Sensor and Simulation Notes

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Tiny Fast-Pulse B-Dot and D-Dot Sensors in Dielectric Media

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Abstract

The measurement of fast (subhundred-picosecond) electromagnetic pulses inside a high-permittivity medium presents some new challenges. These are especially associated with the shorter wavelengths and the contat of the D-dot antenna with the medium. This paper discusses some techniques to mitigate these problems to some degree.

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1. Introduction

By way of a little history, since the 1960s, there has been the problem of measuring electric and magnetic fields in the presence of significant conductivity (nonlinear) (as well as γ-rays, Compton currents, and neutrons). This is summarized in [11]. As we discovered, the design principles had some significant differences between the two types of sensors, with the magnetic (B-dot) sensors being the easier to make valid measurements.

For tests in HEMP (high-altitude electromagnetic pulse) simulators (such as for in-flight missiles and aircraft) the requirements became significantly easier. This was associated with the relaxation of the source-region requirements to a situation where the D-dot and B-dot sensors were located in benign one-atmosphere (absolute) pressure air. The ACD (D-dot) and MGL (B-dot) designs have been commercially manufactured in various sizes (and associated bnadwidths) by EG&G and Prodyne, and have found wide application in EMP and HPE (high-power electromagnetic) testing.

We are now faced with another problem as we extend our measurements into high-relative-dielectric-constant (ε_r) media with extreme required high-frequency response. In the EMP days we were concerned with nanoseconds. Now we are concerned with subhundred picoseconds [9, 10].

2. B-dot Sensors

When optimized for air, MGL (multigap loop) sensors have rise times of roughly two sensor sizes in speed-of-light units. With a as the radius of the (cylindrical) loop with four gaps it has been found that an MGL has a flat response (as a b-dot) sensor (3-dB sense) up to [4]

$$
\begin{aligned}
&\frac{\lambda\!\!\!^{-}}{a} \simeq 1 \\
&\lambda\!\!\!^{-} = \frac{\lambda}{2\pi} \equiv \text{radian wavelength} \\
&f = \frac{c}{\lambda} \equiv \text{frequency} \\
&c \simeq 3 \times 10^8 \ m/s \\
&\quad \equiv \text{speed of light (free space or air)}
\end{aligned}
\qquad (1.1)
$$

Now we are faced with embedding a loop in a high-dielectric medium. As found in [2], it is advantageous to place the loop in a dielectric medium to significantly increase the high frequency response in the presence of a high-conductivity medium. In this case the upper frequency response is given by

$$\frac{\delta}{a} \simeq 1$$

$$\delta \equiv \text{skin depth in external conducting medium} \qquad (1.2)$$

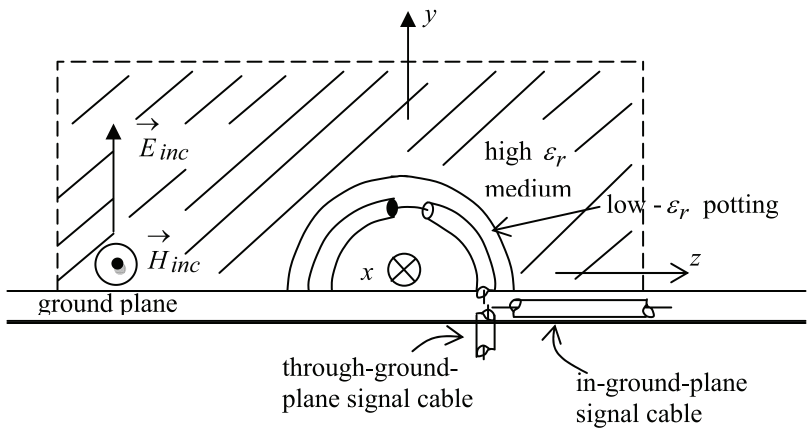
(depending on cylinder length, or equivalently cable loading impedance on loop).

Instead of skin depth for an external conducting medium we have a small radian wavelength , $\lambda\!\!\!^{-}$, in the high ε_r external medium. Something similar should happen as in (1.1) where now $\lambda\!\!\!^{-}$ corresponds to the external medium in which the measurement is to be made. The ε_r in which the loop is encapsulated can be much smaller (e.g., 2.25 for polyethylene).

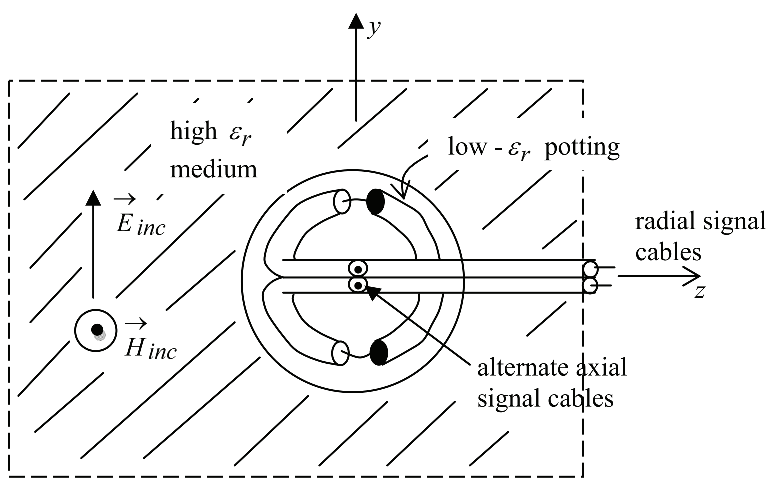
This type of sensor is illustrated in Fig. 2.1. Figure 2.1A shows a ground-plane version. In this case the magnetic field (incident for a wave propagating in the *z* direction) is constrained to be parallel to a highly conducting ground plane. The signal cable can be routed away from the sensor in various directions. If one wishes to penetrate the ground plane (with circumferential connection to it), the ground plane might also serve for shielding the recording instruments. Alternately the signal cable can follow the ground plane (recessed?) in a radial direction (*z* direction) or an axial direction ($\pm \times$ direction). In any event the cable shield must be well electrically connected to the ground plane at the positions of first reaching it.

Note that the signal enters the cable at the position farthest from the ground plane. This adds symmetry such that, with the image, this is a two-gap loop, thereby achieving some cancellation of unwanted higher-order terms [4]. In this design one can still extend the loop as a cylinder for improved bandwidth [1]. However, since the high-dielectric medium limits the bandwidth to $\lambda\!\!\!^{-}$ of order of one, the loop inductance can be somewhat higher, consistent with the above. The signal output cable would normally be 50 Ω .

Figure 2.1B shows a full loop such as one might use away from a ground plane. In this case the output could be differential. As illustrated, the signal-cable pair might exit the sensor in axial or radial directions. As illustrated, the signal cables cross through the sensor before going to the loop caps. This is done to prevent the left (-*z*) portion of the loop from floating to some potential different from the right side, giving a large common-mode signal. Alternately, the signal cables can become part of the loop structure on the right (+*z*) side, provided a conductor on the $y = 0$ plane is provided to electrically connect the two sides on this symmetry plane.



A. Ground-plane version



B. In-medium version

Fig. 2.1 Small B-Dot Sensors

3. D-dot Sensors

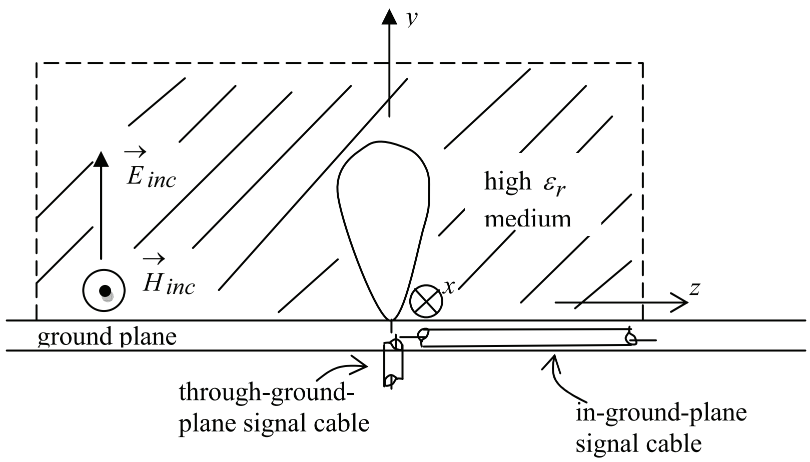
When optimized for air, ACD (asymptotic conical dipole) sensors also have large bandwidths with rise times of the order of 2*h*. Here h is the physical height of the ground-plane version (single-ended), and 2*h* is the full height of the differential version [7, 8].

The situation for an ACD-type D-dot sensor is quite different from that of an MGL. In this case the continuity from the conducting antenna element to the high ε_r medium is very important. Its fundamental operation is in a quasi-static sense in which radian wavelengths, $\lambda\!\!\!^{-}$, in the medium are large compared to *h*, the electrode length. As such, the sensor high-frequency response is reduced from the free-space case, roughly like $\varepsilon_r^{-1/2}$, for a given *h*. There is also the question of adjusting the sensor geometry to match the medium to the sensor output impedance.

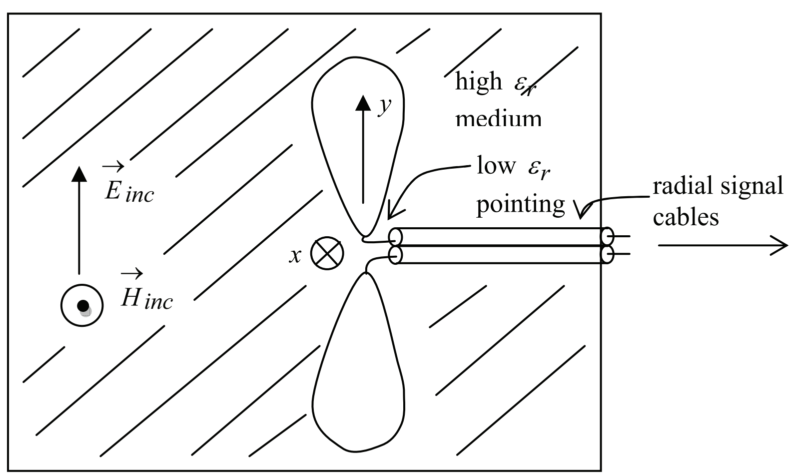
Concerning the importance of contact to the medium, one can think of this by imagining different cases of contact of the electrode with the high ε_r (like high σ) medium. If the contact is good only at the extreme end (or ends in the differential case) one is sampling a higher potential (voltage) than if one is only contacting the medium near the feed to the cable at the sensor output. If one is to think of the sensor calibration as though it were in free space, then the contact of the high ε_r medium to the exposed sensor conductors must be the same as in the free-space case.

Figure 3.1A shows a ground-plane version which senses the electric field normal to this plane. Also shown are two possible paths for the signal cable: through the ground plane (say with a connector there) which is an axial output, and in the ground plane which is a radial output.

Figure 3.1B shows an example of how one might configure such a sensor away from a ground plane. In this case symmetry is very important. The output cable pair (bonded together or in an enclosing shield) should be truly radial (*z* axis). Furthermore, it is important that the incident electric field have a negligible *z*-axis component, because any such component introduces a strong common-mode signal due to the antenna now being largely the signal-cable shields, not just the ACD conductors [11]. Note also the connections of the coax center conductors to the ACD conductors. There should be as little exposure of these conductors to the external medium as possible. They can also be coated in a low ε_r medium (e.g., polyethylene) to better maintain the cable characteristic medium right up to the ACD conductors.



A. Ground-plane version



B. In-medium version

Fig. 3.1. Small D-Dot Sensors.

Noting the importance of the contact of the ACD conductors with the high ε_r medium, we can now try to match the 50 Ω load (or 100 Ω differential). This changes the shape of the ACD conductors as in [5, 6]. The asymptotic cone at the sensor base has a pulse impedance of [3]

$$Z_a = \frac{Z_w}{2\pi} \ell n\left(\cot\left(\frac{\theta_0}{2}\right)\right) \text{ (single-ended form)}$$

$$\theta_0 = \text{angle of cone surface from } y \text{ axis}$$

$$Z_w = \left[\frac{\mu_0}{\varepsilon}\right]^{1/2} = \varepsilon_r^{-1/2} Z_0 \equiv \text{ wave impedance of medium} \tag{3.1}$$

$$Z_0 \equiv \left[\frac{\mu_0}{\varepsilon_0}\right]^{1/2} \simeq 377\,\Omega$$

Stated another way we have

$$Z_a = 50\,\Omega \simeq \varepsilon_r^{-1/2} \; 60 \ell n\left(\cos\left(\frac{\theta_0}{2}\right)\right) \tag{3.2}$$

From this we can construct the following table

Table 3.1 Asymptotic Cone Angles

ε_r	θ_0 (degrees)
1	47
3	28.2
9	16.5
27	9.6
81	5.5

As we can see, as we go to higher ε_r, the ACD sensor becomes thinner, approaching a needle, provided we match to 50 Ω.

4. Comments Concerning Calibration

With sensors embedded in the high ε_r, medium one needs to know their accuracy. Assuming all permeabilities are μ_0, the magnetic sensor is the easiest to understand in this sense. Below the upper rolloff frequency this is a simple quasistatic problem. From a first-principles point of view one can calculate the sensitivity (equivalent area), obtaining upper and lower bounds as discussed in [7].

For tiny B-dot sensors one may not be satisfied with the above bounds, due to the small loop dimensions, and "large" cable diameters involved. In that case one can calibrate the sensor by comparing its response to a more accurate (larger), standard B-dot sensor in a clean plane-wave environment as discussed in [8]. Remember that, from the reciprocity theorem, producing an accurately known wave is fundamentally no different than accurately measuring such a wave. Both involve accurate knowledge of geometric dimensions.

Calibrating the D-dot sensor in the high ε_r medium is quite another matter. As previously discussed, the contact of the electrode with the medium is critical. How does one know how well contact has been made? Is the contact continuous over all the electrode, or just in spots? If one inserts the electrode in the medium, removes it, and reinserts it, is the contact the same?

One check might be to measure the capacitance of the electrode to the ground plane (single ended sensor), or between the two electrodes (differential sensor). Using known ACD formulae and the value of ε_r the capacitance can also be calculated [5, 6], and compared to the measured value. A measured capacitance less than the theoretical value indicates some lack of contact with the medium.

Perhaps a better technique is to measure a plane wave in the dielectric with both B-dot and D-dot sensors, and compare their outputs. One needs to accurately know ε_r. This can be measured from the transit time through a slab of the material with known thickness, provided the fast-rising electromagnetic pulse used is not significantly dispersed. (Equivalently ε_r needs to be frequency independent over the range of frequencies of interest.) Of course, the medium must be nonmagnetic.

With both B-dot and D-dot sensors embedded in the medium the B-dot signal can be used for an in situ calibration of the D-dot sensor. This can be accomplished each time the D-dot sensor is inserted into the medium. One can even see if there is any difference in the calibrations after two insertions.

5. Concluding Remarks

As one can see, measurements of pulsed electromagnetic fields with subhunded picoseconds resolution in high ε_r media presents some considerable challenges. It is not just the speed involved. It includes the shorter wavelengths in the high ε_r medium, and the contact of the sensor with the medium (especially for the ACD). (This seems to be a job for a Swiss watch maker.)

References

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