A LOW COST BROADBAND PROBE FOR ELECTRIC FIELD MEASUREMENT

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ABSTRACT
Design and fabrication of a low cost sensor for measuring electric field over a broad range of electromagnetic (EM) frequency is presented. The electric field probe consists of an electrically short dipole antenna and diode detector connected to an instrumentation amplifier via a high impedance line. The rectified diode voltage is conveyed over the high impedance line for real time data acquisition. A low cost probe is fabricated using homemade screen printable carbon ink on flexible polyethylene sheet for electric field measurement. Carbon ink composition with good adherence to polyethylene substrate and high impedance (1M&!/m) is chosen for sensor fabrication. Preliminary results are presented for near field EM radiation from a spiral antenna irradiating a lossy dielectric medium at 433 MHz.

Keywords: Electric field probe, broadband, carbon ink, screen printing.

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INTRODUCTION
Accurate measurement of electric field has become an important requirement with the expanding spectrum of applications involving electromagnetic fields. Electric field probes are extensively used to study the radiation hazards to human, measure EM field distributions from antenna towers and base stations, to measure fields in air for electromagnetic compatibility of industrial and domestic appliances and, to estimate weather conditions [1-4]. It is also widely used to characterize antennas developed for medical diagnostic and therapeutic applications particularly, to provide feedback for antenna power control during hyperthermia treatment [5].

A broadband electric field probe consists of an electrically short dipole antenna connected to a diode detector and high impedance transmission line to measure the incident EM field. Figure 1 shows schematic representation of the electric field probe with shunt diode detector. The voltage induced across the dipole antenna \( V_{oc} \) is related to the incident electric field \( E(r, \omega) \) by [1],

\[
V_{oc}(\omega) = hE(r, \omega)
\]

where \( h \) is the half-length of the dipole. For spatial resolution of field measurements, the antenna is often made physically and electrically short such that [1],

\[
\beta_0 h = \frac{2 \pi h}{\lambda_0} \approx 1
\]

where \( \lambda_0 \) and \( \beta_0 \) are free space wavelength and propagation constant respectively. The rectified dc output of the diode detector for the time harmonic induced voltage is conveyed to the data acquisition unit via a high resistance transmission line. The diode detector yields broadband frequency response and, the high resistance line provides electrical isolation between the antenna and data acquisition circuit. When an alternating EM field is incident on the antenna, voltage drop proportional to the square of the amplitude of the incident field is induced across the diode for low field strengths. For larger EM field, voltage linearly proportional to the incident electric field is induced across the diode. Here we present the design and fabrication of a low cost electric field probe with broadband frequency response for electric field measurement. Homemade carbon ink and screen printing are used for low fabrication cost. Preliminary results of the electric field are presented for near field EM radiation incident on a lossy dielectric medium.

METHODOLOGY
Sensor design
A dipole antenna consists of two identically sized thin metal conductors (wire or rod) positioned collinear and parallel to each other as shown in Figure 1. A radiofrequency (RF) diode detector connected between the conducting arms of the antenna measures the EM field induced on the antenna. Electrically short dipole antenna of dimension \( 2aAxh \) was fabricated using conductive adhesive tape made of aluminum (3M® brand) for 2D electric field measurements.

RF diode detector with low forward bias voltage and fast switching time is desired to respond fast to time varying EM
Schottky-barrier diode is widely used in RF detector and mixer circuits. Zero bias and low forward barrier voltage features of Schottky-barrier diode due to the metal semiconductor junction provide higher diode sensitivity for the incident EM field. A zero bias Schottky diode with low forward voltage and fast switching time is selected as the RF detector to ensure faster response and better sensitivity.

**Sensor transmission line**

The high impedance of the transmission line, $Z_c = R_c - jX_c$ serves several purposes namely i) it reduces direct reception of the incident EM field by the lines, ii) reduces field scattering by the lines, iii) low pass filters the rectified diode voltage and iv) provides electrical isolation between the sensor and measurement circuit. Carbon ink was made by mixing fine graphite powder in an inert plasticizer diluted to required viscosity using a solvent. The plasticizer-solvent mixing ratio was varied from 50:50 to 70:30% in steps of 10% to assess adhesion to substrate using screen printing technique. The graphite powder content was fixed at 30% in the plasticizer-solvent mixture. Multiple 10 mm square samples were printed to account for variability in screen printing process. Carbon ink with good adhesion to polyethylene sheet was used to print the high impedance transmission line. The impedance of the carbon ink was characterized by measuring the DC sheet resistance $\rho/t$.

$$Rs = \rho/t$$

where $\rho$ is the bulk resistivity of the thin film in $\Omega m$ and $t$ is film thickness in meters. For a thin film of conductivity $\sigma$ and thickness $t$ less than the skin depth ($\delta = 1 / \sqrt{\pi f \mu \sigma}$) at the operating frequency ($f$), the RF sheet resistance is approximately equal to DC sheet resistance. Resistivity of the homemade screen printable carbon inks were measured using four point probe method based on Van der Pauw resistivity measurement technique widely used in semiconductor industry to characterize thin films [6]. Carbon ink with high sheet resistance was used to screen print the sensor transmission line. The width and spacing of the transmission line are chosen based on the carbon ink sheet resistivity and foot print of the diode surface mount package.

**Data acquisition**

The rectified dc voltage transmitted over the high impedance line was amplified using an instrumentation amplifier with high input impedance and low offset voltage. The instrumentation amplifier output is connected to an analog to digital convertor for real time data display and storage on a computer. The data acquisition (DAQ) circuit was fabricated on a flexible printed circuit board and glued to the transmission line terminals using silver epoxy. On board placement of instrumentation circuitry eliminates the need for shielded lines between the high impedance transmission line and DAQ. The output of the instrumentation amplifier was connected to the computer via an analog to digital convertor for digital data display and storage.

**Sensor testing**

Figure 2 shows the experimental setup for testing the electric field probe. In the test setup, a low power time harmonic signal from the RF signal generator is amplified by a RF amplifier and delivered to a logarithmic spiral antenna irradiating a lossy dielectric load with relative permittivity $\varepsilon_r = 53.5 - j50.23$. Power delivered to the antenna was measured using a RF watt meter. Power reflected by the dielectric medium due to impedance mismatch with the spiral antenna was measured using vector network analyser. The electric field probe was sandwiched between the antenna and dielectric medium with
the diode detector positioned at the origin of the spiral arm where the field strength is maximum. The probe response to the EM radiation from the spiral antenna was recorded by logging the output voltage of the instrumentation amplifier connected to a computer via data acquisition card. Sensor voltage was recorded for 1 and 1.8 watts power delivered to the load at 433 MHz and dipole half length $h = 6$ and 8 mm.

RESULTS

Electric field sensor

Adhesive Aluminum patches of width, $2a_A = 2 \text{mm}$ were used for the conducting arms of the electrically short dipole antenna. For arm length $h = 4 \text{mm}$ and $f = 433 \text{ MHz}$, dipole antenna dimension is electrically short and satisfies equation (2) i.e., $\beta h = 0.056$. Zero bias Schottky diode with low junction capacitance (0.18 pF) and high junction resistance (8.8 kΩ at 300 °K) from Avago Technologies was chosen for fast switching and higher diode sensitivity. Surface mount diode detector (HSMS2850) was glued to the high impedance transmission line using silver epoxy.

Sensor transmission line

Carbon ink with 70:30 polymer mixture ratio exhibited good adhesion to the substrate and offered sufficiently high sheet resistance for the transmission line. Mean sheet resistance of the carbon ink coatings on 10 mm square patches were measured as 4.3 and 2.9 kΩ for two and three coatings respectively using the four point probe (Model BA, Kulicke & Sofia Ltd., UK). The dc sheet resistance lowered as the number of coating increased. Sensor transmission line was screen printed (2 coatings) using carbon ink with 70:30 polymer ratio and 30% graphite. Impedance of the carbon ink lines was measured as 1 MΩ/m. The transmission line width and spacing are 1.5 and 1 mm respectively.

Sensor testing

Figure 3 shows the single electric field probe screen printed on thin flexible polyethylene sheet using carbon ink and connected to a flexible PCB with electronics for real time data acquisition using computer. Instrumentation amplifier (INA121, Texas Instruments) with high input impedance and low offset voltage (0.2 mV) is used to acquire the rectified dc voltage conveyed over the high impedance transmission line. The output of the instrumentation amplifier is connected to the computer via an analog to digital convertor (USB6210, National Instruments Pvt. Ltd., India). Power reflection coefficient ($10 \log |S_{11}|$) was measured to be 10% at 433 MHz for the spiral antenna on the lossy dielectric medium. Thus, 10% of the incident power is reflected due to impedance mismatch and the remaining is transmitted through the dielectric medium. Figure 4 shows the rectified dc voltage measurements of the sensor for varying dipole arm length and power delivered to the load at 433 MHz. It can be observed

Fig. 3 : Electrically short dipole antenna consisting of adhesive Aluminum tape (B) with surface mount shunt diode detector (C) connected to onboard readout electronics through high impedance line (A) fabricated using screen printable homemade carbon ink.

Fig. 4 : Sensor voltage for varying dipole length and power delivered to load at 433 MHz.
that the probe response increases with increase in dipole arm length and incident power (refer Eqn 1). It should be noted that the sensor is in the antenna near field and the field incident on the dipole arm is not a time harmonic plane wave. For dipole half length \( h = 6 \text{ mm} \), the electric field probe with the chosen Schottky diode detector could be used for electric field measurements over 100-1000 MHz frequency range.

**CONCLUSION**

Electric field probes are widely used to measure far and near field of an EM source. Electrically short dipole antennas terminated with high impedance load yield electric field probes with broadband frequency response. Dipole antenna with resistive loading or tapering is often used to suppress antenna resonance and extend the frequency range to as high as 40 GHz [1].

In this work, we report the design and low cost fabrication of an electric field probe for 2D measurement of the electric field. Several carbon ink compositions were homemade and tested for adherence to substrate. Screen printable carbon ink with high sheet resistance and was chosen to fabricate the sensor transmission line (1 M\( \Omega \)/m). Though initial sensor testing was carried out in the near field region where the field intensity is at its maximum, preliminary results indicate increase in sensor output for increasing dipole arm length and incident power. The influence of frequency, polarization and propagation direction of the incident field and, orientation of the probe with respect to EM field will be studied for a known EM source. A 2D array of this electric field probe can be used to measure 2D electric field distribution over a broad frequency range (100-1000 MHz).

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**REFERENCES**