Characterization of Antennas on Dielectric and Magnetic Substrates Effective Medium Approximation

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Abstract. *This paper presents a study of the effective medium approximation of a monopole antenna printed on either a dielectric or a magnetic substrate. Simple analytical formulas to determine the effective permeability of such an antenna have been proposed and validated. For this type of antenna as μ_r increases, the effective permeability will reach the value of 2 (maximum) whereas, with the dielectric substrate, the effective permittivity continues to rise when increasing ε_r. This shows that, for very high permeability values, we will always have a size reduction below 30%.*

Keywords

Antennas on dielectric and magnetic substrates, effective medium, analytical model.

1. Introduction

In the last few years, materials have played an important role in the design of antennas. The research axes in industries of communication are oriented mainly towards smaller size devices; the antenna miniaturization is in constant demand. One of the most common miniaturization techniques is the loading of the antenna volume with different materials, and recently using, magnetic materials [1-5]. Some antenna configurations with ground plane and using magnetic materials such as patch antennas [6] and PIFA antennas [7] have already been studied. These antenna configurations have showed an important size reduction with high permeability materials. Many studies dealing with the impact of dielectric substrate on these antenna configurations have been proposed in the literature [8] whereas, equivalent studies, for magnetic substrates, are rarely reported.

In this paper, we focus our study on the effects of using magnetic materials in the design of compact antenna without ground plane such as dipole antenna (or equivalent monopole antenna using image theory). We propose analytical formulas, based on quasi static approximation usually used for dielectric substrates, to give the effective permeability for such structures. The antenna performances will be computed with CST Microwave Studio Software and compared to analytical formulas.

2. Geometry of Monopole Antenna

We consider a printed monopole antenna constituted of a copper strip line of length L and width W (Fig. 1). The coaxial line is used in the feeding of the antenna. The thickness and width of the substrate are defined by t and b respectively.

To simplify this structure, we assume that the monopole antenna is filled with a hypothetical dispersion-free, lossless, and isotropic material characterized by either the relative permittivity ε_r or the relative permeability μ_r. Moreover, to eliminate unwanted effects of the finite dimensions of the ground plane and to highlight the effect of the material, we assume that the monopole antenna is mounted over an infinite ground plane throughout our study.

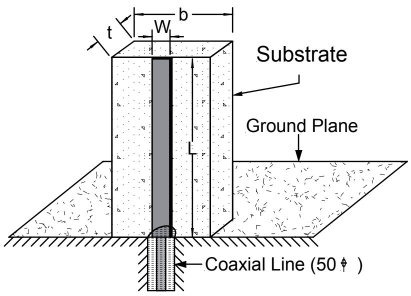

Fig. 1. Geometry of the printed monopole antenna.

3. Analysis

In order to determine the effective medium of a monopole antenna printed on a dielectric substrate, we use the method developed by Popovic [8]. This author assumes that, if the substrate width is of infinite extent, the printed monopole antenna is approximated by a two dimensional two conductor system, giving the coplanar strip lines shown in Fig. 2. The two lines have the same width w, are separated by a large distance s>>9w/4 and are printed on a substrate of thickness t.

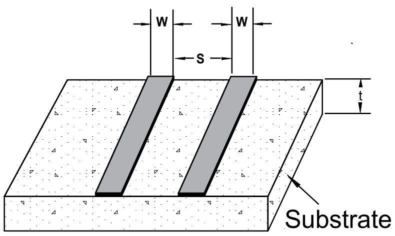

Fig. 2. Configuration of symmetric line.

3.1 Antenna Printed on a Dielectric Substrate

For a dielectric substrate, we can easily calculate the antenna's effective permittivity using the following well-known formulas [9]:

$$\varepsilon_{eff} = 1 + \frac{(\varepsilon_r - 1)}{2} \frac{K(k_1^{'})K(k)}{K(k_1)K(k')}, \tag{1}$$

$$\varepsilon_{eff}(t \to \infty) = \frac{\varepsilon_r + 1}{2} \tag{2}$$

where $K(m)$ is the elliptic function of the 1st order as:

$$K(m) = \int_0^1 \left[\left(1 - t^2\right)\left(1 - mt^2\right) \right]^{-0.5} dt \; . \tag{3}$$

The parameter k is related to the geometry of the line (4) whereas, the parameter k_1 is related to both the substrate and the line geometry (5). The parameters k' and k_1 are directly calculated from (6) and (7).

$$k = \frac{s}{s + 2w}, \tag{4}$$

$$k_1 = \frac{\tanh(\frac{\pi s}{4t})}{\tanh(\frac{\pi\left(s + 2w\right)}{4t})}, \tag{5}$$

$$k' = \sqrt{1 - k^2}, \tag{6}$$

$$k_1^{'} = \sqrt{1 - k_1^2} \; . \tag{7}$$

In (1), we can show that the more ε_r increases, the more ε_{eff} increases as well. Moreover, when the dielectric substrate thickness is assumed infinite, the effective media of monopole antenna is proportional to ε_r (2).

If the antenna is inserted between two dielectric substrates, and using the same approach, we can easily extend formula (1) to calculate the effective medium as follows:

$$\varepsilon_{eff} = 1 + (\varepsilon_r - 1) \frac{K(k_1^{'})K(k)}{K(k_1)K(k')}, \tag{8}$$

$$\varepsilon_{eff}(t \to \infty) = \varepsilon_r \; . \tag{9}$$

3.2 Antenna Printed on a Magnetic Substrate

For a magnetic substrate, we propose to use the same method but applying the duality principle as presented by Pucel & Masse in [5]. This relationship is given by:

$$\mu = \frac{1}{\varepsilon} \; . \tag{10}$$

Combining (1) and (10), we get the following new expressions:

$$\mu_{eff} = \frac{2\mu_r}{2\mu_r + \left(1 - \mu_r\right)\frac{K(k_1^{'})K(k)}{K(k_1)K(k')}}, \tag{11}$$

$$\mu_{eff}(t \to \infty) = \frac{2\mu_r}{\mu_r + 1} \; . \tag{12}$$

From (11), we can see again that the more μ_r increases, the more μ_{eff} increases as well. However, when the magnetic substrate thickness is assumed infinite, in (12), the effective media of the symmetric line is not proportional to μ_r. In contrast with (2), the more μ_r increases, the more μ_{eff} tend to 2. Consequently, using the magnetic substrate, we always get a miniaturization lower than 30%. Following the same approach, it is possible to extend these formulas for monopole antennas localized in homogeneous media to obtain:

$$\mu_{eff} = \frac{\mu_r}{\mu_r + \left(1 - \mu_r\right)\frac{K(k_1^{'})K(k)}{K(k_1)K(k')}}, \tag{13}$$

$$\mu_{eff}(t \to \infty) = \mu_r \; . \tag{14}$$

From (8) and (13), we can see that ε_{eff} and μ_{eff} increase when increasing ε_r and μ_r. Moreover, when the monopole antenna is located in an infinite homogeneous dielectric media (12) and (14), the antenna's ε_{eff} and μ_{eff} are equal to ε_r and μ_r respectively.

4. Analytical and Numerical Results

In order to validate the analytical formulas previously presented, we compare the results obtained by these formulas to those computed by the MWS code. So, we determine the effective medium of a monopole antenna printed either on a dielectric substrate or on a magnetic substrate.

We first consider the monopole antenna with a resonance frequency in the air close to 0.9 GHz (whose dimensions are W=7.4 mm, L=72 mm, t and b are infinite) printed either on dielectric substrate with different values of ε_r or on magnetic substrate with different values of μ_r going from 2 to 10 (see Figs 3 to 6). In these figures, we show the simulated real and imaginary parts of the antenna input impedance versus frequency. As expected, we get a frequency shift due to the increasing ε or μ. We can deduce the effective permittivity or permeability from the resonance frequency shifts by using this well known relationship:

$$\frac{\lambda_g}{\lambda_0} = \frac{1}{\sqrt{\varepsilon_{eff}\mu_{eff}}} \quad . \tag{15}$$

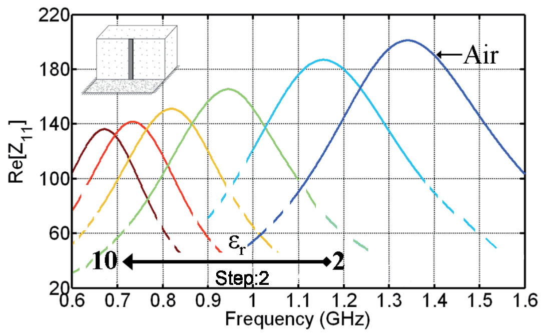

Fig. 3. Real part of the input impedance with dielectric substrate.

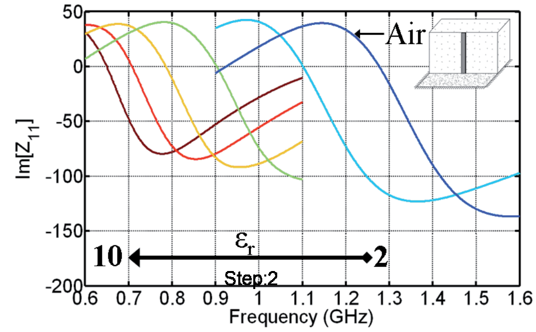

Fig. 4. Imaginary part of the input impedance with dielectric substrate.

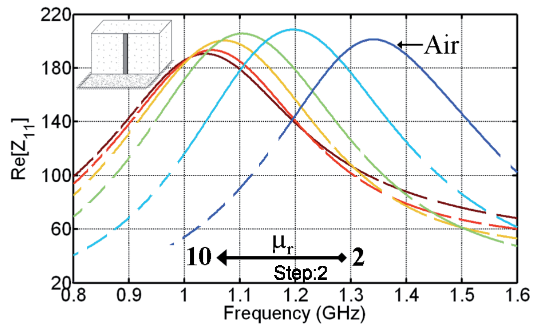

Fig. 5. Real part of the input impedance with magnetic substrate.

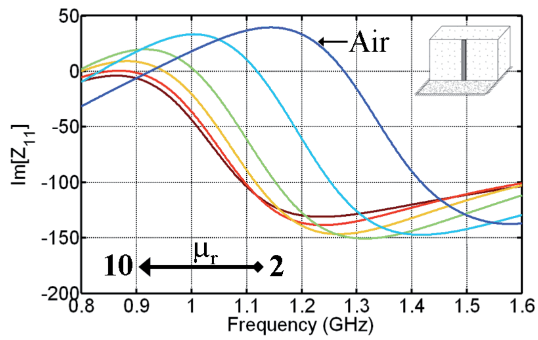

Fig. 6. Imaginary part of the input impedance with magnetic substrate.

Using this method, we can plot the effective permittivity versus the relative permittivity (and similarly, the effective permeability versus the relative permeability) (see Fig. 7). We can note that we obtain a good agreement between analytical and simulation results for ε_r<6 and μ_{eff}<6 with a slight difference of $\Delta\varepsilon_{eff}$=1.5 in the case of a dielectric substrate and a small difference $\Delta\mu_{eff}$=0.15 in the case of a magnetic substrate.

When μ_r increases, the effective permeability will reach 2 (maximum) as predicted whereas, for the dielectric substrate, the effective permittivity continues to rise when increasing ε_r. This shows that, for very high permeability values, we will always have a size reduction below 30%.

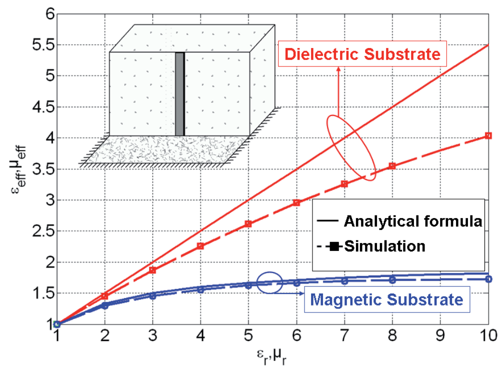

Fig. 7. ε_{eff} and μ_{eff} versus ε_r and μ_r respectively for a monopole antenna printed on a dielectric and a magnetic substrate.

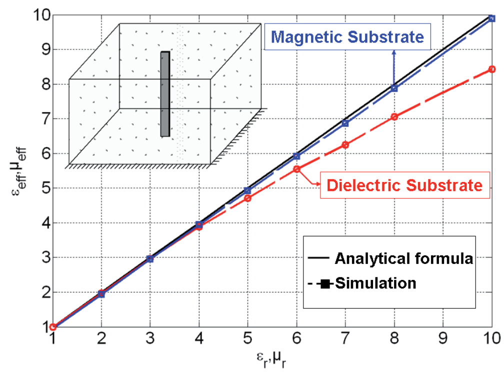

Fig. 8. ε_{eff} and μ_{eff} versus ε_r and μ_r respectively for a monopole antenna inside both homogeneous dielectric and magnetic substrate.

The same results can be noticed if the antenna is located within infinite homogeneous substrate as shown in Fig. 8. We can verify that the ε_{eff} and μ_{eff} are equal to ε_r and μ_r respectively with a slight difference in the dielectric case.

Globally, the proposed analytical models and simulations give almost the same results when we use an infinite substrate. If we consider now the same monopole antenna with finite substrate dimensions t=1.6 mm and b=22.2 mm, the effective characteristics of the medium performed with CST Microwave Studio Software are slightly greater than those obtained by analytical formulas. Next, we have plotted μ_{eff}=f(μ_r), for a printed monopole Fig. 9 and for a monopole within a homogeneous and symmetrical finite substrate Fig. 10.

Next, for a relative permeability μ_r=4 and by varying the substrate thickness t from 0.2 mm to 10 mm, we have plotted μ_{eff}=f(t) obtained by the analytical formulas in solid line and compare it to the simulation plotted in dashed line. This has been done in the two previous cases: printed monopole Fig.11, and monopole in a homogeneous medium Fig. 12. We can note that we obtain a good agreement between analytical and simulation results with a slight difference of about $\Delta\mu_{eff}$=0.35 maximum. This is probably due to the quasi static approximations and the fact that the substrate is not infinite.

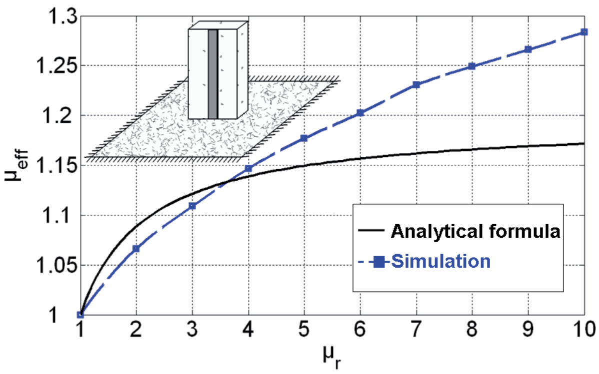

Fig. 9. Effective permeability vs relative permeability for an antenna printed on a magnetic substrate.

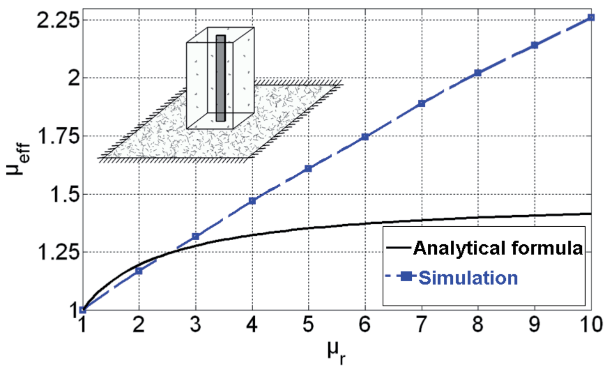

Fig. 10. Effective permeability vs relative permeability for an antenna within a homogeneous magnetic substrate.

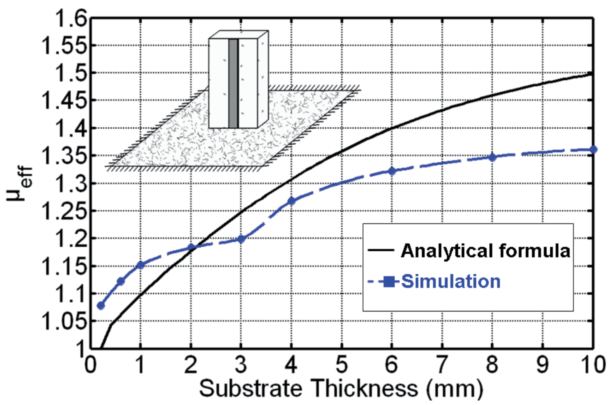

Fig. 11. Effective permeability vs substrate thickness for an antenna printed on a magnetic substrate.

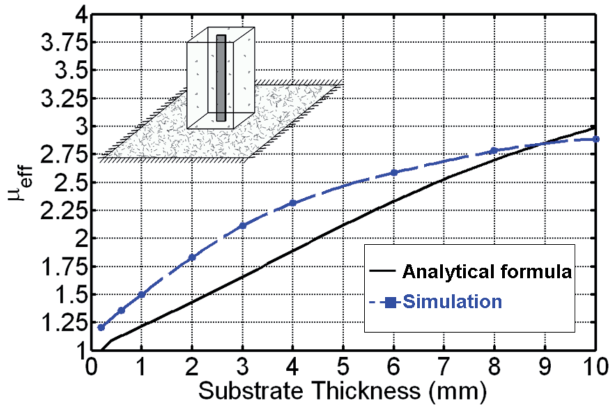

Fig. 12. Effective permeability vs substrate thickness for an antenna within a homogeneous magnetic substrate.

5. Experimental Results

To validate these observations, three monopole antennas have been realized and measured using different types of commercial magnetodielectric substrates [10] : MF110 (ε_r≈5 & μ_r≈1.1), MF114 (ε_r≈17 & μ_r≈3.5), MF117 (ε_r≈32 & μ_r≈4.5) (Fig. 13 and Fig. 14). These magneto-dielectric monopoles have the same dimensions.

The metal strip is made of silver, selected for its high conductivity (σ_{Ag}=6.3×10^7 S/m). The strip is deposited by an evaporation technique through a shadow mask. A sacrificial stencil, made of polyimide sticky tapes (65µm thick), is directly glued onto the magneto-dielectric substrate (beam dimensions: L = 72 mm length, b = 22 mm width and t = 3.125 mm thickness, see Fig. 13). The sample (substrate + stencil) is then clamped in the vacuum chamber. After pumping down to 2×10^{-6}mbar, silver is thermally evaporated to a 2 µm layer thickness. Lifting the sticky tapes reveals the silver strip, centered onto the beam. Dimensions of the strip are W = 7.3 mm width and L = 72 mm length (Fig. 13).

This monopole antenna is excited via a 50Ω SMA connector and is mounted over a large ground plane (700 mm×700 mm) (Fig. 14).

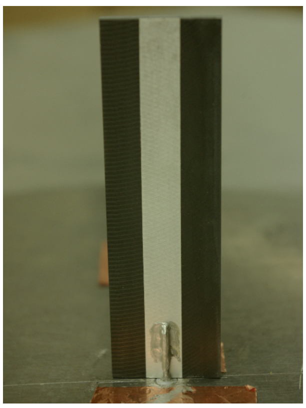

Fig. 13. Picture of a printed monopole antenna on magneto-dielectric material.

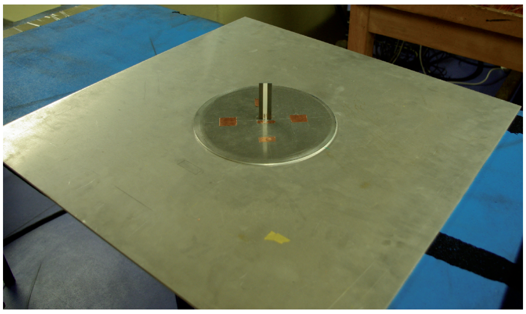

Fig. 14. Picture of a printed monopole antenna mounted over a large ground plane.

Fig. 15 shows the measured and simulated return loss of the magnetodielectric monopole antennas compared to a foam monopole antenna with a resonance frequency close to 0.9 GHz and having also the same dimensions. From these results, it can be seen that when the refraction index of the substrate $n = \sqrt{\varepsilon_{eff}}\sqrt{\mu_{eff}}$ increases the resonant frequency decreases. For example, using MF117-magnetodielectric substrate has reduced the resonance frequency of about 45% (from 900 MHz to 480 MHz).

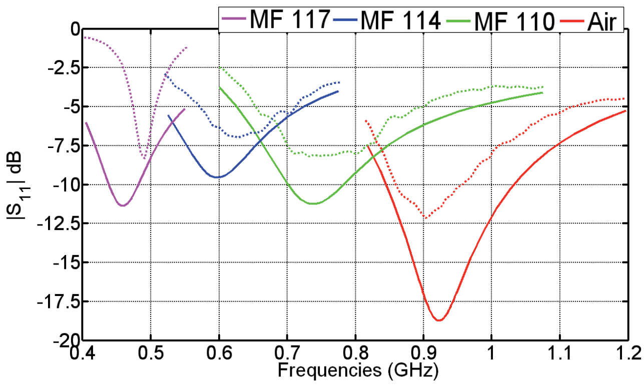

Fig. 15. Input reflection coefficient S_{11} of monopole antenna with the magnetodielectric materials : (dot) measured and (solid) simulation.

The difference between the measured and simulated results may be due to the incertitude of the value of ε_r and μ_r for the different substrates given by the manufacturer.

Nevertheless, from Fig. 15, we are not able to distinguish the effect of the permittivity ε_r from the permeability μ_r. For this, two simulations have been provided one using only dielectric material (with $\varepsilon_{r,MF110}$, $\varepsilon_{r,MF114}$ and $\varepsilon_{r,MF117}$ and μ_r=1) and the other using only magnetic material (with $\mu_{r,MF110}$, $\mu_{r,MF114}$ and $\mu_{r,MF117}$ and ε_r=1). The numerical results of these simulations are gathered, and compared with the analytical formula (13) to give the effective parameters of the substrates as shown in Fig. 16.

The results given by the back-simulations distinctly separate the effect of the permittivity ε_r from the permeability μ_r. Moreover, the analytical formula is close to numerical results. For example, the use of MF117-magnetodielectric substrate gives an effective permittivity ε_{eff}≈2.7 and an effective permeability μ_{eff}≈1.45 (i.e. index n_{eff}≈3.9). These values provide a resonance frequency shift of about 50%, that is confirm the value previously given.

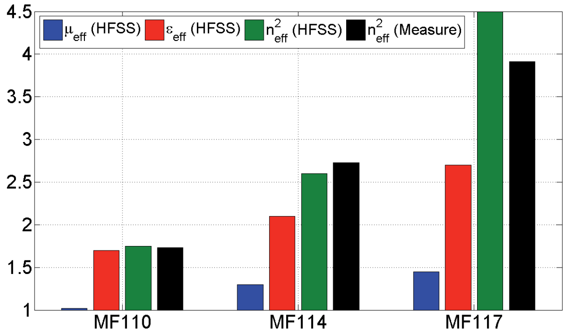

Fig. 16. Extraction of the effective permittivity ε_{eff}, the effective permeability μ_{eff} and the effective index n^2_{eff} versus different magnetodielectric materials.

6. Conclusions

In this paper, we have presented new formulas to estimate the effective medium of a monopole antenna printed on a magnetic substrate. A good agreement between the analytical and the numerical results has been obtained with both a finite and infinite substrate dimensions. These formulas give a good approximation of the value of μ_{eff} and ε_{eff} and can be used for magnetodielectric substrates. Moreover, we have shown that, for this antenna configuration (ungrounded antenna) printed on a magnetic substrate, the size reduction cannot exceed 30%.

Acknowledgment

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