A Review of an Electrically Small Antenna Immersed in a Dielectric

Edward E. Altshuler[1], Terry H. O'Donnell[1], Steven R. Best[2], Brian Kaanta[1]

[1]Air Force Research Laboratory, Electromagnetics Technology Division,Hanscom AFB, MA 01731, edward.altshuler@hanscom.af.mil, teresa.odonnell.ctr@hanscom.af.mil, brian.kaanta@hanscom.af.mil.
[2]Mitre Corp. M/S E087, 202 Burlington Rd., Bedford, MA 01730, sbest@mitre.org

Abstract

Placing an electrically small antenna in a dielectric reduces its resonant frequency, making it electrically smaller. The radiation efficiency of the smaller antenna is also reduced because of the higher concentration of fields within the lossy dielectric at the lower frequencies. Two factors affect the antenna Q: The lower resonant frequency associated with the increased dielectric constant causes Q to increase, while the increased loss within the dielectric causes Q to decrease. We investigate this relationship by simulating and measuring two electrically small antennas in free space and immersed in multiferroic media and in powders with various dielectric constants.

1. Introduction

Placing an electrically small antenna in a dielectric produces two results. First, the resonant frequency of the antenna is reduced. If the dielectric were infinite in extent, the frequency would be reduced by $(1/\varepsilon')^{1/2}$. In practice, it does not take a large volume of dielectric material to significantly reduce the resonant frequency. The second effect is the reduction in radiation efficiency due to losses within the dielectric. At any given frequency, the loss within the dielectric is proportional to its loss tangent. An increase in the dielectric constant is generally accompanied by a corresponding increase in the loss tangent. Thus, higher dielectric constant materials usually have higher loss. As the dielectric constant of the material is increased, the Q of the antenna structure itself also increases since the antenna becomes electrically smaller (operates at a lower frequency). This increase in antenna Q corresponds to higher reactive fields near the antenna, which in turn produces higher losses in the dielectric. The net result is that the increased dielectric constant causes the Q to increase (relative to that for free space) and the increase in loss tangent causes the Q to decrease.

We conducted simulations and measurements on two electrically small antennas. The smaller antenna was a 3-dimensional, 7-wire genetic antenna that fits in a volume of about 2.6 cm on a side. It had a resonant frequency in free space of about 720 MHz; thus the electrical size was about 0.062λ on a side. The larger antenna was a planar, modified Inverted–F antenna that had dimensions of about 3.75 cm on a side. It had a resonant frequency at about 1.1 GHz in free space. This corresponds to electrical dimensions of about 0.137λ on a side. We then immersed these antennas in powders having dielectric constants of 4, 9 and 12. Unfortunately, we have not yet been able to verify the accuracy of the dielectric constants and loss tangents quoted by the manufacturer. We also tested ceramic type dielectric powders which were discovered to have much lower dielectric constants than their solid ceramic counterparts. Finally, we made some preliminary measurements of a monopole antenna immersed in two different multiferroic materials. Gadolidium magnetic ions were added to a ferroelectric polymer to make the first material multiferroic; cobalt magnetic ions were added to the polymer to make a second multiferroic material. Although the resultant materials were found to have a high equivalent permittivity and permeability, they also had relatively high losses.

2. Approach

The Q of the antenna immersed in a dielectric has a dependence on the antenna's electrical size and both the real, ε', and imaginary, ε'', parts of the dielectric constant, ε, where $\varepsilon = \varepsilon' - j\,\varepsilon''$. As ε' is increased, the antenna becomes electrically smaller and the Q increases. As ε'' is increased, the Q decreases. The dielectric loss is often expressed by the loss tangent, $\tan\delta = \varepsilon''/\varepsilon'$. Thus we have an increase in the real part of the dielectric constant increasing the Q and an increase in the imaginary part of the dielectric constant decreasing the Q.

We compute the Q and radiation efficiency (dielectric loss) for the electrically small self-resonant antenna for both free space and when it is immersed in a dielectric.

2.1 Simulations

Simulation results presented here were computed using CST's Microwave Studio (MWS 2008). Free space simulated results were compared and verified against simulations performed using the Numerical Electromagnetics Code (NEC4). In each case, they were in very good agreement. The antennas were simulated as perfect electric conducting, finite diameter cylindrical wires. For the purposes of these simulations, the antennas were mounted at the center of an infinite ground plane. In addition to the free space simulations, the antennas were simulated within dielectrics of $\varepsilon' = 4$, 9 and 12, with loss tangents of 0.0004, 0.0007.and 0.0007, respectively.

2.2 Measurements

The impedance and gain measurements were made with a Hewlett Packard 8510C Network Analyzer. In each case the antenna was mounted on a 1.22 x 1.22 m ground plane. To measure the antenna gain, the transmit resonant monopole and the small receiving antenna were mounted on the same ground plane [1]. The resonant frequency of the transmit monopole was adjusted to match that of the electrically small antenna.

The Q of the antenna was determined from the ½-power conductance bandwidth. The admittance was measured and the Q was computed from $Q = f_0 /(f_2 - f_1)$, where f_0 is the resonant frequency and f_1 and f_2 are the frequencies at which the conductance decreases to ½ of its value at resonance. The antennas were first measured in free space; then they were placed in the empty containers which were later filled with dielectric powders. The measurement results with the empty containers were found to be almost identical to those in free space. Finally the containers were filled with the dielectric powder. We used powders having dielectric constants of 4, 9 and 12. The loss tangent for $\varepsilon' = 4$ was 0.0004; the loss tangents for $\varepsilon' = 9$ and 12 were both 0.0007. We also made some preliminary measurements of the antenna in ceramic powders. We also measured a monopole in the multiferroic materials.

3. Results

We were not able to achieve very good agreement between the simulations and the measurements. We believe this to be primarily a function of the uncertainty in the dielectric properties of the materials used in the measurements. We did not yet perform a parametric study (using simulations) of how slight variations in both the dielectric constant and loss tangent affect the results. We believe this would provide better insight into whether the quoted dielectric properties are accurate. Each of the antennas had to be analyzed separately because the volumes of the dielectric material were different for each antenna. However, we were able to compare the qualitative behavior of the simulations with the measurements and found they were similar. Quantitative results for both the measurements and simulations are presented in Table 1.

3.1 Simulations

The impedance, Q and gain of the 7-wire genetic antenna in free space and within a dielectric were simulated using Microwave Studio. The Q of the antenna was determined using the antenna's impedance. In the case of the free space results, very good agreement between the simulation and measurements was obtained. The antenna was resonant at 721 MHz, with a Q of 25.6 and a gain of 5 dBi. With increasing dielectric constant, there was a corresponding decrease in resonant frequency, decrease in gain and increase in Q until $\varepsilon' = 12$, in which case the Q decreased. The decrease in Q is attributed to the substantial decrease in gain with increasing values of ε' and decreasing frequency. In this case, the dielectric loss dominates the antenna's total Q.

With the modified Inverted-F antenna, there is also a corresponding decrease in resonant frequency and increase in Q with increasing dielectric constant. In all cases, the Q continues to increase. This is believed to a result of the fact that the antenna is not as small as the 7-wire genetic antenna. With a further increase in dielectric constant and decrease in frequency, we expect that the dielectric losses would become dominant and the Q would eventually decrease. Gain was not simulated.

3.2 Measurements

The realized gain (not corrected for mismatch loss), VSWR, impedance and admittance were measured as a function of frequency. The test frequency was selected to maximize the realized gain. The transmitting monopole was tuned to the same frequency. In order to compute the Q, it was sometimes necessary to introduce a time delay so that the admittance had a resonance at the same frequency as the peak gain. After these measurements were completed the gain of the antenna was determined by comparing it with the gain of a reference monopole. The reference monopole height was adjusted for a minimum VSWR and its gain was corrected for the mismatch loss. The mismatch correction for the AUT was computed from the VSWR and the total gain was determined. The gain in dBi was then calculated by taking the difference of the AUT and the RA and assuming that the reference monopole had a gain of 5.14 dB to obtain the gain of the AUT in dBi.

This procedure was then repeated for the antennas immersed in their respective cups which were filled with the dielectric powders. We found that with a small amount of dielectric surrounding each antenna, the resonant frequency decreased significantly. For example, for $\varepsilon' = 4$, 9 and 12 the resonant frequencies of the modified Inverted-F antenna decrease to 63%, 56% and 52% of their free space values rather than the 50%, 33% and 29% decreases that would have occurred had the antenna been immersed in an infinite dielectric volume. It should also be noted that the corresponding electrical size of the antenna decreases from 0.137λ in free space to values of 0.088λ, 0.070λ and 0.062λ for $\varepsilon' = 4$, 9 and 12 respectively. For the 7-wire genetic antenna the frequencies decreased to 64%, 50% and 41% of the free space values for the same dielectric constants. The electrical sizes ranged from 0.063λ for free space down to 0.026λ for the antenna immersed in a dielectric constant of 12. The values of Q ranged from about 5 for the modified Inverted-F antenna in free space to close to 200 for the genetic antenna immersed in a dielectric constant of 12. The antenna gains in free space were close to that of a monopole in free space. They gradually decreased as the dielectric constant increased and the electrical size of the antenna became smaller. For the genetic antenna in a dielectric constant of 12 and having an electrical size of 0.026λ the gain was about -3.4 dBi. It is also significant to note that in free space and for all values of dielectric constant, the VSWR's of the antennas were less than 2:1. While the resonant frequency decreased and the antenna became electrically smaller, there was not a substantial increase in VSWR.

4. Conclusions

A dielectric powder was used for this investigation because that was the most convenient way to immerse the antennas in a dielectric; it is not likely that a powder would necessarily be used for an actual application since we would normally want to protect the antenna with a solid dielectric. The results however were consistent with those that would have been expected, had a solid dielectric been used. It is seen that the resonant frequency can be significantly reduced by immersing an antenna in a dielectric. In all cases, the VSWR of the antenna remained less than 2:1. However, reducing the electrical size of the antenna comes at a cost. It is seen that the *Q* increases significantly for a smaller antenna, thus producing a corresponding decrease in the bandwidth. Also, the gain and efficiency are further reduced as the antenna becomes electrically smaller. However, if space is a factor, one can certainly make the antenna physically smaller by immersing it in a dielectric.

5. Acknowledgements

The authors wish to thank AFOSR for financial support and for Drs. Arthur Yaghjian and Everett Crisman for helpful discussions.

6. References

[1] E.E. Altshuler and T.H.O'Donnell, " The Measurement of Antenna Gain with Transmitting and Receiving Antennas on a Finite Ground Plane," 2007 IEEE Antennas and Propagation Society International Symposium, Honolulu , Hawaii, June, 2007, p. 13.

7-Wire Genetic Antenna Experiment

ε'	Freq. (MHz)	h/λ	Gain (dBi)	Q
1	722.4	0.063	4.1	41
4	464.8	0.040	1.8	137
9	352.8	0.031	-3.0	147
12	296.8	0.026	-3.4	199

Modified Inverted-F Antenna Measurements

ε'	Freq. (MHz)	h/λ	Gain (dBi)	Q
1	1096.8	0.137	4.9	4.6
4	702.4	0.088	4.7	11.9
9	557.6	0.070	4.0	31.7
12	496	0.062	4.5	36.5

7-Wire Genetic Antenna Simulation

ε'	Freq. (MHz)	h/λ	Gain (dBi)	Q
1	721	0.070	5.0	25.6
4	454.5	0.044	2.4	99.2
9	327.6	0.032	-5.1	61.6
12	289	0.028	-8.5	47.5

Modified Inverted-F Antenna Simulations

ε'	Freq. (MHz)	h/λ	Gain (dBi)	Q
1	1160.3	0.145		3.9
4	718.5	0.090		12.6
9	522.5	0.065		56.7
12	464	0.058		172.5

Table 1. Quantitative summary of the measured and simulated results for the 7-wire genetic antenna and the modified Inverted-F antenna.