A tapered-permittivity rod antenna for ground penetrating radar applications

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Abstract

A new dielectric rod antenna design modified from its previous version developed by Chen [IEEE Trans. Geosci. Remote Sens. (accepted for publication)] is presented. Such an antenna is useful in detecting small and shallow subsurface objects with excellent depth and spatial resolutions. These features make it useful in detecting small anti-personnel (AP) mines, pavement cracks and the surface layer. Broad bandwidth electromagnetic energy is fed into the rod from one end, guided along the rod and then radiated from the other end where the rod diameter is linearly tapered to a point. The tapered-permittivity design uses an additional permittivity taper to overcome the problem of a frequency-dependent pattern when high dielectric material is used for size reduction. This new design reduces the internal reflections at the tapered section and results in better efficiency and less antenna clutter. © 2001 Published by Elsevier Science B.V.

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1. Introduction

Ground penetrating radars (GPR’s) have been used as non-intrusive instruments for subsurface investigation (Noon et al., 2000; Plumb, 1998; Sato, 1996; Redman, 1994). For deep applications, a GPR is usually operated in the MHz frequency range to achieve a greater penetration but with a poorer depth resolution. For shallow applications, such as the detection of buried landmines, the 1–6 GHz frequency range gives a reasonable trade-off between penetration and depth resolution. For all GPR systems, the antenna design plays a vital role in measurement performance. Broad bandwidth, good efficiency, low antenna clutter, and weak antenna–ground interaction are the major requirements of a good GPR antenna. Note that antenna clutter could be broadband such as feed point reflection and direct coupling, or narrowband such as ringing. Most deep-application GPR’s place their antennas close to the ground surface for coupling more energy into ground, and less radiation above the ground and less surface scattering. A major drawback of this configuration is the strong antenna–ground interaction that can significantly change the characteristics of the antenna. This has been shown in the literature (Procter, 1950; Abul-Kassem, 1972; Hayes, 1983). Such an interaction produces noticeable antenna clutter and limits the antenna to be applicable to only a few ground conditions. In a well-controlled environment, the effects of the interaction can be removed via the use of a known buried calibration target; however, in reality, it is not practical to dig a hole for the placement of a calibration target since the disturbance of the soil usually changes the electrical char-
acteristics of the soil as well. In addition, the performance of such a GPR system would depend heavily on the surface and soil conditions, which often vary from time to time and from place to place.

It is usually desirable to elevate the GPR antenna off the ground for shallow applications to achieve faster survey speed and less antenna–target and antenna–ground interactions. Faster speed is gained from a larger radiation beam coverage and freedom of sensor motion. However, two major problems are the ground surface scattering that reduces both radar efficiency, and sensitivity. The surface roughness creates undesirable clutter that arrives at the radar over a wide time range due to scattering from different patches of surface within the illumination spot. This clutter also masks out the desired responses from shallow targets. This situation becomes worse as the antenna height above the ground increases.

One way to reduce the reflection from the ground surface is to illuminate the ground at an oblique angle when the surface is not too rough. Unfortunately, this remedy increases the illumination area and causes further spreading of the surface clutter and makes it even more difficult to detect a buried object. A focused-beam illumination can be used to achieve a greater antenna-to-ground distance while minimizing the illumination spot on the ground (Chen et al., 2000b). The minimum achievable spot size is limited to approximately one wavelength associated with the lowest operation frequency. However, this minimum spot size can only be achieved when the reflector size is several wavelengths. Although a stronger surface reflection was received from the vertical illumination, it was shown that such a reflection can be easily separated from the desired landmine responses because of the broad bandwidth and minimal ringing. Some disadvantages associated with a focused reflector system include frequency-dependent spot size, bulky reflector, high wind resistance, visual blockage and difficult calibration. These disadvantages make a focused-beam design less desirable than the new dielectric rod antenna design for field operations.

An ultra-wide bandwidth dielectric rod antenna design was introduced for improved performance in detecting anti-personnel (AP) landmines (Chen et al., accepted for publication). Chen’s design is similar to previous narrowband “ployrod antennas” (Mueller and Tyrrell, 1947; Walter, 1965) but has much greater bandwidth due to the introduction of broadband excitation structure. A dielectric rod with a circular or square cross-section was used to guide broadband electromagnetic energy. The HE_{11} hybrid mode is first excited from one end of the rod using a special broadband feed structure. The electromagnetic energy then propagates along the rod with most of its energy confined within the rod when the cross-section dimension is greater then the longest operational wavelength in the material. The phase velocity is nearly constant and solely determined by the internal material. As the diameter becomes less than a wavelength, more energy begins to propagate external to the rod and causes the phase velocity to be a function of both the internal and external materials. At the other end of the rod, radiation was introduced by gradually tapering the rod dimension to a point. This approach works well for a rod made of low dielectric material. In order to further reduce the rod size, material with high permittivity must be used. This would require a long taper section such that the end reflection occurring at the material–air interface is kept small. However, a longer taper section results in undesirable spreading of the radiation center. That is, the lower frequency energy is radiated from the beginning of the taper and the higher frequency energy is radiated close to the tip. Such a spreading causes the radiation pattern to be frequency-dependent and a careful calibration is required to remove such a dependency.

Section 2 discusses modified dielectric rod antenna design with a permittivity taper in addition to the diameter taper. The field characteristics of the new rod will be presented in Section 3 using a three-dimensional (3D) numerical model based on finite difference time domain (FDTD) technique (Yee, 1966). Final conclusions will be given in Section 4.

2. Tapered-permittivity dielectric rod antenna

The ultra-wide bandwidth dielectric rod antenna developed by Chen et al. (accepted for publication) utilizes a circular dielectric cylinder made of homogeneous material to guide the electromagnetic energy
using the fundamental hybrid mode. The electromagnetic radiation was then generated by removing the guiding structure in the end taper section where the diameter was gradually reduced to zero to minimize internal reflections occurring at the material–air interface. The design of this tapered section is very important. It serves as both a smooth terminator as well as an efficient broadband radiator. If the tapering is done too rapidly, large internal reflections would occur due to impedance mismatch. This increases the antenna clutter as well as reduces the antenna efficiency. The radiated fields propagate mainly in the forward direction with spherical phase fronts. The illumination spot size on the ground can

Fig. 1. Illumination spot size as a function of tip height above the ground.

Fig. 2. Scanned data of buried low-metallic mines: (a) TS-50 (AP), 2.5-cm depth; (b) PMA-3 (AP), 5-cm depth; (c) M-19 (AT), 4.4-cm depth; (d) VS-2.2 (AT), 8.3-cm depth.
be controlled by the antenna height as illustrated in Fig. 1. By placing the antenna tip close to the ground surface, a small illumination spot can be obtained to reduce the undesired clutter due to rough surface scattering, as well as to improve the spatial resolution that is important in detecting a small target.

The rod antenna design has been applied to the detection of buried, small, non-metallic anti-personnel landmines with good success. Some measurement data obtained from a government landmine test site, Fort A.P. Hill, are shown in Fig. 2 for various mine types and depths. The soil in the site contains a mixture of sand, clay and small gravels. The relative permittivity and conductivity at the site was measured to be approximately 8 and 0.01 S/m, respectively. Each figure plots the time-domain radar responses converted from the original swept-frequency data (2–6 GHz) as the rod antenna moved across the ground. The delay time of the received signal and the antenna position are indicated by the vertical and horizontal scales, respectively. The measured field amplitude is indicated by grayscale where the positive and negative amplitudes are represented by light and dark colors, respectively. These are unprocessed data. The strong surface reflections are clearly seen at earlier time (top of the figure). This surface reflection can be significantly reduced, if desired, using processing techniques (Salvati et al., 1998). It is also noticed that different mine types show different spatial–temporal features that can be used for further target identification. These results demonstrate the fine spatial and time resolution achieved by the low antenna clutter and broadband characteristics of the new dielectric rod antenna.

In the previous design (Chen et al., accepted for publication), the rod was made of a homogeneous material that has a constant permittivity. A rod made of higher permittivity is highly desirable since it can be small, light and have finer spatial resolution. However, a high-permittivity rod requires a longer taper section in order to keep the internal reflection to a minimum. A longer taper also results in undesired dispersion and frequency-dependent radiation patterns similar to that found in narrowband “polyrod antennas” in the early days (Mueller and Tyrrell, 1947; Watson and Horton, 1948). This is because the lower frequency components radiate earlier in the taper region and the higher frequency components radiate near the end. Such a frequency-dependent behavior requires additional complicated procedures to calibrate the measured data.

The new tapered-permittivity rod antenna design introduces an additional permittivity taper to the tapered section. Notice that the previous design attempted to vary wave impedance by gradually reducing the rod dimension to match that of free space. This is similar to the problem of matching two transmission lines with different characteristic impedances investigated by Collin (1956) and many other people. The new design attempts to vary the wave impedance by varying both the diameter and the permittivity simultaneously.

3. Numerical model of the tapered-permittivity rod antenna

A three-dimensional numerical model was set up using the FDTD technique to study the field characteristics of the new design. Fig. 3 shows the sideview of the tip portion of the 3D model. The model was enclosed by a perfectly matched layer (PML) (Zhao and Cangellaris, 1996) to avoid artificial reflections caused by space truncation. The diameter and relative permittivity of the rod are 7.62 cm and 3, respectively. Different permittivity layers are shown by different grayscale in the tip section. The actual profile of the relative permittivity is also plotted in Fig. 4. The taper section was made of seven layers with relative permittivity varying from 3 to 1.15 at the tip. Each layer has the same thickness that was chosen to be approximately a quarter of the waveguide wavelength at the center frequency. The diameter of the rod in the taper section decreases linearly to nearly a point at the tip.

Two snap shots of the calculated electromagnetic fields propagating down the rod are plotted in Fig. 5. The amplitude of the electric fields is indicated by the grayscale. This simulation uses a transient current pulse in the form of a differentiated Gaussian given by Eq. (1):

$$I_0(t) = \sqrt{2} e^{-0.5a^2}$$  \hspace{1cm} (1)
where $\alpha = (t - 3.2T_b)/T_b$ and $T_b = 7.2 \times 10^{-11}$ s. This pulse was chosen to contain significant frequency content over the desired 2–6 GHz frequency range. It is noticed that the electromagnetic energy is effectively guided within the rod before radiating out. One can also see the electromagnetic fields radiating away from the taper section with spherical phase fronts. These results are similar to those obtained from a rod made of constant permittivity (Chen et al., accepted for publication). A closer investigation reveals that the new design generates much less internal reflections in the taper section. This is shown in Fig. 6 by comparing the reflected responses from constant-permittivity and tapered-permittivity cases. It is observed that instead of having a large reflection near the tip (see dashed line) for the constant-permittivity case, many small reflections occur at the interfaces between the layers for the tapered cases. The total reflected energy from the tapered-permittivity case was found to be 16 dB less than that from the constant-permittivity case with the same cone geometry.

It should be noted that no optimization has been applied yet to the above design. One can certainly utilize many existing optimization algorithms to obtain an optimal taper design in both dimension and permittivity to meet a tolerable reflection level with a minimal taper length. This goal is important in minimizing the movement of the radiation center over the operational frequency range such that the radiation pattern is relatively insensitive to frequency variation.
Fig. 5. Snap shots of the FDTD simulated field distributions: (a) guided fields; (b) field radiating out from the tapered section.

Fig. 7 plots the magnitude of the radiated field as a function of both frequency and position along a straight line 2.5 cm away from the rod tip and parallel to the electric field. It is observed that the radiation beamwidth varies only a little over a broad frequency range (above 2.5 GHz). It is noted that for frequencies below approximately 2.4 GHz, the diameter of the rod, i.e. 7.62 cm, becomes less than one wavelength (in material) and the electromagnetic energy becomes loosely guided in this low frequency region. It was also found that the above pattern from the tapered-permittivity design is more stable than

Fig. 6. Comparison of the responses reflected from the tapered section between the constant-permittivity and tapered-permittivity design.

Fig. 7. Radiated field distribution plotted as a function of frequency and position on the ground surface 2.5 cm away from the rod tip.
that from the constant-permittivity design. Fig. 8 plots the amplitude contour of the radiated field at 4 GHz on the ground surface 2.5 cm away from the rod tip. Fig. 8(a) and (b) corresponds to the parallel and perpendicular field components with respect to the polarization of the excitation. These patterns also show improved rotational symmetry compared to that obtained from a constant-permittivity rod.

4. Conclusions

A new broadband dielectric rod antenna with a tapered-permittivity radiation head was presented. The original constant-permittivity taper design works well for low-permittivity rod. However, it faces a potential dispersion problem for high-permittivity rod due to the requirement of a long taper length. The new tapered-permittivity rod antenna design significantly reduced the internal reflections from the radiation head (tapered section) for the same taper length. This means a shorter taper length can be achieved for a similar reflection level obtained from the constant-permittivity rod. It was also found that the radiated pattern on the ground surface from the new design is relatively frequency-independent and rotationally symmetric. The 10-dB spot size on the ground 2.5 cm away was found to be approximately one wavelength at the lowest frequency, i.e. 2 GHz. Such a small spot size is important in detecting small objects. The antenna size of the new rod antenna is significantly smaller than a focusing reflector in achieving a similar spot size. The new tapered-permittivity design allows one to design a rod antenna with high permittivity material such that one can achieve a smaller size, lighter weight and finer spatial resolution.

In addition to the landmine application, this new antenna design will also be useful for other non-destructive inspections that require high spatial and temporal resolutions. Fully polarimetric version of the broadband dielectric rod antenna is also being developed.

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