shafran, J. S., Kuang, J., Judy, M., Denison, T. A, *Proceedings of the 2006 American Control Conference,* Minneapolis, Minnesota, USA, June 14-16, 2006.
10. Peng, C., Chen, X., Ye, C., Tao, H., Cui, G., Bai, Q., Chen, S., Xia, S., *J. Micromech. Microeng.*, 16 (2006) 914–919.
11. http://www.trekinc.com
12. Reid, B., Nuccitelli, R., Min Zhao, M., *Nature Protocols,* 2 (3) (2007) 661-669.
13. Cecelja, F., Balachandran, W., Bordovski, M., *Measurement* 40 (2007) 450-458
14. Cecelja, F., Bordovski, M.,Balachandran, W., *IEEE Trans Instru and Meas*. 51 (2) (2002) 282-286.
15. Choi,Y-K., Santagi, M., Nakajima, M., *J. IEE Proceedings*, 140 (2) (1995) 137-140.
16. www.kyosemi.co.jp/product/pdf/en_EFST-13.pdf
17. Choi, Y.-K., Sanagi, M., Nakajima, M*., IEEE Proc.-J*, 140, (2) (1993) 137-140.
18. Kuwabara, N., Tajima, K. , Kobayashi, R., Amemiya, F., *IEEE Trans. on Electromagnetic Compatibility*, 34 (4) **(**1992) 391-396.
19. C Guti´errez-Mart´ınez, J Santos-Aguilar and R Ochoa-Valiente, Meas. Sci. Technol. 18 (2007) 3223–3229.
20. Suemune, T., Takahashi, Y., *Optics and Lasers in Engineering,* 45 (2007) 789–794.
21. Shafran, J.S., *A MEMS-Based, High-Resolution Electric-Field Meter*, Masters Thesis M.I.T., June 2005.
22. R.E. Vosteen, R. Bartnikas, *Engineering Dielectrics*, ASTM 2nd edition, 1987, 440-489.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.