Characterization of Antennas on Dielectric and Magnetic Substrates Effective Medium Approximation

Damien RIALET¹, Ala SHARAIHA¹, Anne-Claude TAROT¹, Xavier CASTEL¹, Christophe DELAVEAUD²

¹ IETR (Institut d’Electronique et de Télécommunication de Rennes), Rennes, France
² CEA-LETI, MINATEC, Grenoble, France

{damien.rialet, ala.sharaiha, anne-claude.tarot, xavier.castel}@univ-rennes1.fr, christophe.delaveaud@cea.fr

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 \( \mu_r \) increases, the effective permeability will reach the value of 2 (maximum) whereas, with the dielectric substrate, the effective permittivity continues to rise when increasing \( \varepsilon_r \). 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 \( \varepsilon_r \) or the relative permeability \( \mu_r \). 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.

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 \( s \gg 9w/4 \) and are printed on a substrate of thickness \( t \).
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]:

\[
\varepsilon_{\text{eff}} = 1 + \frac{(\varepsilon_r - 1) K(k') K(k)}{2 K(k_1) K(k')} ,
\]

(1)

\[
\varepsilon_{\text{eff}}(t \to \infty) = \frac{\varepsilon_r + 1}{2} ,
\]

(2)

where \( K(m) \) is the elliptic function of the 1\(^{st}\) order as:

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

(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).

\[
k = \frac{s}{s + 2w} ,
\]

(4)

\[
k_1 = \frac{\tanh \left( \frac{\pi s}{4t} \right)}{\tanh \left( \frac{\pi (s + 2w)}{4t} \right)} ,
\]

(5)

\[
k' = \sqrt{1 - k^2} ,
\]

(6)

\[
k_1' = \sqrt{1 - k_1^2} .
\]

(7)

In (1), we can show that the more \( \varepsilon_r \) increases, the more \( \varepsilon_{\text{eff}} \) increases as well. Moreover, when the dielectric substrate thickness is assumed infinite, the effective media of monopole antenna is proportional to \( \varepsilon_r \) (2). In contrast with (2), the more \( \mu_r \) increases, the more \( \mu_{\text{eff}} \) increase. Consequently, using the magnetic substrate, we always get a miniaturization lower than 30%

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:

\[
\mu = \frac{1}{\varepsilon} .
\]

(10)

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

\[
\mu_{\text{eff}} = \frac{2 \mu_r}{2 \mu_r + (1 - \mu_r) \frac{K(k') K(k)}{K(k_1) K(k')} ,}
\]

(11)

\[
\mu_{\text{eff}}(t \to \infty) = \frac{2 \mu_r}{\mu_r + 1} .
\]

(12)

From (11), we can see again that the more \( \mu_r \) increases, the more \( \mu_{\text{eff}} \) 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 \( \mu_r \). In contrast with (2), the more \( \mu_r \) increases, the more \( \mu_{\text{eff}} \) 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:

\[
\mu_{\text{eff}} = \frac{\mu_r}{\mu_r + (1 - \mu_r) \frac{K(k') K(k)}{K(k_1) K(k')} ,}
\]

(13)

\[
\mu_{\text{eff}}(t \to \infty) = \frac{\mu_r}{\mu_r + 1} .
\]

(14)

From (8) and (13), we can see that \( \varepsilon_{\text{eff}} \) and \( \mu_{\text{eff}} \) increase when increasing \( \varepsilon_r \) or \( \mu_r \). Moreover, when the monopole antenna is located in an infinite homogeneous dielectric media (12) and (14), the antenna’s \( \varepsilon_{\text{eff}} \) and \( \mu_{\text{eff}} \) are equal to \( \varepsilon_r \) and \( \mu_r \) 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 \( \varepsilon_r \) or on magnetic substrate with different values of \( \mu_r \) 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 \( \varepsilon \) or \( \mu \). We can deduce...
the effective permittivity or permeability from the resonance frequency shifts by using this well known relationship:

\[
\frac{\lambda_{\text{eff}}}{\lambda_0} = \sqrt{\varepsilon_{\text{eff}} \mu_{\text{eff}}}.
\]  

(15)

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 \(\varepsilon_r < 6\) and \(\mu_{\text{eff}} < 6\) with a slight difference of \(\Delta\varepsilon_{\text{eff}} = 1.5\) in the case of a dielectric substrate and a small difference \(\Delta\mu_{\text{eff}} = 0.15\) in the case of a magnetic substrate.

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

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 \(\varepsilon_{\text{eff}}\) and \(\mu_{\text{eff}}\) are equal to \(\varepsilon_r\) and \(\mu_r\) 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 \(\mu_{\text{eff}} = f(\mu_r)\), for a printed monopole Fig. 9 and for...
a monopole within a homogeneous and symmetrical finite substrate Fig. 10.

Next, for a relative permeability \( \mu_r=4 \) and by varying the substrate thickness \( t \) from 0.2 mm to 10 mm, we have plotted \( \mu_{\text{eff}}=f(t) \) 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 \( \Delta \mu_{\text{eff}}=0.35 \) maximum. This is probably due to the quasi static approximations and the fact that the substrate is not infinite.

5. Experimental Results

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

The metal strip is made of silver, selected for its high conductivity (\( \sigma_{\text{Ag}}=6.3\times10^7 \) 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 \( 2\times10^{-6} \) 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. 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 $n = \sqrt{\varepsilon_r \mu_r}$ 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).

The difference between the measured and simulated results may be due to the incertitude of the value of $\varepsilon_r$ and $\mu_r$ for the different substrates given by the manufacturer.

Nevertheless, from Fig. 15, we are not able to distinguish the effect of the permittivity $\varepsilon_r$ from the permeability $\mu_r$. For this, two simulations have been provided one using only dielectric material (with $\varepsilon_r, \text{MF110}$, $\varepsilon_r, \text{MF114}$, and $\varepsilon_r, \text{MF117}$ and $\mu_r=1$) and the other using only magnetic material (with $\mu_r, \text{MF110}$, $\mu_r, \text{MF114}$, and $\mu_r, \text{MF117}$ and $\varepsilon_r=1$). 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 $\varepsilon_r$ from the permeability $\mu_r$. Moreover, the analytical formula is close to numerical results. For example, the use of MF117-magnetodielectric substrate gives an effective permittivity $\varepsilon_{\text{eff}}=2.7$ and an effective permeability $\mu_{\text{eff}}=1.45$ (i.e. index $n_{\text{eff}}=3.9$). These values provide a resonance frequency shift of about 50%, that is confirm the value previously given.

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 $\mu_{\text{eff}}$ and $\varepsilon_{\text{eff}}$ 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%.

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References


**About Authors ...**

**Damien RIALET** was born in Rennes, France, in 1984. He received a degree in Telecommunication and Engineering from the Institut de Formation Supérieur en Informatique et Télécommunications (IFSIC), and a Master’s Degree in telecommunications and electronics from the University of Rennes, France. Since 2007, he has been working toward the Ph.D degree in signal processing and telecommunications at the Institute of Electronics and Telecommunications of Rennes (IETR), University of Rennes in Rennes, France in collaboration with the department of the Commissariat à l’Énergie Atomique (CEA), in Grenoble, France. His main fields of interest include the analysis of magnetic materials for antenna applications.

**Ala SHARAIHA** received his degrees of Ph. D. and HDR (Habilitation à Diriger la Recherche) in telecommunication in 1990 and 2001 respectively. Currently a Professor at the University of Rennes 1 and a researcher in the Group of Antennas & High frequency at the institute of Telecommunications of Rennes, where he is the responsible of a research theme concerning the new concepts and architecture of antennas design. Main research activities include broadband and UWB antennas, miniaturization, printed spiral and helical antennas, antennas for mobile communications,... Conducted and involved in more than 15 development projects for private companies and participates in the European Network of Excellence ACE (Antenna Center of Excellence) in the small antenna WP. A reviewer for IEEE APS, AWPL, IET Letters….Author and co-author of 30 international papers, 90 conference presentations and holds 8 European patents. He was the conference Chairman of the 11th International Canadian Conference ANTEM (Antenna Technology and Applied ElectroMagnetics), held at Saint Malo in France, 2005.

**Anne-Claude TAROT** was born in 1969. She received the Ph.D. degree from the University of Rennes, France in 1995. Since 1998, she has been an Associate Professor at the Institute of Electronics and Telecommunications of Rennes (IETR), University of Rennes. Her research interests include printed antennas, EBG materials and metamaterials. Dr. Tarot received the Best Paper Award at the JINA Conference in November 2004. She organized the 11th edition of ANTEM Symposium in June 2005 (Saint-Malo, France).

**Xavier CASTEL** received his degree of Ph. D. in Material Science in 1997. He is an Associate Professor at the Technological Institute of Saint-Brieuc (University of Rennes 1) since 1999. His main research activities include thin film elaboration of smart materials (transparent conducting oxides; superconductors; semiconductors) for microwave applications, their physical-chemical characterization (electrical, optical, structural, morphological properties…) and the manufacturing of microwave devices (by photolithographic technique, wet etching process and lift-off process). He is author and co-author of 18 international papers, 56 conference presentations and holds 2 European patents.

**Christophe DELAVEAUD** received the Doctoral degree in high-frequency electronics from the University of Limoges, Limoges, France, in 1996. In 1997, he was Research Engineer with the Research Center on Electromagnetism Applied to Electronically Scanned Antennas (CREAPE), Optical and Microwave Communications Research Institute (IRCOM), Limoges, France. One year later, he joined the European Research and Development Center, Radiall/Larsen Antenna Technology, Voreppe, France, where he was in charge of the development of new antenna concepts with emphasis on miniature antennas and wideband and multiband antennas for customer applications in wireless communications. From 1991 to 1997, he was a Teaching Assistant with the University Institute of Technology of Limoges, Limoges, France. In 2000, he was a Visiting Lecturer with the University of Savoie, Chambéry, France. In 2002, he joined the Atomic Energy Commission (CEA), Laboratory of Electronics and Information Technology (LETI), Grenoble, France. His current research interests include the analysis and developments of radiating structures with emphasis on miniature integrated antennas, combined antenna, UWB antennas, and smart antennas for future wireless communications systems.