OPTIMIZATION OF VIVALDI ANTENNA FOR DEMINING BY GPR

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1. Introduction

As GPR is used for detecting shallowly buried objects with higher resolution, it usually requires antenna units lift from ground surface since some external reasons, for example, for landmine detection applications. Unfortunately, the Ultra-WideBand(UWB) antennas used in many GPR systems are dielectric-coupling dipole antenna, including bow-tie antennas and spiral antennas as well as cylinder dipole antennas and so on. The radiation energy into underground decreases sharply as such antennas lift from ground surface, i.e., the detection depth decrease sharply. It is necessary to develop new antennas for such application. From antenna theory, it is known that there mainly are two kinds UWB antennas satisfying this requirement. One is a horn antenna and the other is Tapered slot antenna(TSA), both belong to air-coupling antenna family. But the size of a horn antenna at GPR operating frequency band is generally larger. It is unfavorably to use such bulk antenna in many engineering application, especially for hand-held detection system.

Because the low frequency limit of a TSA is mainly dependent by its ended aperture width, the non-linear tapered slot antenna, i.e., Vivaldi antenna, will have smaller axial length for same operation frequency band. Introduced by Gibson[1], Vivaldi antenna is also belonged to the family surface wave antennas in which the phase velocity of electromagnetic(EM) wave along the antenna structure is less than or equal to the propagation velocity of EM wave in air and can produce end-fire radiation. Except its it low profile, like other printed circuit TSA, it is inexpensive to fabricate, and can offer moderately high directivity(10~17dB) and very wideband performance, for instance, several octaves. As has been pointed by Gibson[1], the Vivaldi antenna has theoretically unlimited operating frequency band. Because at a given wavelength, only the section corresponding to the frequency component will actually radiate efficiently. But, the operating frequency bandwidth is practically limited by the transition from the feeding transmission line to the slot line of the antenna and also by its finite dimensions. In order to improve such limitation, the antipodal Vivaldi antenna was proposed by Gazit[2]. Since then, because of its excellent advantages, Vivaldi antennas have widely been used in microwave and millimeter wave field, especially as antenna elements in wideband phased arrays of radars or other electric equipments[3].

In this paper, we study the properties of such antenna used in GPR system for underground landmine detection, which operating frequency band range is approximately between 1GHz to 5GHz. FDTD method[4] has been used to calculate its return loss or VSWR, far-field radiation pattern and so on. The properties of different antennas have been calculated as the shape and thickness as well as dielectric constant of printed circuit board are changed.

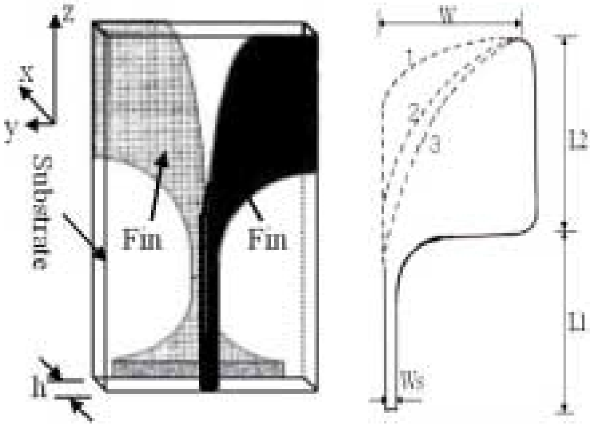
2. Design and Numerical Calculation by FDTD method

As has stated, for Vivaldi antennas, the slot is tapered non-linearly from feeding point along its axial direction z as shown in Fig.1. The shape of the slot is usually defined by the following exponential function

$$z(y) = \pm A e^{py} \qquad (1)$$

where y and z are in same unit, z is in the substrate axial direction and y is in the horizontal direction as shown in Fig.1(a).

The radiation properties from a Vivaldi antenna depend on its correct design, including the shape of the fin, dielectric constant and the thickness of the substrate as well as the form of the feeding part and so on. Many studies have been verified that its feed part in general determines its high frequency limit, and its end aperture size the low frequency limit. But unfortunately, up to now, the design about the shapes and dimensions of the Vivaldi antennas are half based on the empirical methods as no detailed theory can be available for step by step.



(a) (b)

Fig.1 Antipodal Vivaldi antenna

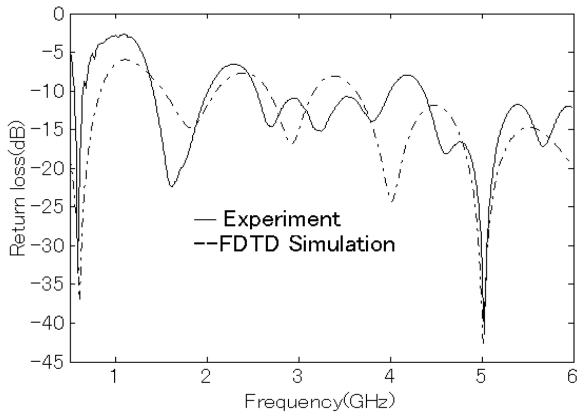


Fig.2 The return loss of the antenna with inner edge as curve 3 by experiment and FDTD

From microstrip line theory[4], the strip width W_s in Fig.1(b) can be exactly designed. If the thickness of the metal layer on the substrate is negligible compared with the thickness of the substrate h. Supposing its relative dielectric constant is ε_r and its characteristic impedance is Z_0. Then, the following formulas can be used to design the width of the microstrip line.

$$\frac{W_s}{h} = \frac{8\exp H_e}{\exp(2H_e) - 2} \qquad (2a)$$

where

$$H_e = \frac{Z_0\sqrt{2(\varepsilon_r + 1)}}{120} + \frac{1}{2}\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1}\right)\left(\ln\frac{\pi}{2} + \frac{1}{\varepsilon_r}\ln\frac{4}{\pi}\right) \qquad (2b)$$

Generally, there are two types of substrates used for microstrip antenna design: soft and hard substrate. Soft substrates are flexible, cheap and can be fabricated easily. However, it possesses higher thermal expansion coefficients. Typical examples of soft substrates are RT Duriod 5870($\varepsilon_r = 2.3$), RT Duriod 5880($\varepsilon_r = 2.2$) and RT Duriod 6010.5($\varepsilon_r = 10.5$). As for hard substrates, it has better reliability and lower thermal expansion coefficients. On the other hand, it is more expensive and non-flexible. Typical examples of hard substrates are quartz ($\varepsilon_r = 3.8$), alumina($\varepsilon_r = 9.7$), sapphire($\varepsilon_r = 11.7$) and Gallium Arsenide GaAs($\varepsilon_r = 12.3$). Because its low cost, the soft substrates have been usually used to develop Vivaldi antennas. Here, we also chose such soft substrates, i.e., RT Duriod 5870($\varepsilon_r = 2.3$) and RT Duriod 6010.5($\varepsilon_r = 10.5$). Their radiation properties will be compared in the following section.

The objective of this study is to design an antenna used in a GPR system for landmine detection by FDTD method. In the following calculation, The QFDTD90 software is used and the parameters are taken as: dx=1.5mm, dy=1.3mm, dz=1.2mm. A sinusoidally modulated Gaussian pulse is taken as the source excitation[5],

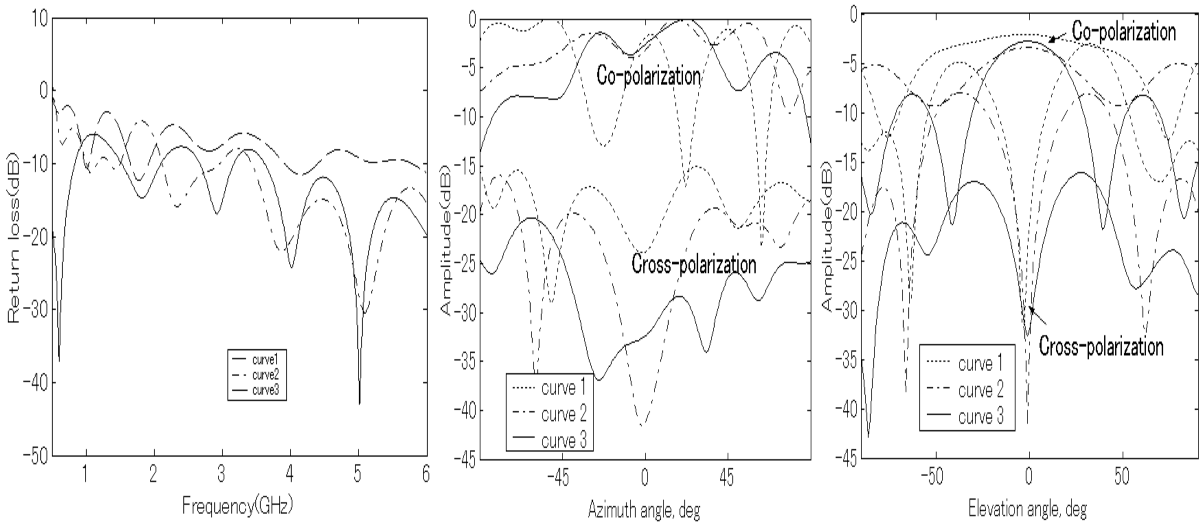
$$s(t) = \exp\left(-\frac{t - t_0}{t_w}\right)^2 \sin\left[2\pi f_0 (t - t_0)\right] \qquad (3)$$

where $t_0 = 3t_w$ is the center of the pulse, t_w=50.0ps is the pulse width at its 1/e characteristic decay point, f_0=10GHz is the modulation frequency.

Considering both the resolution and penetrating depth, the operating frequency band should be between 1.0GHz to 5.0GHz.

As has stated above, because the low frequency limit(1.0GHz) is mainly dependent on the aperture width, i.e., the value 2W in Fig.1(b). The frequency components cannot be radiated when λ/2>2W, λ is the wavelength corresponding to the frequency component. Therefore, we take W=7.5cm. Other parameters taken as: $L_1 = 6.0cm$, $L_2 = 8.0cm$; and h=1.5mm, ε_r=2.3, conductivity σ=0.0001 S/m, which is corresponding to the substrate RT Duriod 5870.

Keeping the outer edge of the fins not to change in Fig.1(a) and 1(b), when the inner edges of the each fin takes as the shape of curve 1, curve 2 and curve 3, respectively, three different Vivaldi antennas with the same outer edge and thickness but their inner edges are different with each other can be got. From FDTD calculation, Fig.3 shows their return loss. The far-field radiation patterns of the three antennas in E-plane and H-plane at f=3.0GHz are shown in Fig.3(a) and 3(b).



(a) Return Loss (b) E-Plane (c) H-Plane

Fig.3 The return loss and radiation patterns of three Vivaldi antennas at f=3.0GHz

Comparing the curves in Fig.2 and Fig.3, we can see that the return loss and radiation properties(beam-width, cross-polarization) of the antenna with the shape of curve 3 as its inner edge is much better than other two antennas. It is probably deduced that as the notch length increased, the beam-width become sharper, especially for H-plane.

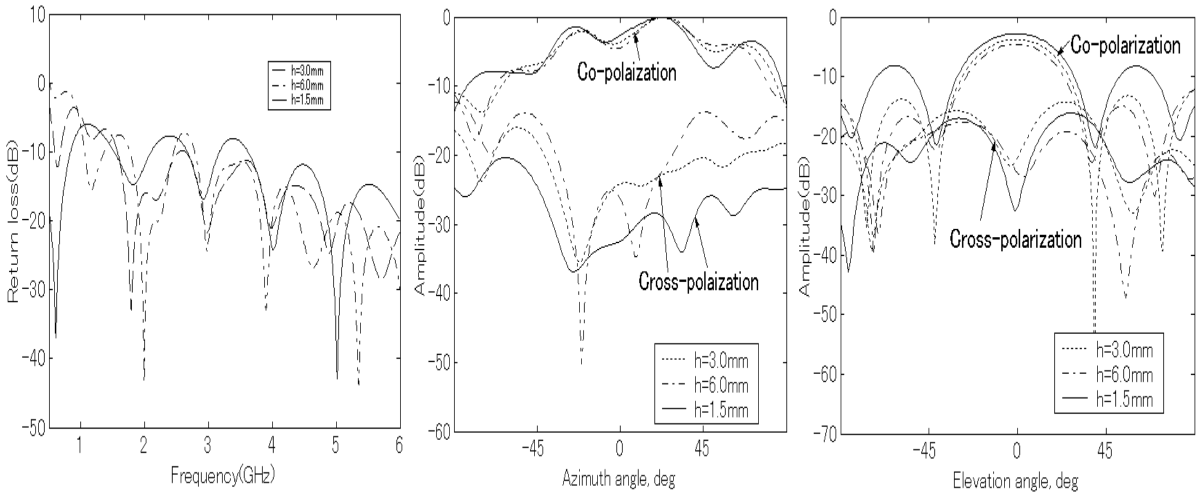
In Fig.2, we have compared the measured result with the one by FDTD calculation for the antenna with curve 3 as its inner edge. Good agreement is obtained.

For the antenna with the inner edge of the shape of curve 3, if the thickness h of the substrate is taken as 1.5mm, 3.0mm, 6.0mm,respectively, the return loss and radiation properties are shown in Fig.4(a), (b)and (c).

It can be seen that as the thickness is increased, the cross polarization properties become worse. That is because the electric field components within the antenna structure are much more skewed with respect to the physical axis of the antenna when the thickness is increased. The return loss property at low frequency band range is also become worse, but at higher frequency range is superior.

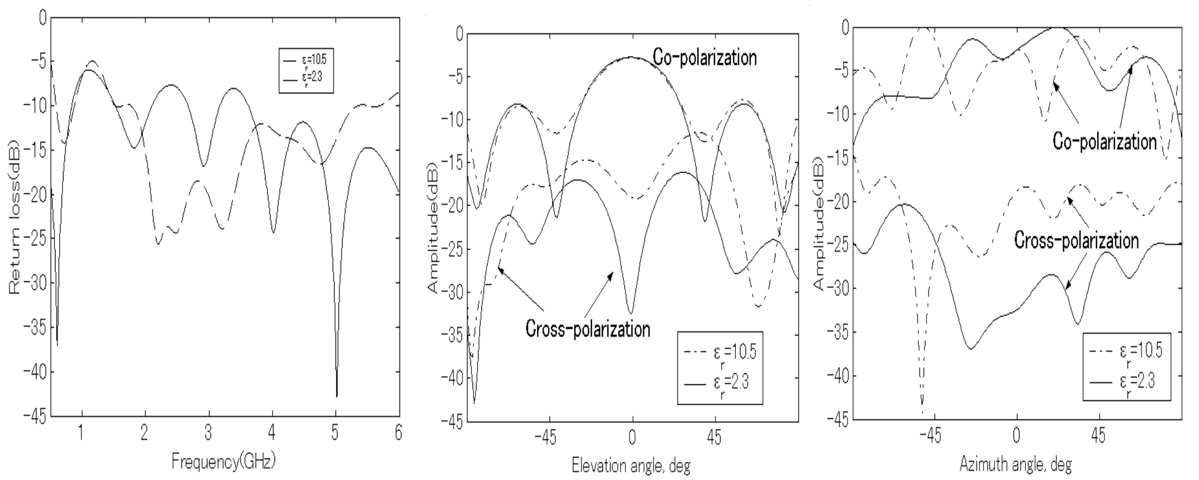
If the substrate replace by RT Duriod 6010.5($\varepsilon_r = 10.5$), then its return loss and radiation properties at 3GHz are shown in Fig.5.

Fig.5(a) shows that as the permittivity of the substrate is increased, its return loss at high frequency band range becomes worse but at the 2GHz to 3.5GHz, its return loss is batter. From Fig.5(b) and (c), it can be seen that cross polarization properties become worse as the permittivity is increased.



(a) Return Loss (b) E-Plane (c) H-Plane

Fig.4 The return loss characteristics and radiation patterns by three Vivaldi antennas at f=3.0GHz



(a) Return Loss (b) E-Plane (c) H-Plane

Fig.5 The return loss characteristics and radiation patterns by three Vivaldi antennas at f=3.0GHz

3. Conclusion

The Vivaldi antennas with different structures are calculated and analyzed in this paper by FDTD method. For Vivaldi antenna, if its inner edge is tapered sharply, i.e., its inner notch length is shorter, then its traveling wave property and radiation properties are worse than these of the antennas with gradually tapered inner edge. The thickness and permittivity of substrate are also the factors to influence the antenna properties. As the thickness or permittivity is increased, antenna properties become worse.

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