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Design of Electric Field Sensors for Measurement of Electromagnetic Pulse

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Abstract: In this paper, a D-dot electric field sensor and a fiber-optic transmission electric field sensor are developed for measurement of electromagnetic pulse. The D-dot sensor is a differential model sensor without source and has a simple structure. The fiber-optic transmission sensor is in the type of small dipole antenna, which uses its outside shielding layer as a pair of antennas. Design of the sensor circuit and the test system are introduced in this paper. A calibration system for these pulsed field sensors is established and the test results verified the ability of the developed sensors for measurement of the standard electromagnetic pulse field (the half peak width is 25 ns and the rising time is 2.5 ns). *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Electromagnetic pulse, Electric field sensor, Fiber-optic transmission, D-dot, Antenna.

1. Introduction

Electromagnetic pulse (EMP) is a kind of transient electromagnetic phenomenon with fast leading edge, wide frequency band and large amplitude. It can be produced by nuclear explosion, lightning, electro-static discharge and power switching process [1]. For the example of nuclear explosion produced EMP, some international standards have specified its basic waveform for test verification. In the revised IEC61000-2-9(1998) [2] and MIL-STD-461E [3], the amplitude, rise-time and half peak width of EMP is 50 kV/m, 2.5 ns and 25 ns, respectively. This kind of environment will severely damage or disturb modern electronic and electric facilities if they are not perfectly protected. It is of vital importance for the traffic systems, the security systems, the power system and the communication system to be hardened and tested against EMP. The measurement of such kind of pulsed electromagnetic fields receives great attention [4, 5].

Unlike other traditional small antennas, EMP electric field sensor is mainly used for time-domain waveform measurement and its response should be a constant over the whole frequency band from DC to hundreds of mega-Hertz. Additionally, EMP sensors usually work in the environment with strong interference, the data transmission system should have good immunity to the environmental noises. Some EMP sensors have been developed in recent years and they can be divided into two categories, the differential mode sensor and the self-integral mode sensor. For the differential mode sensor, the output is proportional to the time derivative of the measured electric or magnetic field. To prevent the interference in data transmission form the sensor to the recording instruments, semi-ridged coaxial cable or the fiber-optic transmission link are adopted [6, 7]. However, the market available sensors are very expensive and in practical measurement we usually need to use multiple sensors for distributed measurement. The aim of this paper is to develop low cost and high efficient EMP sensors. A D-dot electric field sensor and a fiber-optic transmission electric field sensor are developed, the first one is a passive sensor for measurement of strong field and works in differential mode, the second one is an active sensor with very compact fiber-optic transmission system and works in self integral mode [8-10]. In the following parts, design of the sensor circuit and experimental verification of the sensor's characteristics are introduced.

2. Sensors Design

2.1. The Equivalent Circuit of Electric Field Sensor

The basic form of EMP electric field sensor is a pair of electrically small antenna. The response of such sensor depends on its capacitance, resistance and the frequency band of the measured pulse field. An equivalent circuit of the electric field sensor is shown in Fig. 1, where A_e is the equivalent area of the sensor, C is the equivalent capacitance, R is the load resistance, U_0 is the equivalent voltage of the load and $\dot{D}$ is the time-derivative of the measured electric flux density. By Eq. (1), we can get electric field intensity E from D, where ε_0 is the free space permittivity.

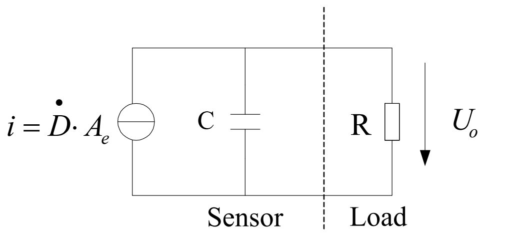

Fig. 1. Equivalent circuit of the electric field sensor.

$$D = \varepsilon_0 E , \tag{1}$$

We can consider the sensor as a current source, then the output current I_s is given by

$$I_s = \dot{D} \cdot A_e , \tag{2}$$

In time domain, we have

$$\dot{D}(t) \cdot A_e = C\frac{du_o(t)}{dt} + \frac{u_o(t)}{R} , \tag{3}$$

In frequency domain, we have

$$U_o(j\omega) = \frac{j\omega\varepsilon_0 E(j\omega) A_e R}{j\omega RC + 1} , \tag{4}$$

If $\omega RC << 1$, then

$$U_o(j\omega) = j\omega\varepsilon_0 E(j\omega) A_e R , \tag{5}$$

$$u_o(t) = \varepsilon_0 A_e R \frac{\partial}{\partial t} E(t) , \tag{6}$$

This is the time domain response of a D-dot sensor. It should be noted that the available frequency band of such sensor is below $f = 1/(2\pi RC)$. With $R = 50\,\Omega$ and C equals a few pico-coulomb, f could be as high as a few GHz.

If $\omega RC >> 1$, then

$$U_o(j\omega) = \frac{\varepsilon_0 E(j\omega) A_e}{C} , \tag{7}$$

$$u_o(t) = \frac{\varepsilon_0 A_e E(t)}{C} , \tag{8}$$

This is the time domain response of an E sensor (the self integral sensor). It should be noted that the available frequency band of such sensor is above $f = 1/(2\pi RC)$. With high input impedance circuit, f could be as low as tens-Hertz.

2.2. The Structure of Electric Field Sensor

According to the principle of the D-dot and the E field sensors, we designed two types of EMP electric field sensors. A ground plane mounted small circular cone is used as the D-dot sensor to measure the strong EMP field, its output is connected to a $50\,\Omega$ double-layer shielded coaxial cable to eliminate environmental noises. And a small dipole antenna is used as the E field sensor to measure free-field EMP or the induced disturbance within small enclosures. Its dipole is in the form of hollow cylinders to include fiber-optic emitting circuit in the antenna. The structure of the sensors is given in Fig. 2.

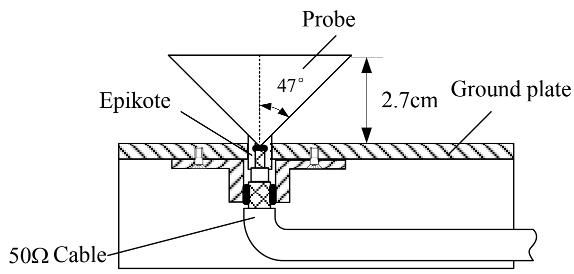

Fig. 2 (a). Structure of the sensors: D-dot sensor.

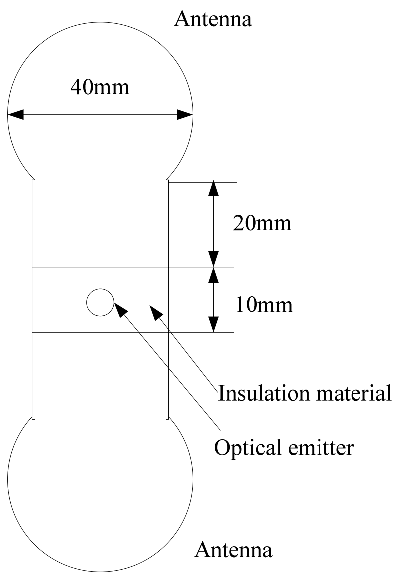

Fig. 2 (b). Structure of the sensors: E field sensor.

Since the spherical structure can reflect a smaller distortion to the measured field and not easy to appear point discharge. The antenna structure of the E field sensor is spherical.

2.3. Data Processing and Fiber-optic Transmission

The original output of the D-dot sensor needs to be integrated to obtain the true waveform of the measured EMP. We choose a digital filtering approach to perform this task. Eq. (6) can be rewritten in discret time domain as

$$x(i) = RCl_e \frac{y(i) - y(i-1)}{\Delta t} \ (x(i) = u_0(i), y(i) = E(i)), \quad (9)$$

Then we can get

$$y(i) - y(i-1) = \frac{\Delta t}{RCl_e} x(i) \ (x(i) = u_0(i), y(i) = E(i)), \quad (10)$$

By using function *filter (b, a, X)* in MATLAB software and specifying a=[1,-1], b=[$\frac{\Delta t}{RCl_e}$], we can get the true waveform of the measured electric field.

The induced voltage of the E field sensor is fed to an electro-optical modulation circuit shown in Fig. 3, where the antenna voltage can directly control the emitter and collector current of the BUT(Bipolar Junction Transistor). This circuit is very compact and can work as both amplifier and electro-optical converter. The analog bandwidth of the electro-optical converter is 800 MHz and the output wavelength is 1310 nm laser signal. By adjusting the variable resistor *R1*, the collector current of BJT can be 40 mA so as to reach the current work area. Because of the simple circuit structure, the transmission time of induction signal will be shorten. Optical signal transmits to the receiver through 50 μm multimode optical. An optical receiver then converts it to voltage signal ranging from -1 V to +1 V.

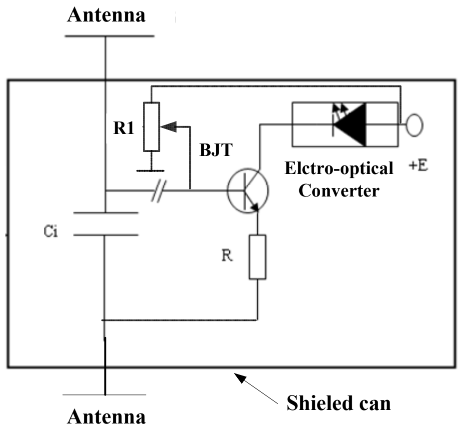

Fig. 3. Principle circuit of the electro-optical modulation.

3. Experimental Verification

3.1. Test Setup

A parallel plate bounded ware electromagnetic pulse simulator is used to verify the characteristics of the developed sensor [11, 12]. Fig. 4 is the test setup, where the left side is the pulse source which can generates a double-exponential pulse waveform. The right side is a terminal which uses a 176 Ω matched load. Electromagnetic pulse field is generated in the work space which is between the two parallel plates. We must place D-dot sensor on bottom plate to work in normal. But for E field sensor, we can place anywhere in the work space. If $U(t)$ is the peak of the input voltage, and $E(t)$ is the electric field strength inside the simulator, we can get $E(t)$ by $U(t)/h$, where h is the height of the working space and equals to 0.8 m. The highest electric field produced is 62500 V/m when the input is 50000 V. A Tektronix 3034C digital oscilloscope with bandwidth of 300 MHz and sampling rate of 2.5 Gs/s is used to monitor for the sensor output.

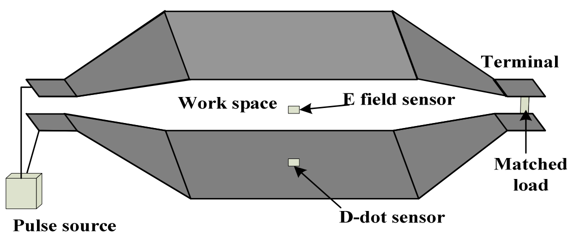

Fig. 4. Testing setup of electric field sensor.

3.2. Response of the D-dot Sensor

When a pulse (10 %-90 % rise time: 2.5 ns, 50 %-50 % pulse width: 25 ns) is applied, the measured pulse waveform by D-dot sensor is shown in Fig. 5, where the waveform is the differential result of the measured electric field. By using the digital filter mentioned in 2.3, we compare the integration waveform with the standard field waveform (normalized waveform), the result is shown in Fig. 6 and Fig. 7

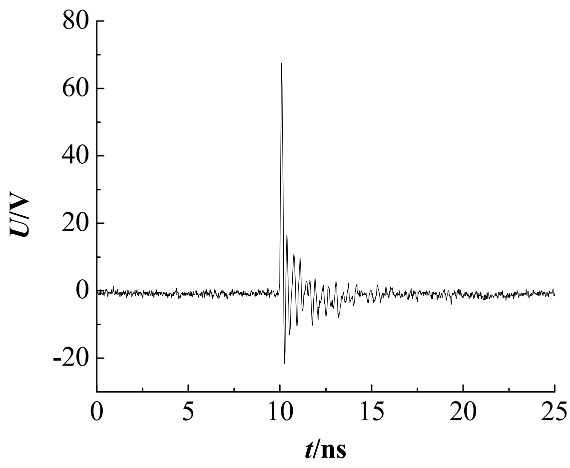

Fig. 5. Pulse response of D-dot sensor.

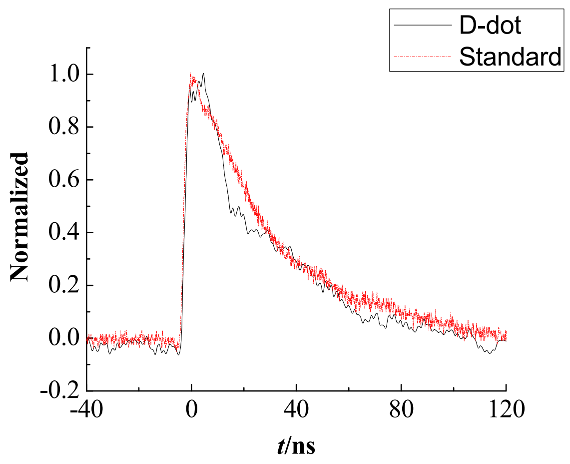

Fig. 6. Whole waveform of D-dot sensor.

From Fig. 6, we know that the waveform of D-dot sensor is basically the same as the standard field waveform.

Fig. 7 illustrates that the rising time is approximately 2.5 ns. This sensor has the advantage of fast response and stable output because it uses passive circuit. It can be used as a standard sensor to monitor the incident EMP fields in various tests.

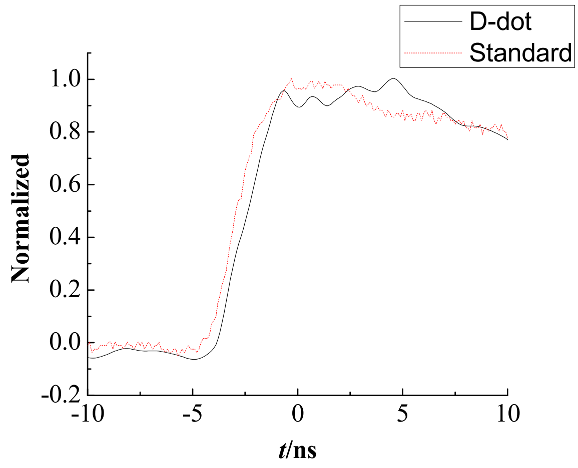

Fig. 7. Leading edge of D-dot sensor.

3.3. Response of the E field Sensor

The same pulse electric field is applied to the E field sensor with fiber-optic transmission. Fig. 8 and Fig. 9 show the normalized sensor waveform and the standard field waveform. The normalized output of the E field sensor is slightly different from the real input field. This difference is probably due to the overshoot of the response at its leading edge, Fig. 9 also this effect, where the rising time is 2 ns and a little less than the input. Although a fast rising time is desired for EMP sensors, the unwanted fast leading edge still need to be adjusted in later circuit design.

The E field sensor has the advantage of adjustable amplitude response and fiber-optic data link. It need not to use a ground reference plane and is suitable to measure EMP fields inside a small enclosure.

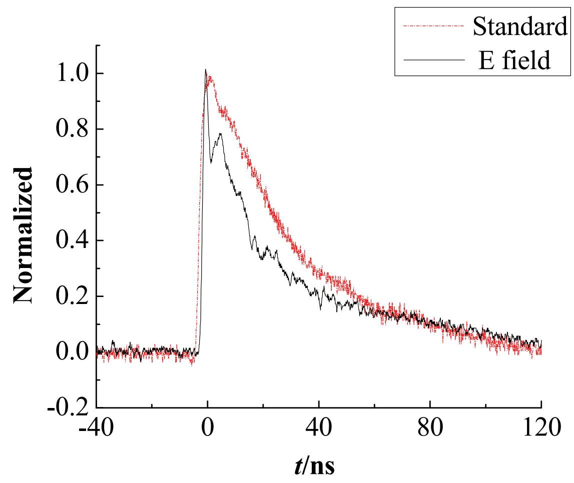

Fig. 8. Whole waveform of E field sensor.

4. Conclusion

This paper presented design and testing of two kinds of electric field sensors for EMP measurement.

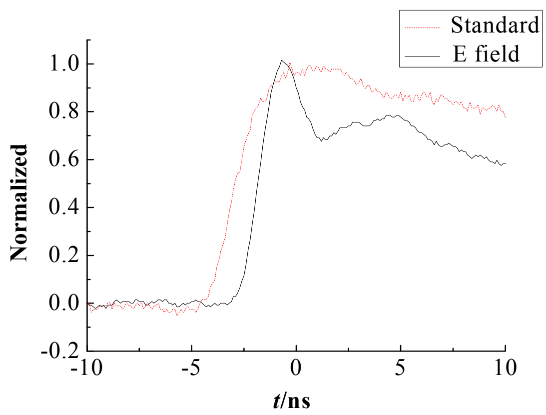

Fig. 9. Leading edge of E field sensor.

The D-dot sensor can be used as a standard sensor for monitoring of EMP environment and the E field sensor can be used as a sensitive sensor to measure the induced fields inside shielded enclosures to study its EMP response. Experimental research has verified the response characteristics of these sensors. Further improvement is till under consideration to solve the overshoot problem of the E field sensor.

Acknowledgements

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