Analysis of the Far field pattern of Ungrounded Embedded Dipole in different dielectric slabs

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Abstract: The characteristics of dipoles in free space are reported by many researchers. However such characteristics are not considered by many. The data on Far-field patterns of embedded dipoles is generated in the present work. The dipoles are considered to be embedded in different dielectrics, and also they are unique.

I. Introduction

Antenna is a source as well as a sensor of microwaves. An antenna is basically a transducer. It converts RF electrical current into an electromagnetic wave of same frequency[1]. Embedded antenna is a printed type of antenna consisting of a dielectric substrate with dielectric strength εr and permeability µr (usually µr=1) where sandwiched in between a ground plane and metallic dipole.

The embedded antenna is physically very simple and flat, these are two of the reasons for the great interest in this type of antenna. These antennas have several advantages compared to other bulky type of antennas [2]. The main advantages of embedded antennas are that it has low fabrication cost, its light weight, low volume, and low profile configurations that it can be made conformal. It can be easily be mounted on aeroplanes, rockets, missiles and satellites. It does not give rise to aerodynamic drag when used in aircraft. In this case the dipole antenna is embedded in a dielectric slab, the lower conductor is called ground plane [3]. These antennas are commonly used at frequency from UHF to microwave frequency.

The first step in designing embedded antenna is to choose the suitable substrate. There are various types of substrates available in market that provides considerable flexibility in the choice of a substrate for particular applications.

In most cases, consideration in substrate characteristics involved the dielectric constant and frequency. In order to provide support and protection for the dipole, the dielectric substrate must be strong and able to endure high temperature during soldering process and has high resistant towards chemicals that are used in fabrication process.

The substrate thickness and permittivity determine the electrical characteristics of the antenna. Thicker substrate will increase the band width but it will cause the surface waves to propagate and spurious coupling will happen. This problem however, can be reduced or avoided by using a suitably low permittivity substrate.

In this paper tan δ of different dielectric materials are calculated and presented. Although a line of demarcation between good conductors and lossy dielectrics is not easy to make, tan δ or δ may be used to determine how lossy a medium is [12],[14].

A medium is said to be a good (lossless or perfect) dielectric if tan δ is very small (σ << ωε) or a good conductor if tan δ is very large (σ >> ωε). From the view point of wave propagation, the characteristic behavior of a medium depends not only on its constitutive parameters σ, ε and µ but also on the frequency of operation.

A medium that is regarded as a good conductor at low frequencies may be a good dielectric at high frequencies [4]. The polarization of an antenna in a given direction from the antenna is the polarization of the wave transmitted by the antenna. The polarization in a given direction is that of the local plane wave at points on a radiation sphere centered on the antenna. Thus, polarization is that of what the wave is radiated when the antenna is transmitting. Most antennas are reciprocal, and the transmitting and receiving polarization properties are identical.

There are three most common antenna polarization are linear polarization, elliptical polarization and circular polarization. The polarization of embedded dipole in a dielectric slab is vertically linear. Radiation of the antenna is mostly resulted from the fringing fields along the open circuited edges of the dipole. This fringing fields can be resolved into two components; vertical and tangential components with the respect to the ground plane. The tangential components, which are horizontal to the ground plane, are in phase and the resulting fields give the maximum radiated field vertical to the surface as well as structure.

In the present paper horizontal and vertical dipole antenna embedded in a dielectric slab with no ground plane is considered. The radiation characteristics of dipole antenna depend on dielectric material characteristics as well as dielectric slab thickness [5-8]. The purpose of this work is to determine far field radiation.
II. Analysis

Now consider a case of embedded horizontal and vertical dipole in a dielectric slab with no ground plane, designated as dipole ‘A’ embedded in a dielectric slab as shown in figure 1. The radiation field of dipole ‘A’ is to be found. Since the field of dipole is unique everywhere, according to the reciprocity theorem of Carson [5 ] [9 ] using a second dipole ‘B’ but completely arbitrary (both in magnitude and direction) source, and the field of this source is to find the field of dipole ‘A’.

Suppose dipole ‘B’ has been chosen as the second source the r, θ and φ components of the electric field of dipole ‘A’ can be found first by orienting ‘ B’ in the r, θ and φ directions respectively and then applying reciprocity theorem each case. It is found that

\[
E_{rA} = \frac{l_A}{l_B} \hat{r}_A E_B^r
\]

\[
E_{\theta A} = \frac{l_A}{l_B} \hat{\theta}_A E_B^\theta
\]

\[
E_{\phi A} = \frac{l_A}{l_B} \hat{\phi}_A E_B^\phi
\]

Where \( E_B^r, E_B^\theta \) and \( E_B^\phi \) are the electric field vectors of r, θ and φ oriented dipole ‘B’ evaluated at dipole ‘A’ \((x,y,z)\).

\( E_{rA}, E_{\theta A}, E_{\phi A} \) is the r, θ and φ components respectively of \( E_A \), the electric field of dipole ‘A’ \((x,y,z)\) evaluated at dipole ‘B’ \((r,\theta,\phi)\).

Equations (1 -3) are a general expression for the electric field \( E_A \) radiated by dipole ‘A’ as function of position \((r,\theta,\phi)\) where dipole ‘B’ is located. According geometry show in the figure 1, the far field of \( E_A \) are only \( \theta \) and \( \phi \) component. Therefore the incident field generated by dipole ‘B’ can be approximated as a plane wave near the origin when \( \phi \) oriented corresponds to a plane wave with perpendicular polarization, and that generated by dipole ‘B’ when \( \theta \) oriented to a plane wave with horizontal polarization.

1.1 Vertical dipole embedded in a dielectric slab with no ground plane

As shown in fig 2 \( \theta \) oriented dipole ‘B’ is generated uniform plane wave at a distance ‘r’ from the origin incident on a plane dielectric slab in the YZ plane. Since the plane wave is with horizontal polarization the field in the slab is given by

\[
E_B^\theta = E_{Bx}^\theta \hat{a}_x + E_{By}^\theta \hat{a}_y + E_{Bz}^\theta \hat{a}_z
\]
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Fig. 2 - Uniform plane wave incident on a plane dielectric slab with vertical polarization.

When no ground plane is presented at z = -d, the field in the slab is given by

\[ E_{Br}^\theta = 0 \]  

\[ E_{B\phi}^\theta = \frac{\beta N H_0^I}{\omega \varepsilon} \left( P e^{jB_NZ} - Q e^{-jB_NZ} \right) e^{jBz \sin \theta} \]  

\[ E_{Br}^\phi = -\frac{\beta \sin \theta H_0^I}{\omega \varepsilon} \left( P e^{jB_NZ} + Q e^{-jB_NZ} \right) e^{jBz \sin \theta} \]  

Where \( H_0^I \) is the magnetic field intensity of dipole ‘B’ (r, \( \theta, \phi \)) evaluated at the origin.

\[ H_0^I = j\beta l_i B e^{jB_N} \]  

\[ P = \frac{1 + \rho_p}{1 - \rho_p^2 e^{-j2B_Nd}} \]  

\[ Q = -\rho_p (1 + \rho_p^2 e^{-j2B_Nd}) \]  

\( \rho_p \) = boundary reflection coefficient with horizontal polarization

\[ = \frac{\varepsilon_r \cos \theta - N}{\varepsilon_r \cos \theta + N} \]  

\[ N = \sqrt{\varepsilon_r - \sin^2 \theta} \]  

From above analysis the radiation pattern of a vertical dipole in a dielectric slab is given by

\[ E_{\phi I} = 0 \]  

\[ E_{\phi I} = -\frac{j \beta^2 \sin \theta l_i e^{jB_N}}{4 \pi \omega \varepsilon_r} \left( P e^{jB_NZ} + Q e^{-jB_NZ} \right) e^{jBz \sin \theta} \]  

1.2 The radiation pattern of a horizontal dipole embedded in a dielectric slab with no ground plane

The electric field in the dielectric slab in YZ plane due to plane wave generated by \( \phi \)-oriented dipole ‘B’ at a great distance ‘r’ from the origin as shown in fig.3 is given by

\[ E_{Bx}^\phi = E_{Rx}^\phi \hat{a}_x + E_{By}^\phi \hat{a}_y + E_{Br}^\phi \hat{a}_z \]  

where

\[ E_{Rx}^\phi = -E_0^i \left( M e^{jB_NZ} + N e^{-jB_NZ} \right) e^{jBz \sin \theta} \]  

\[ E_{By}^\phi = 0 \]  

\[ E_{Br}^\phi = 0 \]
Where \( E'_0 \) = the electric field intensity of dipole ‘B’ evaluated at the origin.

\[
E'_0 = j \omega \mu_0 i_b \frac{e^{-j\beta r}}{4\pi r}
\]

\[
M = \frac{1 + \rho_\perp}{1 - \rho_\perp^2} e^{-j2\beta d}
\]

\[
D = \frac{-\rho_\perp (1 + \rho_\perp) e^{-j2\beta d}}{1 - \rho_\perp^2} e^{-j2\beta d}
\]

\( \rho_\perp = \) boundary reflection coefficient with perpendicular polarization.

\[
\frac{\cos \theta - N}{\cos \theta + N}
\]

Fig.3-Uniform plane wave incident on a plan dielectric slab with horizontal polarization.

For a horizontal dipole with \( \hat{I}_d = \cos \phi \hat{a}_x + \sin \phi \hat{a}_y \) in a dielectric slab with ground plane, the radiation pattern is found to be

\[
E_{\phi t} = -j \omega \mu_0 i_d \hat{a}_d \cos \phi e^{-j\beta r} \left( Me^{jRNz} + Ne^{-jRNz} \right) e^{j\beta \sin \theta}
\]

\[
E_{\phi t} = j \beta^2 N i_d \hat{a}_d \sin \phi e^{-j\beta r} \left( Pe^{jRNz} - Qe^{-jRNz} \right) e^{j\beta \sin \theta}
\]

The general solution for a dipole at \((x, y, z)\) and the field point at \((r, \theta, \phi)\) can be obtained simply by transformation of coordinates due to rotation of x-y plane around the z-axis. This is done simply by replacing \((\phi_0 - \pi/2)\) by \((\phi_0 - \phi)\) or \(\phi_0\) by \((\phi_0 - \phi) + \pi/2\) and \(y\) by \((x \cos \phi + y \sin \phi)\). Again by equations (1), (2) and (3) the radiation patterns of perpendicular and horizontal dipoles are readily found.

Vertical dipole in a dielectric slab with ground plane.

\[
E_{\phi t} = 0
\]

\[
E_{\phi t} = -j \beta^2 \sin \theta i_d \hat{a}_d e^{-j\beta r} \left( Pe^{jRNz} + Qe^{-jRNz} \right) e^{j\beta (x \sin \theta \cos \phi + y \sin \theta \sin \phi)}
\]

Horizontal dipole with \( \hat{I}_d = \cos \phi \hat{a}_x + \sin \phi \hat{a}_y \) in a dielectric slab with ground plane.

\[
E_{\phi t} = \sin(\phi_0 - \phi) \frac{j \omega \mu_0 i_d \hat{a}_d e^{-j\beta r}}{4\pi} \left( Me^{jRNz} + Ne^{-jRNz} \right) e^{j\beta (x \sin \theta \cos \phi + y \sin \theta \sin \phi)}
\]

\[
E_{\phi t} = \cos(\phi_0 - \phi) \frac{j \beta^2 N i_d \hat{a}_d e^{-j\beta r}}{4\pi \omega e} \left( Pe^{jRNz} - Qe^{-jRNz} \right) e^{j\beta (x \sin \theta \cos \phi + y \sin \theta \sin \phi)}
\]
III. Formulation & Results

By taking the magnitudes of equations (27) and (28) the following expressions are obtained for the computation of far field pattern and they are listed below for a dipole in a dielectric slab. In these expressions subscript ‘A’ is suppressed since there is one dipole at \(-d < z < 0\) radiates.

2.1 Dielectric slab with no ground plane

i) Vertical dipole \((E_\phi = 0)\)

\[
|E_\phi(\theta)| = \frac{K}{2} \frac{\sin \theta (1 + \rho_p)}{\varepsilon_r} \left[ (1 - \rho_p)^2 \cos^2 \beta N(d + z) + (1 + \rho_p)^2 \sin^2 \beta N(d + z) \right]^{1/2}
\]

\[
(29)
\]

ii) Horizontal dipole

\[
|E_\phi(\theta, \phi)| = \frac{K}{2} \frac{N(1 + \rho_p) \cos(\phi_0 - \phi)}{\varepsilon_r} \left[ (1 - \rho_p)^2 \cos^2 \beta N(z + d) + (1 + \rho_p)^2 \sin^2 \beta N(z + d) \right]^{1/2}
\]

\[
(30)
\]

\[
|E_\phi(\theta, \phi)| = \frac{K}{2} \frac{\sin(\phi_0 - \phi)(1 + \rho_p)}{\varepsilon_r} \left[ (1 - \rho_p)^2 \cos^2 \beta N(z + d) + (1 + \rho_p)^2 \sin^2 \beta N(z + d) \right]^{1/2}
\]

\[
(31)
\]

Where \(K = \frac{2\omega \mu_0 |J_\perp|}{2\pi} \).

Based on above formulae the far field patterns of dipole in a dielectric slab for different dielectric slabs and different dielectric slab thickness with no ground plane is considered and graphs are plotted.

Fig:1 The vertical dipole far field pattern of different dielectric slab thickness \(d=\lambda, \lambda/8, \lambda/20\) \(\varepsilon_r=9.5\) (Alumina)

Fig:2 The vertical dipole far field pattern of different dielectric slab thickness \(d=\lambda, \lambda/8, \lambda/20\) \(\varepsilon_r=2.08\) (Teflon)
Fig: 3 The vertical dipole far field pattern of different dielectric slab thickness $d=\lambda, \lambda/8, \lambda/20, \varepsilon_r=16$ (Ferrite)

Fig: 4 The vertical dipole far field pattern of different dielectric slab thickness $d=\lambda, \lambda/8, \lambda/20, \varepsilon_r=11.9$ (Silicon)

Fig: 5 The vertical dipole far field pattern of different dielectric slab thickness $d=\lambda, \lambda/8, \lambda/20, \varepsilon_r=4.882$ (Woven fiber glass)
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Fig. 7 The vertical dipole far field pattern of different dielectric slab thickness $d=\lambda, \lambda/8, \lambda/20, \varepsilon_r=6.0$ (Duroid)

Fig. 8 The horizontal dipole far field pattern of different dielectric slab thickness $d=\lambda, \lambda/8, \lambda/20, \varepsilon_r=9.5$ (Alumina)

Fig. 9 The horizontal dipole far field pattern of different dielectric slab thickness $d=\lambda, \lambda/8, \lambda/20, \varepsilon_r=2.08$ (Teflon)
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Fig. 10 The horizontal dipole far field pattern of different dielectric slab thickness $d=\lambda$, $\lambda/8$, $\lambda/20$, $\varepsilon_r=10.8$ (Duroid)

Fig. 11 The horizontal dipole far field pattern of different dielectric slab thickness $d=\lambda$, $\lambda/8$, $\lambda/20$, $\varepsilon_r=6.0$ (Duroid)

Fig. 12 The horizontal dipole far field pattern of different dielectric slab thickness $d=\lambda$, $\lambda/8$, $\lambda/20$, $\varepsilon_r=2.2$ (Duroid)
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![Diagram 1](image1)

Fig. 13 The horizontal dipole far field pattern of different dielectric slab thickness $d=\lambda, \lambda/8, \lambda/20, \varepsilon_r=16$ (Ferrite)

![Diagram 2](image2)

Fig. 14 The horizontal dipole far field pattern of different dielectric slab thickness $d=\lambda, \lambda/8, \lambda/20, \varepsilon_r=11.9$ (Silicon)

![Diagram 3](image3)

Fig. 14 The horizontal dipole far field pattern of different dielectric slab thickness $d=\lambda, \lambda/8, \lambda/20, \varepsilon_r=4.882$ (Woven fiber glass)

IV. Conclusion

It is evident from the results that the phases $\theta$ and $\phi$ are generally not equal. As a result horizontal dipole in a dielectric slab with no ground plane is elliptically polarized and is more advantageous than that of vertical dipole in certain aspects. The far field of a vertical dipole in a dielectric slab has only a $\theta$ component, hence it is linearly polarized. Due to the discontinuity of vertical component of $E$ across the boundary the
dielectric has a stronger effect on the gain of a vertical dipole than that of horizontal dipole. For six different dielectric materials as well as different values of slab thickness ($\lambda/8, \lambda/20$) are considered in this paper and the far field patterns of vertical and horizontal dipoles in a dielectric slab with no ground plane are generated. Based on the above results i.e. from figures 1 to 14, dielectric constant of dielectric materials between 1 to 9 are suitable for embedded antennas.

References:


Author’s Information

G.Anjaneyulu did his B.Tech in Electronics and Communication Engineering from Nagarjuna University in 1994. In 2002, he obtained his M.E (Electronic Instrumentation) degree from Andhra University College of Engineering (A). He is having 15 years of teaching experience and presently he is working as an Associate Professor in Department of ECE, MVGR College of Engineering, Vizianagaram. He is also pursuing Ph.D in the Department of ECE, Andhra University College of Engineering (A), Andhra University, Visakhapatnam. He presented many papers in various national and international conferences and journals of repute. His research interests include Applied Electromagnetics, Array Antennas and EMI/EMC. Mr. Anjaneyulu is the life member of IETE,ISTE,SEMCE,ISOI.

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