A Theoretical and Simulation Study of Dielectrically Loaded Antennas and their Contribution Towards Low-SAR
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Abstract

Current requirements in handset antenna design include high efficiency, small size, low-SAR and a broad bandwidth. In the theoretical part of this study, a spherical analytical model is used to examine these parameters in terms of different mix ratios of permittivity and permeability. A TLM simulation software package is used to model dielectric resonators and predict their efficiency. Results suggest that an optimum permittivity and permeability mix gives rise to the definitive low-SAR antenna whilst maintaining a high efficiency.

1 Introduction

As wireless communications products have become prolific and mobile telephony has become integral to life, the handset antenna should be efficient, small, have a low Specific Absorption Rate (SAR) and a wide bandwidth.

Coating antennas with dielectric affords reduction in size and lowers susceptibility to detuning. The size reduction depends both on the permittivity and the shape of the dielectric [3]. On the other hand, miniaturization reduces the antenna bandwidth and efficiency but this can be mitigated by adding permeability.

SAR is a subject of increasing public awareness and a compliance in mobile telecommunication devices has been a requirement since 1997. The dominant mechanism of EM absorption in human tissue in close proximity to a transmitter is inductive coupling of the near field energy. Magnetic fields have a low impedance and couple strongly to the human body whereas electric fields are largely reflected. Thus, the absorption in tissue can be approximated by the strength of the magnetic fields [3].

Using theoretical analysis and simulations, this paper reports the near field structure of electrically-small material-coated antennas and how a given permittivity and permeability product can reduce SAR while maintaining a high efficiency. The fundamental properties of these antennas are investigated by the analysis of a spherical model. The theoretical findings are then verified by means of a TLM simulation package.

2 Theoretical Study

2.1 Spherical Model

According to the spherical model analysis [1], a ceramic sphere of radius $\alpha$ is excited by either a magnetic (TE) or electric (TM) multipole source at the origin. The permittivity and permeability of the material and the permittivity of the environment surrounding the sphere are defined, along with the corresponding loss tangents, allowing the antenna to operate in a lossy dielectric environment. The fields and sources have $e^{-j\omega t}$ dependence and are expressed in terms of spherical eigenfunctions [2]. Continuity of the tangential fields is invoked at the boundary of the sphere for each $(nm)^{th}$ eigenfunction and an expression is derived for parameter $C$, which governs the amplitude of the fields outside the sphere:

$$C = A_{nm} \times \left[ \rho_1 h_1^{\mu_1}(\rho_2) h_1^{\mu_2}(\rho_1) - \rho_1 h_1^{\mu_2}(\rho_2) h_1^{\mu_1}(\rho_1) \right] K \left[ \rho_2 h_1^{\mu_1}(\rho_2) h_1^{\mu_2}(\rho_1) - \rho_1 h_1^{\mu_2}(\rho_2) h_1^{\mu_1}(\rho_1) \right]$$

where $\rho_1 = k_1 \alpha$, $\rho_2 = k_2 \alpha$, $k_1 = k_0 \sqrt{\varepsilon_{r1} \mu_{r1}}$, $k_2 = k_0 \sqrt{\varepsilon_{r2}}$ and $k_0 = \frac{2\pi}{\lambda_0}$.

The variable $K$ is set to $\mu_{r1}$ for a $TE_{nmv}$ source and to $\varepsilon_{r1}$ for a $TM_{nmv}$ source. The complex roots of the denominator generate the complex eigenvalues of the $TE_{101}$ or $TM_{101}$ modes, depending on the type of source. From the modes, the antenna Q-factor, radiation efficiency and resonant frequency are determined.

2.2 Boundary Conditions

The spherical antenna with $\varepsilon_r \gg 1$ and $\mu_r = 1$ exhibits magnetic wall properties at its surface [3,4]. The tangential magnetic field component will be small and hence the radiation fields will be predominantly magnetic. If the excitation source is also magnetic, more radiation escapes and this is referred to as Compatible Boundary Conditions (CBC). For electric source excitation, the resonator action is strengthened and dominates over the radiation, thus the device is less desirable as an antenna. This is described as Incompatible Boundary Conditions (IBC).

Conversely, with idealised material $\mu_r \gg 1$ and $\varepsilon_r = 1$, the spherical surface exhibits electric wall properties and the radiation fields are predominantly...
electric. In this case, electric and magnetic sources are CBC and IBC respectively.

2.3 Results

To ensure that the antenna resonant frequencies are in the vicinity of mobile bands, \( \mu'_r \varepsilon'_r = 36 \) and \( a = 20mm \). \( K \) is varied with \( 1 \leq K \leq 36 \) and the complex eigenvalues are computed for different losses.

2.3.1 Lossless sphere in air

Figure 1 shows the frequency and Q-factor results for a magnetic dipole in a lossless sphere, when its permeability is varied.

When \( \mu'_r = 1 \) and \( \varepsilon'_r = 36 \) (CBC), the value of frequency is minimum and this is equivalent to a minimum electrical size for a specific frequency. The opposite is true for IBC.

The Q-factor is lowest at \( \mu'_r = \varepsilon'_r = 6 \) and leads to the conclusion that this combination of permittivity and permeability is best for both a small size and a broad bandwidth.

2.3.2 Introducing Losses

Adding material losses to the sphere causes a reduction in the Q-factor (Fig. 2), in \( \eta \) (Fig. 4) and a slight shift in the frequency (due to the ratio of \( \varepsilon'_r \) and \( \mu'_r \)) (Fig. 3). Again, the results show that a mix of \( \mu'_r = \varepsilon'_r = 6 \) produces small size, broad bandwidth and high efficiency (Fig 4).

Having a lossless sphere in a lossy environment slightly lowers the resonant frequency for CBC but has an insignificant effect tending to IBC (Fig 3).

Again, the lowest Q-factor is obtained for the product with equal permittivity and permeability (Fig 2).

Adding losses both to the sphere and the environment results in the Q and \( \eta \) being at their minima. Optimum conditions are met when \( \mu'_r = \varepsilon'_r = 6 \).
Although undesirable for efficiency performance, material losses offer a reduced susceptibility to detuning caused by the user presence. The variation of parameter C with permeability and losses is shown in Fig 5.

Fig 5 shows, in the lossless case and for CBC, the amplitude of the near fields is maximum. For IBC, the near fields are about 12% those of the CBC (lowest SAR), but from Fig 4 the efficiency has lowered, from Fig 3 the size of the sphere has increased and from Fig 2 the Q-factor has increased. When \( \varepsilon_r = \mu_r = 6 \), the near fields are about 25% of the CBC value, the efficiency is maximum, the bandwidth is maximum and the size remains small. It is deduced that having an equal amount of permittivity and permeability is the optimum combination to satisfy these key design issues.

3 TLM Simulations

3.1 TLM Modelling

Flomerics MicroStripes TLM based simulation software was used to model an electric dipole inside different dielectric structures. The permittivity and permeability of the dielectric were varied and the effects on efficiency and SAR were measured.

3.1.1 Dielectric block

Initially, a square block dielectric resonator was modelled. When the block was lossless, the simulation results agreed with the theoretical model. The efficiency had a maximum value of 99.926% for a mix of \( \varepsilon_r = \mu_r = 6 \). The fields dropped to 4% of their original value when varied from CBC to IBC, in agreement with the theoretical study and for the optimum mix they had dropped by 87%.

Due to software restrictions, material losses were only added to the permittivity of the block. In spite of this, adding losses had a noticeable inverse effect on the efficiency. Two values of losses were incorporated in the block, \( \tan \delta = 0.01 \) and \( \tan \delta = 0.03 \), and in both cases the product \( \varepsilon_r = 9 \) and \( \mu_r = 4 \) produced the highest efficiency.

Fig 6 shows the effect that losses have on the efficiency, for different material mixes.

The introduction of losses slightly decreased the amplitude of the fields at CBC but otherwise they were similar to the lossless case (Fig 7). It is speculated that had permeability and environmental losses also been modelled, the efficiency and field amplitude drop would have been more noticeable and similar to the theoretical predictions.

3.1.2 Dielectric sphere

A 20mm dielectric sphere was also modelled. In the lossless case, the spherical resonator had a maximum efficiency for a product with \( \varepsilon_r = 3 \) and \( \mu_r = 12 \). The fields had a value of 261 V/m in CBC and declined by 75% with IBC.

A \( \tan \delta = 0.03 \) was added to the permittivity and the results are shown compared to the lossless case in Fig 8.
It is clear that the addition of losses results in an efficiency drop, which is now at a maximum when $\varepsilon_\varepsilon = 9$. The amplitude of the fields decreases similarly to the dielectric block (Fig 9).

Fig 8 Sphere resonator efficiency

4. Antenna Realisation

The rarity of high permeability ferrite at high frequencies has been an obstacle to the manufacture of the antennas. As a first step, simulations and measurements of magnetic and electric antennas will be made to determine if magnetic antennas have a higher SAR, as suspected. Following this, materials will be researched and incorporated in the antenna, to achieve a design with almost equal amounts of permittivity and permeability.

5. Conclusion

The concept of compatible boundary conditions has been investigated both theoretically and with simulations and it has been established that for arbitrarily shaped electrically-small material-coated antennas, a mix of lower permittivity and higher permeability together with an electric source, can produce maximum efficiency and bandwidth and have minimum SAR. It is anticipated that the practical measurements will support the theory and simulation results, once the manufacturing difficulties are overcome.

3. Literature