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Using polarization diversity in the detection of small discontinuities by an ultra-wide band ground-penetrating radar

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ABSTRACT

A ground-penetrating radar (GPR) has been developed for civil engineering applications. Ultra-wide band (UWB) bowtie slot antennas operating at frequencies from 460 MHz to beyond 4 GHz have been designed to be integrated in a ground-penetrating radar (GPR) positioned very close to the soil surface. FDTD modeling has allowed to define the optimal geometrical parameters associated with the ground-coupled radar system that has been studied in two polarization configurations TE and TM. The ability of the GPR system in detecting small discontinuities using polarization diversity has been analyzed considering several buried canonical objects with different dielectric characteristics. Measurements in a sand box have been compared to full-wave simulations.

1. Introduction

Ground-penetrating radar (GPR) is a well-known non-destructive technique based on electromagnetic waves to detect and image dielectric discontinuities in the subsurface [1]. GPR applications are numerous involving archaeology, geology, civil engineering, environmental geophysics, utilities or target detection. The dielectric properties of a soil correlate with many of the mechanical, geologic and structural parameters of the constituents. The choice of the central frequency and the bandwidth of the GPR is an important issue, and depends on the particular application, mostly of the kind of object one is looking for: size of the object, its electrical properties, depth of the object, properties of the soil, etc. An ultra-wide band (UWB) radar offers an opportunity to probe a soil structure using the benefit from both low and high frequencies and to obtain a compromise in terms of depth resolution and penetration in a single measurement.

The basic GPR system is made of a pair of parallel antennas that radiate a polarized electric field, and the co-polarization configuration is generally chosen. Thus, the GPR system probes the subsurface at a single polarization. An optimal matching of the GPR system with the soil in order to eradicate the significant reflection from the air–soil interface is achieved by positioning both antennas in close proximity to the soil interface. The application of interest is the detection of buried objects or discontinuities in civil engineering structures particularly pipes [2,3], and defaults (cracks, joints, buried repair patches, delaminations, density changes, etc…) which can be caused by mechanical, chemical and biological causes. Because the GPR reflected signal traces issued from embedded objects result from multiple scattering both inside each object and between a given object and its environment, we have considered a simplified soil structure to interpret the radar response by comparing numerical FDTD modeling and field-experiments in the presence of well-separated

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canonical objects. Thus, we have designed a compact UWB GPR system using full-wave FDTD simulations to model and control its radiation characteristics. The experimental GPR system is supposed to operate in the frequency domain using a step-frequency continuous wave (SFCW) to benefit from a wide dynamic range, a low figure noise and the possibility of shaping the power spectral density. The aim of this study is to check the sensitivity of the UWB GPR for the detection of small discontinuities in the two main polarization configurations TM (Transverse Magnetic) and TE (Transverse Electric), and to extract information of dielectric characteristics from reflection hyperbolas. The comparison of theoretical and experimental B-scans has allowed to interpret the polarization phenomena involved by different discontinuities characterized by their shape and their dielectric properties.

2. UWB GPR system

The GPR system consists of a pair of transmitting and receiving shielded bowtie slot antennas. The antennas have been designed in our laboratory using full-wave FDTD simulations under the commercial software EMPIRE. The classical geometry of the bowtie slot antenna, as visualized in Fig. 1a, has been modified to operate in an UWB from frequency 460 MHz to beyond 4 GHz (reflection coefficient $S_{11dB}(f)$ less than -10 dB) and at lower frequencies as usual with a reduced size close to the A4 sheet size [4–9]. The antenna has been designed on a single-sided FR4 substrate ($h = 1.5$ mm, $\varepsilon_r' = 4.4$; $\tan\delta = 0.01$, 35 µm copper-clad) and its overall dimensions are $W_s = 190.4$ mm and $L_s = 332.2$ mm. As visualized in Fig. 1b, the antenna is fed at its port by a tapered coplanar waveguide CPW line with length $W_f = 67.02$ mm and dimensions $a = 0.4$ mm and $b = 2.8$ mm. The antenna port is supposed to be connected to a Vector Network Analyzer (VNA) via a SMA (subminiature version A) connector. To eliminate backward radiations in air induced by the close environment, and to reduce the direct coupling between transmitting and receiving antennas in the GPR system, each antenna has been partially enclosed in a perfectly conductive box opened towards the ground surface as shown in Fig. 2; the conductive box (height h_c = 67.5 mm, width W_c = 231 - mm, and length L_c = 362 mm) has been filled with a layered absorbing material which is supposed to progressively absorb the electromagnetic waves and to reduce multiple reflections inside the cavity. In the numerical modeling, a three-layered radar absorbing material (RAM) with a conductivity profile characterized by the power law $\sigma = 10^{n-3}$ S m^{-1} (n is the layer number, and $n = 1$ is the layer just in contact with the antenna) has been considered; such a structure is supposed to represent the five-layered RAM (150 mm-thick absorbing foam HPS 125 distributed by EUROMC) used in the experiments [10]. Thus, according to a parametric study non presented here, the characteristics of the absorbing layers are finally: $\varepsilon_{1,2,3} = 1.5$, $\sigma_1 = 0.01$ S m^{-1}; $e_1 = 24.2$ mm; $\sigma_2 = 0.1$ S m^{-1}; $e_2 = 29.3$ mm and $\sigma_3 = 1$ S m^{-1}; $e_3 = 14$ mm. The printed face of the antenna, positioned very close to the soil at an elevation h_s around 10 mm to consider potential irregularities on the soil surface, has been protected by a thin PVC sheet.

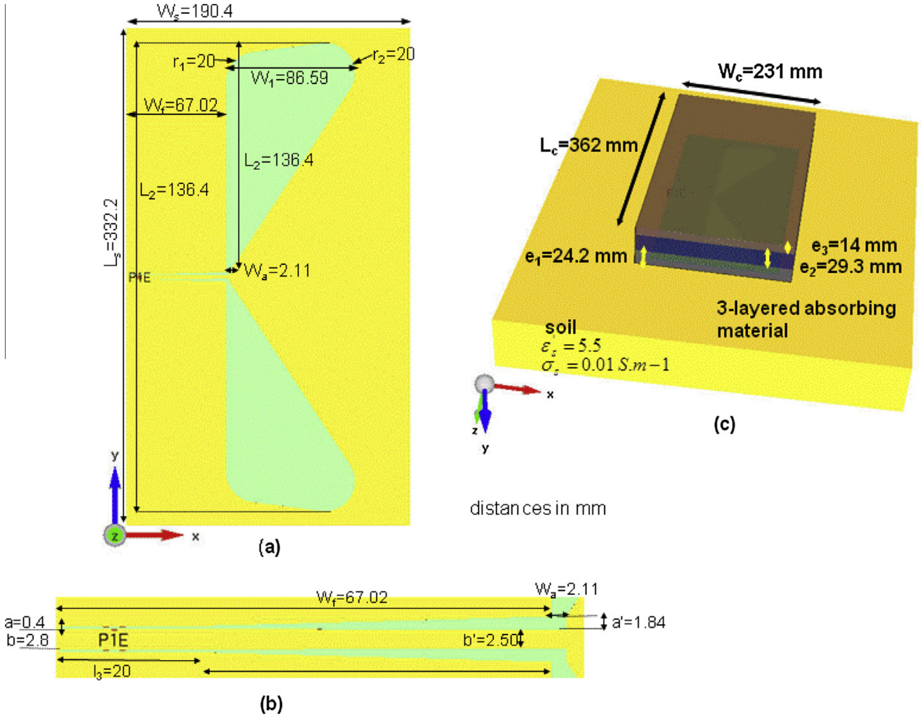

Fig. 1. Geometry of the bowtie slot antenna (a) top view, (b) tappered CPW feed line, and (c) antenna shielded by a back-cavity filled with a layered radar absorbing material.