A Discussion on Electrically Small Antennas Loaded with High Permittivity and Permeability Materials

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ABSTRACT: Electrically small antennas have remained a significant topic of interest for a number of applications, particularly low frequency systems and wireless networks requiring small devices. As is well-known, there are a number of techniques whereby an electrically small antenna can be efficiently matched to a 50Ω system impedance. Ultimately, the primary design challenge is achieving as wide an efficient operating bandwidth as possible, within the constraints of manufacturing tolerance issues and de-tuning effects resulting from the surrounding operating environment. One common size reduction technique is the utilization of dielectric materials to capacitively load the antenna structure. In this paper, which is intended to be mostly a tutorial discussion, we focus on loss and bandwidth issues associated with material loading an antenna using high permittivity and/or high permeability materials. We particularly focus on how these materials impact overall efficiency and discuss the relationship between conductor and material losses within an impedance matched electrically small antenna.

INTRODUCTION

The design of an electrically small antenna primarily focuses on three performance characteristics; these are the impedance match, the radiation efficiency and the operating bandwidth (or quality factor; *Q*). Other performance characteristics such as radiation pattern and polarization are often secondary concerns. It is well-known that any small antenna can, in theory, be matched at any single frequency. The practical challenge is achieving an efficient match over a desired operating bandwidth. In some applications, particularly where the antenna is very small, it is acceptable and perhaps necessary to add loss to the antenna structure so as to increase the usable operating bandwidth. The addition of loss to enhance bandwidth is often necessary where manufacturing tolerances with high *Q* antennas make it difficult to repeatedly achieve the same desired operating frequency. Bandwidth enhancement resulting from increased loss may also be beneficial in applications where the antenna has a tendency to de-tune due to coupling effects associated with the surrounding environment.

Size reduction techniques used in the design of small antennas primarily focus on first achieving resonance and then subsequently matching or transforming the antenna's resistance to the system characteristic impedance. Size reduction techniques (or alternately tuning techniques) include reactive inductive loading, which often occurs in the form of increased conductor length; and reactive capacitive loading, which often occurs in the form of adding some structure at the top or end of the antenna so as to increase the capacitance between the antenna and ground (assuming a monopole-like antenna). Either of these techniques may be used to tune or resonate the small antenna. Material loading, where the small antenna may be surrounded with a dielectric material, is another common technique used to tune or resonate the small antenna.

In this paper, we first consider the performance properties and trade-offs associated with loading a straight-wire dipole with a material having a relative permittivity and/or permeability greater than 1. With the straight-wire dipole we consider how material loading impacts both the resonant frequency and the resonant resistance. We illustrate that the overall length of the antenna is most significant in terms of establishing the loaded dipole's performance properties. Next, we consider the performance of a material loaded small antenna, particularly focusing on the relationship and contrast between conductor and material losses. Prior to discussing these topics, it is noted that this tutorial discussion is not intended to focus on optimizing the bandwidth of the small antenna relative to the lower bound of *Q*, or the Chu limit.

Simulations results presented within this paper were determined using CST's Microwave Studio 3D electromagnetic solver.

THE STRAIGHT-WIRE DIPOLE

It is known that the *Q* of a microstrip patch antenna on a high permeability substrate is lower than the *Q* of the same patch on a high permittivity substrate [1]. It is similarly known that the *Q* of the short dipole loaded with a high permeability material is higher than the *Q* of the short dipole loaded with a high permittivity material. We consider a straight-wire dipole antenna surrounded by a cylindrical-shaped loading material having different values of permittivity and permeability. The dipole is constructed of copper and has a conductor diameter of 2.39 mm. The overall length of the dipole is 12.6 cm. The loading material surrounding the dipole also has an overall length of 12.6 cm. The diameter of the loading material is varied from 1 cm to 5 cm in 1 cm steps and its relative permittivity and relative permeability have values of 4, 9 and 12. Here the materials are assumed to be lossless.

The resonant frequencies of the dipole loaded with the high permittivity and high permeability materials are presented in Fig. 1. The values of resonant resistance as a function of resonant frequency are presented in Fig. 2a. The *Q* of the loaded dipole, made to be resonant at 500 MHz, is presented in Tab. 1. The dipole is made resonant at 500 MHz with different values of material diameter and relative permittivity and permeability. Finally, Fig. 2b presents the resonant frequencies of the dipole as function of loading material diameter for the case where the relative permittivity is equal to 9, the relative permeability is equal to 9 and both the relative permittivity and permeability are simultaneously equal to 3.

From the data presented in these figures and Tab. 1, we see that with the high permittivity material, the resonant frequency gradually decreases in direct relation to either the change in permittivity or the increase in material diameter. Additionally, at any given frequency, the resonant resistance of the loaded dipole is essentially the same, independent of the permittivity or material diameter, implying that the overall resonant length of the dipole is most significant in establishing its resonant properties. A similar result holds for the operating bandwidth and *Q*. With the high permeability material, we see that the resonant frequency decreases quickly with initial introduction of the material but soon levels off with increasing permeability or material diameter. The dipole surrounded with the high permeability material does exhibit lower resonant frequency and higher resistance. However, as seen in Tab. 1, the dipole surrounded with the high permittivity material does exhibit lower *Q*.

The results of Fig. 2b illustrate that when the loading material has equal values of permittivity and permeability, the resulting resonant frequency is approximately equal to the average values of the resonant frequencies exhibited when the material has only a high permittivity and a high permeability. In this case, the product of the equal values of permittivity and permeability (3, 3) equals the separate values of high permittivity (9) and high permeability (9).

The final point to discuss here is the impedance mismatch between free space and the loading material. It is important to understand that the effects of the mismatch at the interface between the dielectric material and free space will manifest itself in changes in the antenna's impedance (including bandwidth), radiation efficiency and radiation pattern. If the material loaded antenna is matched to the source or receiver and is efficient, then the only negative effect of the mismatch at the interface between the material and free space will appear in the antenna's operating bandwidth.

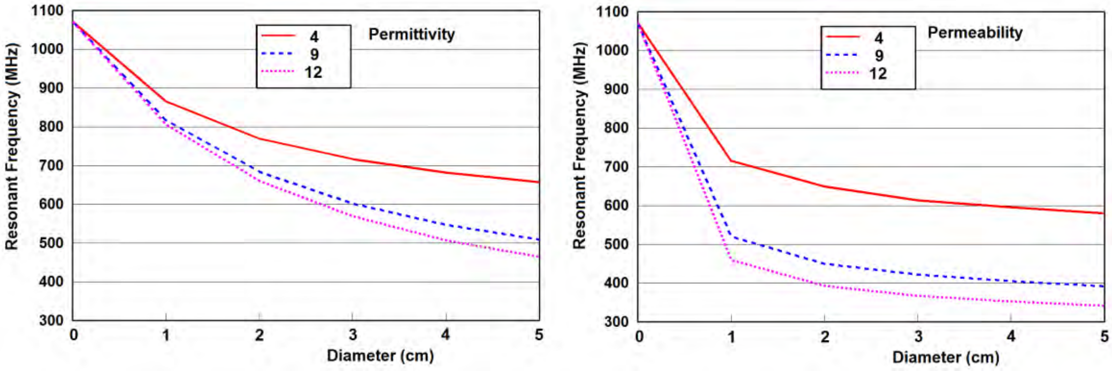
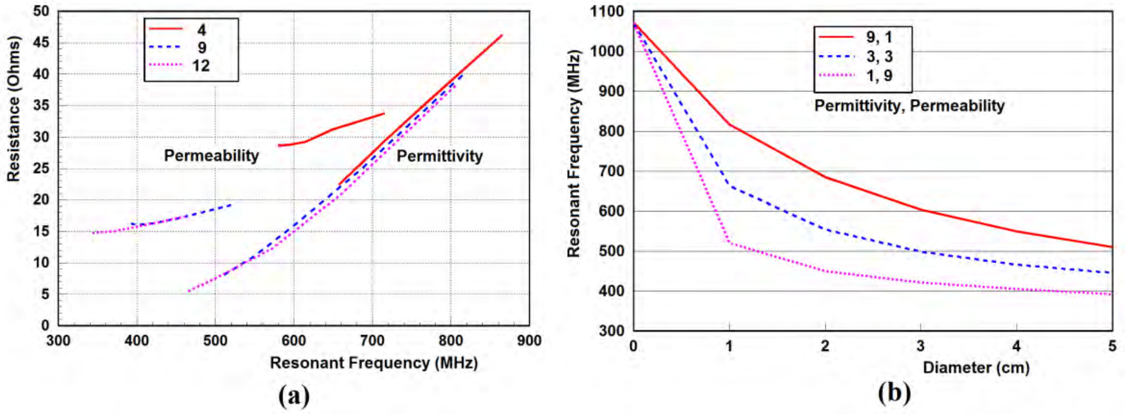


Fig. 1. Resonant frequency of the loaded dipole as a function of loading material diameter and differing values of relative permittivity and permeability.



(a) (b)

Fig. 2. a) Resonant resistance of the loaded dipole as a function of resonant frequency; b) Resonant frequency of the loaded dipole as a function of loading material diameter where the value of relative permittivity equals 9, the value of relative permeability equals 9 and both the relative permittivity and permeability are simultaneously equal to 3.

Tab. 1 Quality factor of the material loaded short dipole.

500 MHz	$\varepsilon_r = 9$ d = 4.6 cm	$\mu_r = 9$ d = 1.17 cm	d = 5 cm $\varepsilon_r = 8.3$	d = 5 cm $\mu_r = 5.48$
Quality Factor	18.9	40.9	19.3	39.3

THE SMALL ANTENNA

In this section, we consider an electrically small antenna [2] – [4] loaded with a dielectric material having permittivity values of 4, 9 and 12. The loss tangents associated with these dielectric values are 0.0004, 0.0004 and 0.0007, respectively. In this case, we do not consider the use of a high permeability material since it offers no benefit in terms of improving the bandwidth of the monopole-like antenna. A depiction of the electrically small antenna with and without the dielectric loading is presented in Fig. 3. The antenna has an overall height of 2.25 cm. A detailed performance summary of the antenna with and without dielectric loading is presented in Tab. 2.

In free space, the small antenna is impedance matched to 50Ω using a matching post (parallel inductor). It exhibits two matched frequencies; 618.3 and 1438 MHz. At the lower operating frequency, the height of the antenna is approximately 0.046 wavelengths. Its radiation efficiency and *Q* are 92.4% and 83, respectively. The first resonant frequency of the antenna decreases with increasing material permittivity as expected. With the exception of a permittivity value of 12, the *Q* increases as expected. The decrease in *Q* for the first resonant frequency for the permittivity of 12 can be attributed to the antenna's lower radiation efficiency.

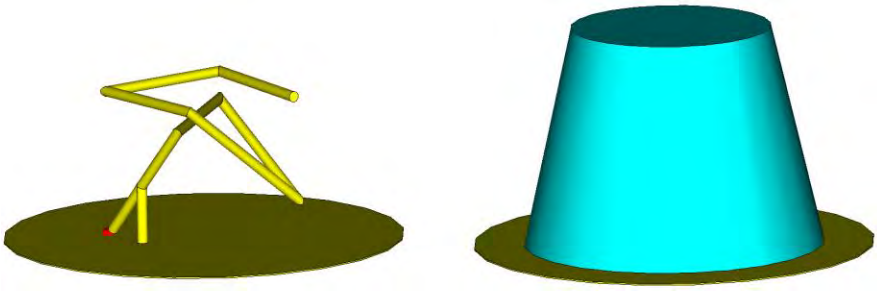


Fig. 3. Depiction of the electrically small antenna with and without dielectric loading.

Tab. 2 Performance summary of the electrically small antenna with and without dielectric loading.

ε	F (MHz)	Gain (dBi)	VSWR	*Q*	Radiation Efficiency (%)			
					Free Space	Cu and ε Losses	Cu Losses Only	ε Losses Only
1	618.3	4.44	2.05	83	92.4	92.4	92.4	N/A
	1438	3.59	1.47	76.9	95.9	95.9	95.9	N/A
4	365.4	2.14	1.21	258.1	1.8	58.8	64.0	87.6
	745.8	2.49	2.37	255.2	39.5	69.1	76.6	87.7
	1286	4.24	1.83	39.7	58.4	96.0	97.5	98.6
9	259.9	-2.07	1.26	396.8	0.26	23.0	26.8	62.2
	504.3	-1.05	3.6	449.3	21.1	33.0	40.4	64.8
	879.6	3.47	2.03	126.2	16.0	85.3	89.6	94.8
	1390	2.47	5.06	11.3	91.8	97.9	98.7	99.4
12	230.1	-4.7	1.51	382.8		12.7		
	438	-3.74	3.21	440.9		18.7		
	767.9	2.49	3	183		71.9		
	1230	2.75	3.12	21.7		96.5		

What is interesting with this antenna is that with the combined use of the matching post and the dielectric loading, the antenna is able to maintain an impedance match at the lower resonant frequencies. Additionally, the antenna exhibits several matched frequencies within ranges where it is electrically small.

Another point of interest is the change in the antenna’s radiation efficiency with the addition of the dielectric loading. Typically, one might assume that the addition of a lossy dielectric material around the antenna would add to the total losses, reducing the overall radiation efficiency of the antenna. This is not necessarily the case here because the addition of the dielectric material increases the antenna’s radiation resistance at many frequencies. For example, at 365.4 MHz, the free space antenna is unmatched and exhibits a radiation resistance close to 0Ω. As a result, its radiation efficiency is 1.8%. With the addition of the lossy dielectric material having a permittivity equal to 4, the antenna’s radiation resistance increases, resulting in an overall radiation efficiency of 59%. Similar results occur in all cases as can be seen in Tab. 2.

Since the results above include only a single case study and relatively low values of loss tangent, a general conclusion is not reached. Additional work in currently underway to determine if this holds with other matching techniques and increasing values of loss tangent.

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