Broadband Active *E*-Field Sensors for Measurement of Transients

Artnarong Thansandote, *Member, IEEE*, Stanislaw S. Stuchly, *Fellow, IEEE*, Maria A. Stuchly, *Fellow, IEEE*, and Mariusz Barski

***Abstract*—Three broadband *E*-field sensors (30 Hz–42 MHz, 143 Hz–140 MHz, and 10 kHz–350 MHz) based on electrically small spherical antennas for measurement of transient fields have been developed. The antenna is coupled to a receiver using a wideband buffer amplifier. The sensitivity of the sensor depends on the size of the antenna, while the broadband performance is determined by the size of the antenna, the input impedance of the amplifier, and the coupling between the two devices. The sensor is calibrated in a TEM cell using CW and pulsed fields. Results of an analysis and calibration of the sensors are presented.**

I. Introduction

Over the years there has been continued research and development of broadband electromagnetic field sensors for EMP applications [1], for studies in EMI/C [2], for measurement of lightning pulses [3], and for investigations of biological effects of pulsed electromagnetic fields [4]. Such sensors are mostly based on electrically small antennas and should have simple transfer functions. Designs and development of these sensors have been aimed at the achievement of many desirable characteristics, which include high-fidelity pulse reproduction of the field, broadband performance, minimal perturbation to the field, well-defined directional responses, wide dynamic range, and high sensitivity. There are two types of sensor response in the measurement of pulsed or transient fields. In the first one, the output is proportional to the field and the second, to the time derivative of the field. Usually, the sensor of the first type is preferred.

Recent efforts have involved designing preamplifiers that couple the antenna to a receiver to make the combined antenna-amplifier (active antenna) characteristics having wideband performance as well as a frequency-independent transfer function [5]–[7]. However, the active antennas reported previously have their wideband performance limited to within a few decades in the high frequency spectrum and cannot be used to measure pulsed fields. In this paper we describe three broadband antennas for measurement of pulsed and transient *E*-fields. These antennas have a "flat" transfer function throughout several decades of frequency.

Manuscript received June 14, 1990. This work was supported by grants from the Natural Science and Engineering Research Council of Canada and the Ontario Ministry of Labour.

A. Thansandote and S. S. Stuchly are with the Department of Electrical Engineering, University of Ottawa, Ottawa, Ont., Canada K1N 6N5.

M. A. Stuchly is with the Bureau of Radiation and Medical Devices, Health and Welfare Canada, Ottawa, Ont., Canada K1A 0L2.

M. Barski was with the University of Ottawa, Ottawa, Ont., Canada. He is now with the Institute of Informatics, University of Gdansk, Gdansk, Poland.

IEEE Log Number 9142764.

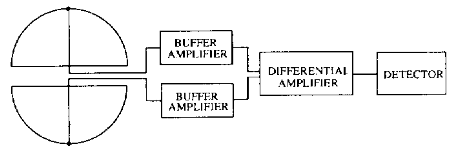

Fig. 1. Block diagram of the active *E*-field sensor.

II. Basic Principles

The active *E*-field sensor (Fig. 1) utilizes a spherical antenna with two high input impedance buffer amplifiers and a differential amplifier located inside the sphere. The antenna consists of two identical hollow metal hemispheres. The apex of each hemisphere is connected to the buffer amplifier using a large-diameter cylindrical conductor.

Consider the monopole configuration of the antenna. If the hemispherical monopole is loaded with a resistance R and located in the field E, its receiving transfer function T at frequencies much lower than its first resonance can be expressed as [1], [8],

$$T = \frac{V}{E} = \frac{j1.5\pi r^2 \omega R\epsilon}{1 + j8r\omega R\epsilon\left[0.9872 - \ln\left\{\tan^{-1}(G/r)\right\}\right]} \quad (1)$$

where V is the voltage across the load, r is the radius of the hemisphere, $\omega = 2\pi f$ is the angular frequency, ϵ is the permittivity of the medium, and G is the gap between the hemisphere edge and the ground plane. A plot of $|T|$ as a function of frequency for $r = 4.8$ cm, $G = 2$ mm, and different values of R is shown in Fig. 2. It can be seen that the monopole has a wide flat-response region when it is loaded with a very high resistance. When operating in this region it provides a terminal voltage proportional to E. In Fig. 2, the 3-dB lower roll-off frequencies for $R = 50\ \Omega$, 1 MΩ, 10 MΩ, and 100 MΩ are 230 MHz, 11 kHz, 1.1 kHz, and 110 Hz, respectively, and $|T|$ in the flat region is 7 mV/(V/m), which is equivalent to an antenna factor of 43 dB/m. Below the roll-off frequency, the antenna response is proportional to the time derivative of E.

The upper frequency of the flat-response antenna is determined by the requirement that the maximum frequency of operation be much lower than the first resonant frequency of the antenna. A sufficient condition for the monopole is

$$h_{eq} \leq 0.05\lambda_{min} \quad (2)$$

where h_{eq} is the equivalent height of the monopole and λ_{min} is the minimum wavelength of interest. With the condition (2), the maximum radius of the hemisphere is [1], [8].

$$r_{max} = \frac{\lambda_{min}}{3.75\pi}\left[0.9872 - \ln\left\{\tan^{-1}(G/r_{max})\right\}\right]. \quad (3)$$

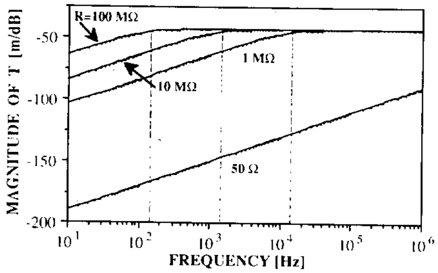

Fig. 2. Frequency response of the hemispherical monopole with $r = 4.8$ cm and $G = 2$ mm for different resistance loading.

As a numerical example, for a hemispherical antenna with $r_{max} = 4.8$ cm and $G = 2$ mm, the maximum frequency of operation calculated from (3) is 2.2 GHz. If the hemisphere is supported by a dielectric substrate, the value of G should be taken larger than the actual gap to offset the increase in capacitance due to the presence of dielectric.

III. Realization

Two monopole-configuration sensors and one free-field (dipole) sensor have been investigated. The first monopole sensor was built using a 9.6-cm diameter hemisphere with $G = 2$ mm and using a Tektronix P6501 FET probe (1-MΩ input impedance) as a buffer amplifier. The simplified diagram of the sensor and its equivalent circuit are shown in Fig. 3.

The second monopole sensor and the free-field sensor were manufactured using 5.6-cm diameter hemispheres with $G \approx 1$ mm (upper frequency $\approx$ 3.9 GHz) and using a FET-input amplifier as a buffer amplifier. The receiving terminal of the antenna is at the hemisphere edge and is connected to the buffer amplifier by a short strip conductor on a printed-circuit board (PCB). The amplifier was designed to obtain a very high input impedance and a 50-Ω output impedance, and was fabricated on the PCB using two surface mount JFET's (Siliconix SST440) and an operational amplifier (Burr-Brown 0PA621KU). In the free-field configuration, the two buffer amplifiers are connected to the differential amplifier built on the same PCB. The amplifier circuit is covered by a copper shield inside the sphere. In the monopole configuration, the amplifier circuit is installed within a cylindrical enclosure, the upper wall of which is the ground plane.

IV. Results

The sensors were tested and calibrated in a TEM cell in both the frequency domain and time domain. In the frequency domain the transfer function of the sensor was measured using HP3577A and HP8510B network analyzers. Measurements of the sensor responses in the time domain were performed using an HP8082A pulse generator, a PSPL 1000C impulse generator, and a Tektronix 11802 digital sampling oscilloscope. The performance of the sensor was also modeled using a computer simulation program SPICE.

The results for the 9.6-cm diameter hemispherical sensor are shown in Figs. 4 and 5. It can be seen in Fig. 4(a) that the experimental results are in agreement with those from the computer simulation, showing the flat response of the sensor from 10 kHz to 350 MHz. The lower roll-off frequency 10 kHz is very close to that calculated from (1) for $R = 1$ MΩ (see Fig. 2). The sensitivity of the sensor has been estimated to be of the order of 1 mV for the incident field of 1 V/m, which is equivalent to an antenna factor of 60 dB. Without 20-dB attenuation in the FET probe, the antenna factor would be 40 dB/m which is also close to 43 dB/m as calculated from (1). The resonance at around 700 MHz results from the input capacitance of the probe (≈ 1.8 pF) and the inductance due to the copper tube (≈ 30 nH). The difference in phase between the two results in Fig. 4(b) is due to the cable connecting the probe to the network analyzer. If plotted on a linear frequency scale, the graph of phase (experiment) above 20 MHz would be linear, which corresponds to a time-shift in the time domain. The time-domain measurement results in Fig. 5 show that the rise time and width of the output pulse are close to those of the input pulse. The difference in the fall time of both pulses is due to overshooting on the output pulse. The noise voltage of the probe was measured using a PAR113 preamplifier and an HP3400A RMS voltmeter, and the noise spectral density at 2 kHz was found to be

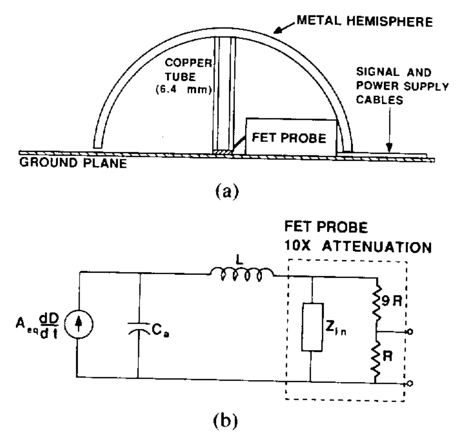

Fig. 3. Monopole-configuration sensor with a Tektronix P6501 FET probe and its equivalent circuit. L is the inductance due to the copper tube, C_a is the antenna capacitance, $A_{eq} = 1.5\pi r^2$, and $D = \epsilon E$.

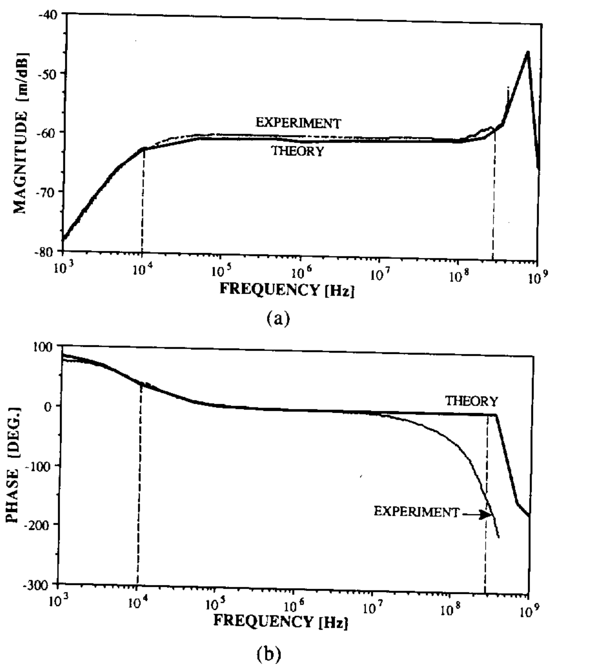

Fig. 4. Amplitude and phase responses of the 9.6-cm diameter hemisphere with a 1-MΩ FET amplifier (Tektronix P6501 probe).

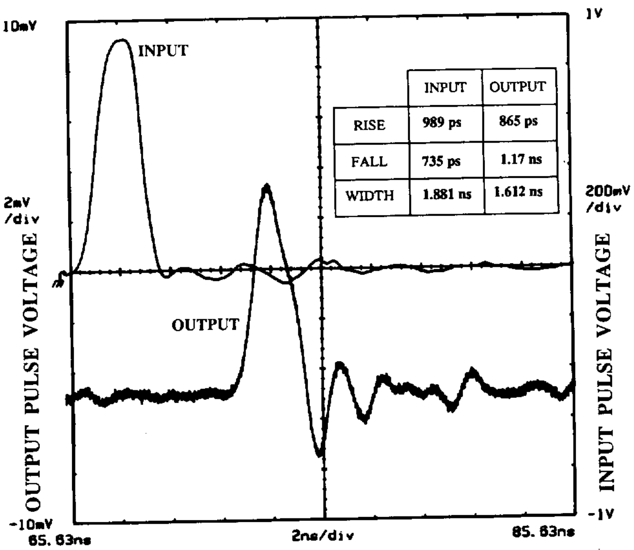

Fig. 5. Time-domain response of the 9.6-cm diameter hemispherical sensor to a narrow pulse.

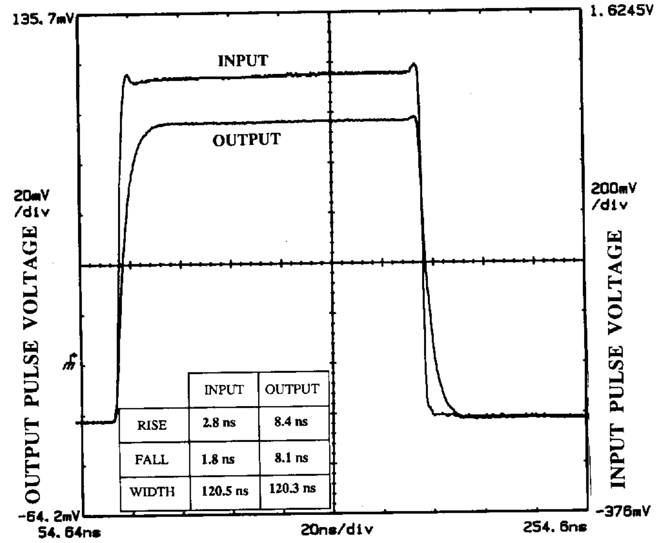

Fig. 7. Time-domain response of the 5.6-cm diameter hemispherical sensor to a 120-ns rectangular pulse. The input pulse is attenuated by 16 dB.

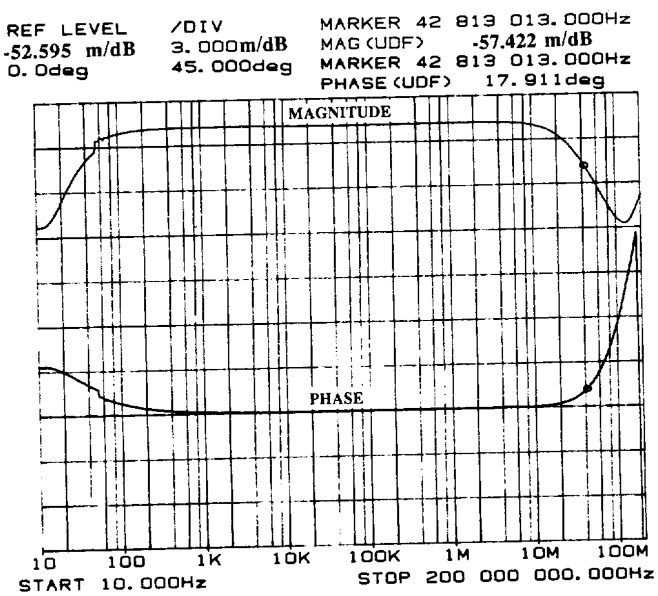

Fig. 6. Amplitude and phase responses of the 5.6-cm diameter hemispherical sensor.

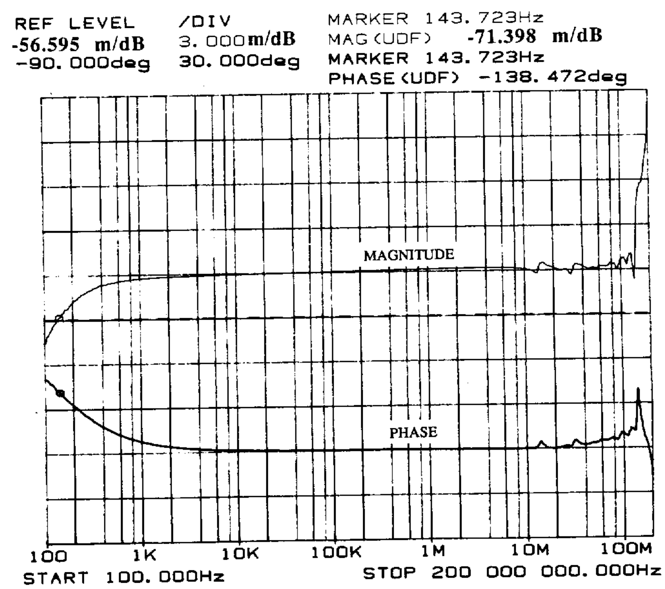

Fig. 8. Amplitude and phase responses of the free-field sensor.

74 nV/$\sqrt{\text{Hz}}$. Based on this value and the specifications of the probe, the dynamic range of the sensor has been estimated to be of the order of 75 dB.

Figs. 6 and 7 show the experimental results for the 5.6-cm diameter hemispherical sensor. The sensor has a flat response region between 30 Hz and 42 MHz (3-dB roll-off frequencies). It can operate from frequencies lower than 60 Hz because the hemisphere is loaded by a buffer amplifier with an input impedance of more than 500 MΩ. The upper frequency roll-off of the sensor is limited by the amplifier bandwidth. The time-domain response of the sensor (Fig. 7) is very clean, although the rise and fall times of the output pulse are 4 times longer than those of the input. The sensitivity of the sensor was determined from Fig. 6 and was found to be 1.9 mV/(V/m) which is equivalent to an antenna factor of 54.4 dB/m. The measured noise spectral density of the amplifier is approximately 22 nV/$\sqrt{\text{Hz}}$ at 2 kHz and increases sharply to 1.1 μV/$\sqrt{\text{Hz}}$ at 65 Hz. Based on this information and the data of OPA621KU operational amplifier, the dynamic range of the sensor was estimated to be of the order of 67 dB.

The experimental results for the free-field sensor are shown in Figs. 8 and 9. Here the flat response region extends from 143 Hz to 140 MHz. The effect of the resonance appears as considerable ringing on the output pulse (Fig. 9). This resonance is believed to be caused by the inductance of the strip conductor between the antenna terminal and the amplifier input, and by the capacitance introduced by the shielding cover. Despite the ringing problem, the rise time, fall time, and pulse width of both pulses are in very good agreement. The sensitivity of the sensor has been estimated to be of the order of 0.4 mV/(V/m), or 68.4 dB/m in terms of an antenna factor. When tested with a Gaussian-pulse incident field (450-ps width), all sensors provide an output pulse with a rise time of less than 1 ns.

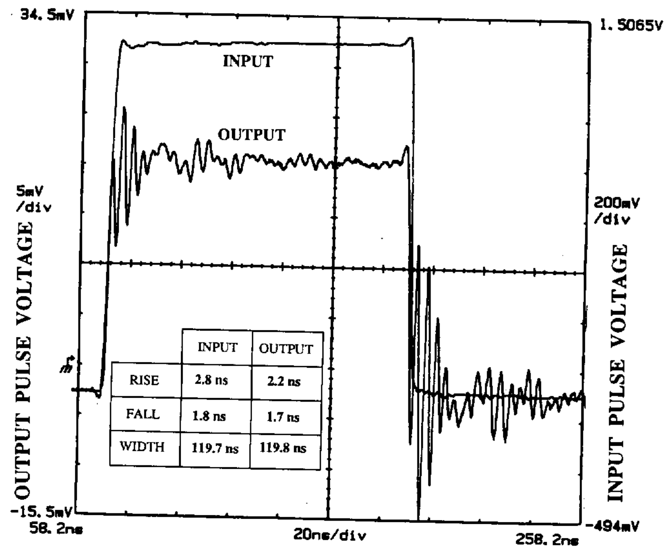

Fig. 9. Time-domain response of the 5.6-cm diameter spherical sensor to a 120-ns rectangular pulse. The input pulse is attenuated by 16 dB.

V. Conclusions

The active E-field sensor based on an electrically small spherical (hemispherical) antenna is viable for measurements of transient and pulsed fields. Wideband performance of the sensor has been achieved by loading the antenna with a buffer amplifier which has a very high input impedance. Two monopole-configuration sensors and one free-field sensor were built, tested, and calibrated in a TEM cell in both the frequency domain and time domain. Each sensor provides a flat frequency-independent response up to almost 6 decades. For example, the 5.6-cm diameter hemispherical sensor has the flat response region extending from 30 Hz to 42 MHz with the sensitivity of 1.9 mV/(V/m). The dynamic range of all sensors has been estimated to be over 65 dB. The rise time of the output pulse for a Gaussian-pulse incident field (450-ps width) is less than 1 ns.

References

[1] C. E. Baum, E. L. Breen, J. C. Gilles, J. O'Neill, and G. D. Sower, "Sensors for electromagnetic pulse measurements both inside and away from nuclear source regions," *IEEE Trans. Electromagn. Compat.*, vol, EMC-20, pp. 22–35, Feb. 1978.

[2] A. J. Kozlowski, M. Barski, and S. S. Stuchly, "Electrostatic discharge research at the University of Ottawa," in *Symposium Record of the IEEE National Symposium on Electromagnetic Compatibility*, Denver, CO, May 23–25, 1989, pp. 343–346.

[3] B. N. Nelson, C. Menzel, and T. G. DiGiuseppe, "Fiber optic field sensor configurations for high bandwidth lightning research measurement applications," *Proc. SPIE*, vol. 720, pp. 85–90, 1986.

[4] M. A. Stuchly and S. S. Stuchly, "Measurements of electromagnetic fields in biomedical applications," *CRC Critical Reviews in Biomedical Engineering*, vol. 14, pp. 241–288, 1987.

[5] H. W. Anderson and R. S. Smith, "Active DF antennas," *RF Design*, pp. 62–68, Nov. 1989.

[6] R. A. Sainati, "Active antenna performance limitation," *IEEE Trans. Antennas Propagat.*, vol. AP-30, pp. 1265–1267, Nov. 1982.

[7] E. H. Nordholt and D. Van Willigen, "A new approach to active antenna design," *IEEE Trans. Antennas Propagat.*, vol. AP-28, pp. 904–910, Nov. 1980.

[8] R. W. Latham and K. S. H. Lee, "Capacitance and equivalent area of a spherical dipole sensor," *Sensor and Simulation Note*, no. 113, July 1970.