Nanoantennas: A Concept for Efficient Electrically Small UWB Devices

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***Abstract*—This paper introduces the concept of a "nanoantenna:" a device that radiates UWB impulses from the discharge of a conducting enclosure antenna. By trapping exterior electrostatic energy, a nanoantenna has the potential to radiate energy more efficiently than generally believed possible, enabling efficient millimeter scale 3.1-10.6 GHz UWB devices.**

***Index Terms*—antennas, antenna theory, nanotechnology, ultrawideband**

I. Introduction

Ultrawideband (UWB) systems are in great demand for precision tracking, radar, and communications. A commercially successful UWB system must be both small and consume very little power. Similarly, there is great interest at present in "smart dust," miniature sensors, and other nanodevices that can wirelessly transmit data, positioning signals, or radar signals using very low power signals and utilizing wavelengths that may be much larger than the device itself [1]. Highly efficient, electrically small antennas are a necessity for UWB systems, smart dust, nanodevices, and numerous other commercial and government applications.

Efficient antennas commonly are on the order of a half-wavelength long for a dipole or a quarter-wavelength long for a monopole. For UWB operation in the 3.1-10.6 GHz, a 5.3cm dipole or a 2.6cm monopole are called for (5.7GHz center frequency). These antennas may be small enough for some applications. For other applications, even smaller antennas may be required. Efficient quarter to half wave antennas that operate in the upper very high frequency (VHF) band or ultrahigh frequency (UHF) band (for instance from 100MHz on up) must be ten times larger. This is too large for many potential applications. In general however, no matter the application, there is always a need to make antennas smaller and less obtrusive while remaining efficient. Existing small VHF/UHF UWB antennas tend to be very inefficient including large current radiators, and resistively loaded antennas. Antennas smaller than a quarter-wavelength are usually referred to as electrically small antennas. Electrically small antennas are prone to be inefficient, particularly when significantly smaller than a quarter-wavelength. Given the low power levels under which UWB systems operate, antenna inefficiency is a serious problem [2].

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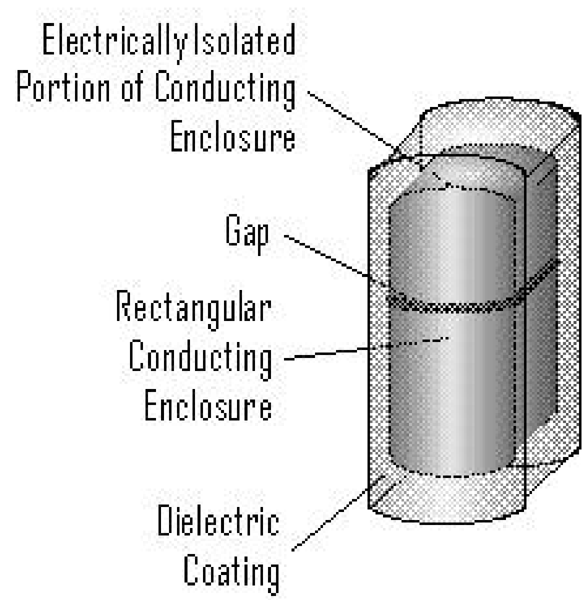

Fig. 1. To maximize antenna dimension with respect to a UWB device, a nanoantenna uses the device enclosure as the antenna: driving one half of the enclosure against the other as a dipole. Dielectric coating helps miniaturize the enclosure size further.

This paper introduces the concept of a "nanoantenna," a highly efficient, yet electrically small UWB radiating device. Analysis predicts that the nanoantenna concept enables millimeter scale UWB devices operating in the 3.1-10.6 GHz band and centimeter scale UWB devices at VHF/UHF frequencies. The aim of this paper is to establish the feasibility of the nanoantenna concept and determine reasonable performance expectations for nanoantenna devices.

II. What is a Nanoantenna?

A. Conducting Enclosure Antenna

A nanoantenna uses the enclosure as radiating elements. By driving one half of the enclosure against the other half in dipole fashion, a nanoantenna maximizes the size of the antenna with respect to the size of the device. A dielectric coating provides additional miniaturization as well as insulating and electrically isolating the nanoantenna device from its surroundings. Figure 1 shows a typical nanoantenna.

The concept of using a device enclosure as a dipole antenna has a long history. In fact, the U.S. Explorer satellites, first launched in 1958, drove half of the satellite's cylindrical enclosure versus the other half for use as a dipole antenna [3].

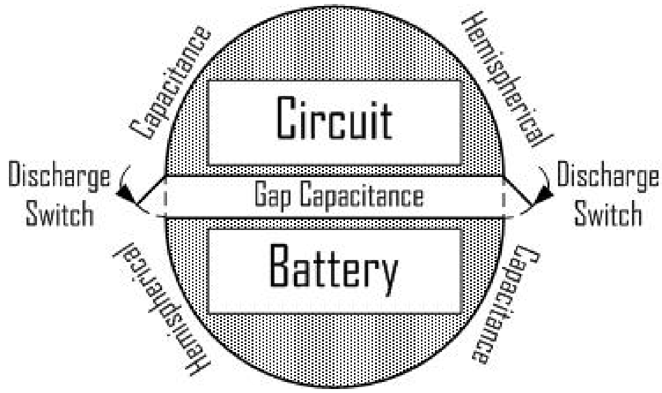

Fig. 2. To maximize antenna dimension with respect to a UWB device, a nanoantenna uses the device enclosure as the antenna: driving one half of the enclosure against the other as a dipole. Dielectric coating helps miniaturize the enclosure size further.

The concept of a conducting enclosure antenna is a key element of the nanoantenna concept, yet does not achieve a significant miniaturization by itself. The other required element is to consider a discharge excited aresonant antenna.

B. Discharge Excited Aresonant Antenna

In typical operation, a nanoantenna slowly charges up one half of a conducting enclosure with respect to the other half. If this charging process occurs sufficiently slowly (i.e. adibatically), no energy will be lost in the charging process. Figure 2 shows this process. Then, the gap around the conducting enclosure is shorted so as to discharge the conducting enclosure. If the switching process that gives rise to the shorting occurs much more rapidly than the characteristic time associated with the discharge process, the enclosure becomes a Faraday cage or equipotential surface. The energy trapped outside the sphere (U_{out}) decouples and radiates away. The energy trapped inside the sphere (U_{in})is absorbed in the discharge process. These energy quantities are proportional to the capacitance of the regions in which the energy is stored.

Thus, the efficiency of a nanoantenna depends upon the relative size of the inner or gap capacitance (C_{in}) and the outer or (in the case of a spherical enclosure) hemispherical capacitance (C_{out}). The efficiency (η) of a nanoantenna will be:

$$\eta = \frac{U_{out}}{U_{in} + U_{out}} = \frac{C_{out}}{C_{in} + C_{out}} \tag{1}$$

These capacitances are difficult to predict analytically except for a few relatively simple geometries.

III. Analysis

A. Potential Surrounding a Hemispherical Nanoantenna

A spherical nanoantenna lends itself to mathematical analysis. In spherical coordinates the general solution for the electric potential (Φ) about an object with azimuthal symmetry in spherical coordinates is:

$$\Phi(r,\theta) = \sum_{\ell=0}^{\infty} \left(A_\ell r^\ell + B_\ell r^{-(\ell+1)} \right) P_\ell(\cos\theta) \tag{2}$$

where $P_\ell(\cos\theta)$ are the Legendre polynomials [4]. Assume two perfectly conducting hemispheres are at equal and opposite electric potentials:

$$\Phi(\theta) = \begin{cases} +V_0 & 0 \le \theta < \frac{\pi}{2} \\ -V_0 & \frac{\pi}{2} < \theta \le \pi \end{cases} \tag{2}$$

Coefficients are obtained by evaluating (2) on the surface of the sphere where R_S is the radius of the spherical shell. Since $\Phi(r, \theta) = 0$ in the limits $r \to 0$ and $r \to \infty$, $B_\ell = 0$ and $A_\ell = 0$, respectively. These coefficients are obtained as follows:

$$A_\ell = \frac{2\ell+1}{2R_S^\ell} \int_0^\pi V(\theta) P_\ell(\cos\theta) \sin\theta \, d\theta \text{, and} \tag{3}$$

$$B_\ell = \frac{2\ell+1}{2} R_S^{\ell+1} \int_0^\pi V(\theta) P_\ell(\cos\theta) \sin\theta \, d\theta . \tag{4}$$

The potential is given by:

$$\Phi(r,\theta) = V_0 \begin{cases} \frac{3}{2}\frac{r}{R_S} P_1(\cos\theta) - \frac{7}{8}\left(\frac{r}{R_S}\right)^3 P_3(\cos\theta) \\ + \frac{11}{16}\left(\frac{r}{R_S}\right)^5 P_5(\cos\theta) - \frac{75}{128}\left(\frac{r}{R_S}\right)^7 P_7(\cos\theta) + \cdots & r \le R_S \\ \frac{3}{2}\left(\frac{R_S}{r}\right)^2 P_1(\cos\theta) - \frac{7}{8}\left(\frac{R_S}{r}\right)^4 P_3(\cos\theta) \\ + \frac{11}{16}\left(\frac{R_S}{r}\right)^6 P_5(\cos\theta) - \frac{75}{128}\left(\frac{R_S}{r}\right)^8 P_7(\cos\theta) + \cdots & r \ge R_S \end{cases} \tag{5}$$

where V_0 is a constant. Equipotentials about a sphere of radius $R_S = 1$ are shown in Figure 3.

The electric fields around the sphere are given by:

$$\begin{aligned} \mathbf{E} &= -\nabla\Phi(r,\theta) \\ &= \hat{\mathbf{r}} \frac{\partial \Phi(r,\theta)}{\partial r} + \hat{\boldsymbol{\theta}} \frac{1}{r} \frac{\partial \Phi(r,\theta)}{\partial \theta} + \hat{\boldsymbol{\varphi}} \frac{1}{r \sin\theta} \frac{\partial \Phi(r,\theta)}{\partial \phi} \\ &= V_0 \begin{pmatrix} -\frac{3R_S^2 \cos\theta}{r^3} + \frac{7R_S^4}{4r^5}\left(5\cos^3\theta - 3\cos\theta\right) \\ -\frac{33R_S^6}{32r^7}\left(\frac{15}{2}\cos\theta - 35\cos^3\theta - \frac{63}{2}\cos^5\theta\right) + \cdots \end{pmatrix} \hat{\mathbf{r}} \\ &+ V_0 \begin{pmatrix} -\frac{3R_S^2 \sin\theta}{2r^3} + \frac{7R_S^4 \sin\theta}{16r^5}\left(15\cos^2\theta - 3\right) \\ -\frac{11R_S^6}{64r^7}\left(\frac{15}{2}\sin\theta - 105\cos^2\theta\sin\theta - \frac{305}{2}\cos^4\theta\sin\theta\right) + \cdots \end{pmatrix} \hat{\boldsymbol{\theta}} \end{aligned} \tag{7}$$

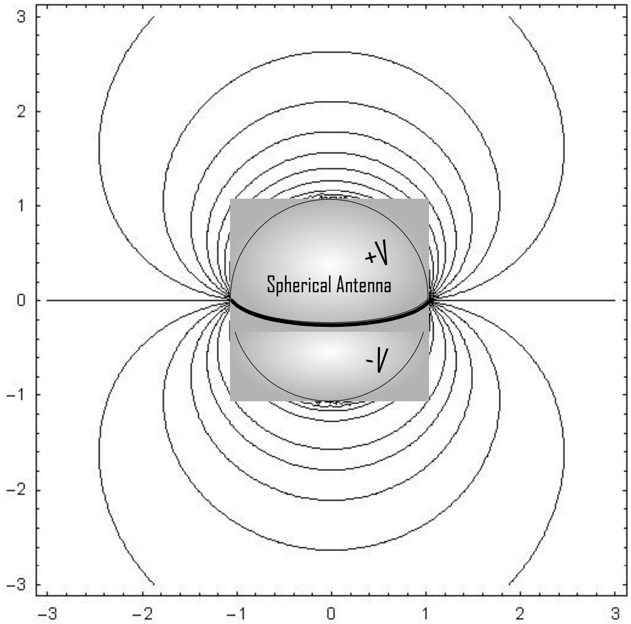

Fig. 3. Equipotentials around a spherical nanoantenna charged to equal and opposite voltages ($\pm V$). The scale is in units of sphere radius R_S. The equipotentials have the highest density near the surface and the equatorial gap. Thus the electric field is strongest there as well.

The energy stored in these external fields out to a distance R is:

$$U = \int_v u \, dV = 2\pi \int_{R_S}^{R} \int_0^{\pi} \frac{1}{2} \varepsilon_0 \left| \mathbf{E} \right|^2 r^2 \sin\theta \, d\theta \, dr \qquad (8)$$

A numerical calculation including terms to order r^{-10} shows that 80% of the energy is stored within 1.5 R_S of the hemispherical capacitor and greater than 90% of the energy is stored within 2.0 R_S (see Figure 4). Thus, only a relatively thin dielectric shell is necessary to support this energy and yield a significant increase in the outer capacitance.

B. Capacitance of a Hemispherical Nanoantenna

A numerical calculation of energy U yields the capacitance using the relationship:

$$U = \tfrac{1}{2} C \Phi^2 \qquad (9)$$

This calculation shows that the capacitance outside a hemispherical capacitor of radius $R_S = 1$ m is about 15 pF. If the gap between the hemispheres is filled by a parallel plate capacitor as in Figure 5, the resulting system is essentially two capacitors in parallel: the outside capacitor due to the hemispherical capacitance, and the inside capacitance due to the capacitance of the circular parallel plates separated by a gap, "*G*."

The outside capacitance for various dielectric constants and size of antenna are shown in Figure 6. In general, the inside capacitance is much greater than the outside capacitance unless dielectric loading is used. Although a fixed dielectric constant is assumed in Figure 6, in general the dielectric constant may be varied in a controlled fashion as a function of radial distance or other geometrical parameter.

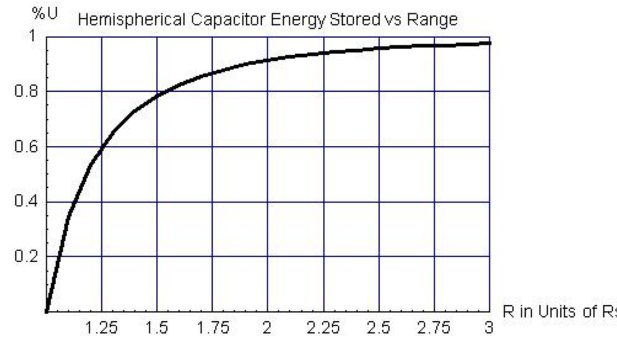

Fig. 4. The fraction of energy stored within a radius R of a hemispherical capacitor is shown in units of the spherical radius R_S. 80% of the energy is stored within a half radius of the spherical shell and 90% of the energy is stored within a shell of thickness equal to the radius.

C. Model of the Discharge

Consider the lowest order dipole mode: the one which will dominate the lowest frequency part of the time domain response of the spherical discharge process. This time domain response is:

$$T(t) = e^{-\frac{ct}{2R_S}} \left(\frac{1}{\sqrt{3}} \sin \frac{\sqrt{3}ct}{2R_S} + \cos \frac{\sqrt{3}ct}{2R_S} \right) \qquad (10)$$

and the time dependence of the resulting radiation is:

$$\ddot{T}(t) = \frac{c^2}{3R_S^2} e^{-\frac{ct}{2R_S}} \left(-3\cos \frac{\sqrt{3}ct}{2R_S} + \sqrt{3} \sin \frac{\sqrt{3}ct}{2R_S} \right). \qquad (11)$$

Assume a spherical conducting enclosure of radius $R_S = 0.1$m. Then the normalized time domain response is shown in Figure 7, and the Fourier transformed and normalized frequency domain response is shown in Figure 8.

IV. Design Examples

A. UHF Design Example

The example of the previous section considered a R_S = 10 cm sphere with a frequency response from about 200-1000MHz. This is still too large for most commercial applications, so consider what might be achievable using dielectric loading with a material (such as TiO_2) that has a dielectric constant ε_r = 100. Since electrical size scales as $\sqrt{\varepsilon_r}$, one may construct an antenna of size R_S = 1cm embedded in ε_r = 100 material that will have the frequency response of a R_S = 10cm sphere in free space. Following the guidance of Figure 4, a dielectric coating of thickness equal to the radius is sufficient to include at least 90% of the electric energy. The exterior capacitance will be about C_{out} = 15pF and the interior capacitance will be about C_{in} = 2pF assuming a 60mil gap. Thus this composite spherical antenna about the size of a golf ball with a radius of

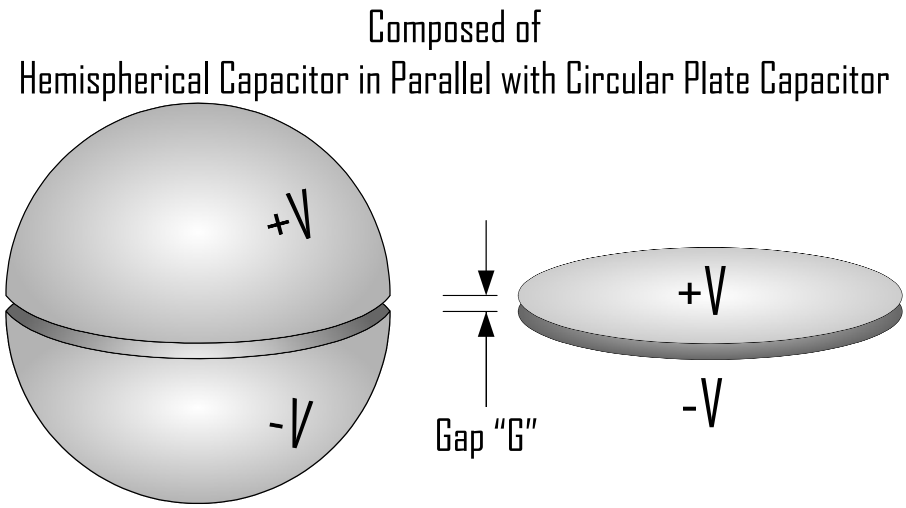

Fig. 5. A spherical nanoantenna may be thought of as a hemispherical or outer capacitance in parallel with a parallel plate or inner capacitance.

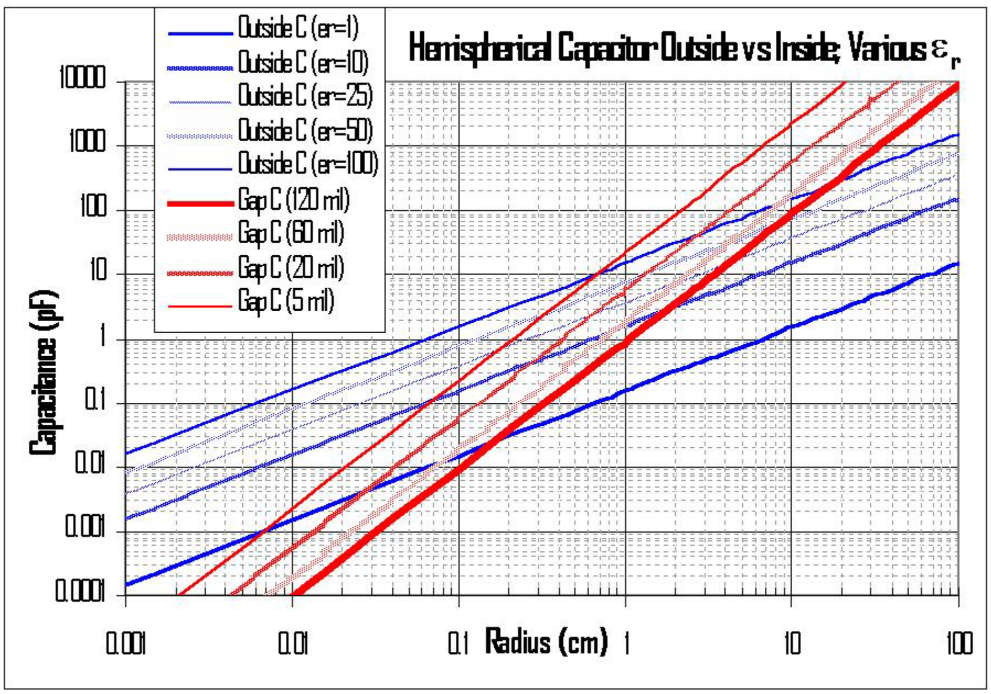

Fig. 6. Inner or gap capacitance and outer or hemispherical capacitance for a variety of geometries and sphere radii.

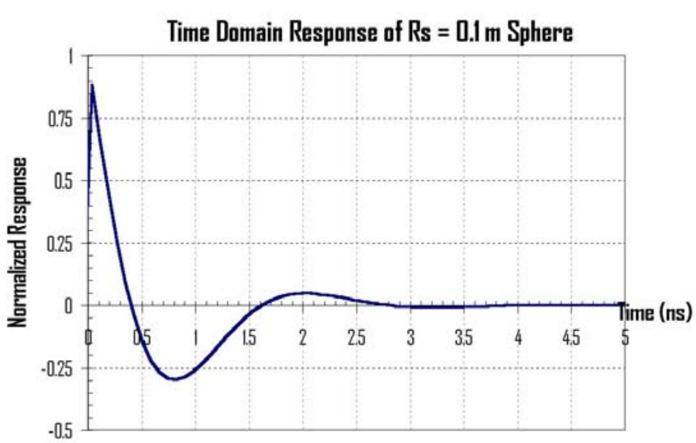

Fig. 7. Fundamental mode time response for a 10 cm radius spherical discharge.

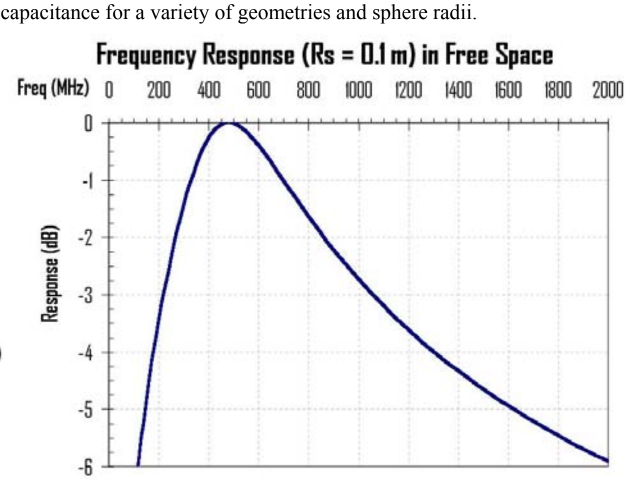

Fig. 8. Frequency domain response for the fundamental mode of a 10 cm radius spherical discharge.

2 cm and a diameter of 4 cm (a bit over 1.5 in) will have an efficiency of:

$$\eta = \frac{C_{out}}{C_{in} + C_{out}} = \frac{15\ pF}{2\ pF + 15\ pF} = 88\% \qquad (12)$$

This is excellent efficiency for an antenna of radius 0.0133λ (i.e. 2cm radius antenna operational at 200MHz or λ = 1.5m).

B. Microwave Design Example

Suppose now the design goal is the frequency response of Figure 8 scaled up by a factor of ten so that the operational frequency lies between 2-10 GHz. A free space antenna with R_S = 1 cm has the correct frequency response, however consulting Figure 6, the exterior capacitance will be about C_{out} = 0.15 pF and the interior capacitance will be about C_{in} = 2 pF assuming a 60 mil gap. The efficiency will be:

$$\eta = \frac{C_{out}}{C_{in} + C_{out}} = \frac{0.15\ pF}{2\ pF + 0.15\ pF} = 6.98\% \qquad (13)$$

Consider instead an antenna with R_S = 1 mm embedded in a material with dielectric constant ε_r = 100 out to a radius R_D = 2 mm. Then the frequency response is as desired (2-10 GHz),the exterior capacitance will be about C_{out} = 1.5 pF and the interior capacitance will be about C_{in} = 0.2 pF assuming a 5 mil gap. Now, the efficiency will be:

$$\eta = \frac{C_{out}}{C_{in} + C_{out}} = \frac{1.5\ pF}{0.2\ pF + 1.5\ pF} = 88\% \qquad (14)$$

With dimensions like these, one could encapsulate a chip and make an ultra miniature UWB transmitter limited only by the ability to include battery or power scavenging means.

C. Other Design Considerations

Spectral control may be implemented by shaping the conducting enclosure or in the discharge circuit using filtering techniques, however out of band components need to be dissipated in the filter. Also, the severe dielectric interface may be prone to reflect signals and disperse the signals. Assuming dielectric losses and ohmic losses in the conducting enclosure antenna and discharge circuits are negligible, the only other loss mechanism is radiation. A further consideration is that the dielectric free space boundary lies within the near field zone, and thus energy is likely to "tunnel" through the boundary. In any event, a dielectric embedded conducting enclosure antenna should radiate efficiently.

Ultimately, the nanoantenna relies on the assumption that the ohmic and dielectric losses inherent to discharge currents on the surface of a conducting enclosure can be made relatively small compared to the desired radiation mechanism.

V. Conclusion

A nanoantenna is a device that radiates UWB impulses from the discharge of a conducting enclosure antenna. By trapping exterior electrostatic energy, a nanoantenna has the potential to radiate energy more efficiently than generally believed possible. Using a rough theoretical analysis, this paper has established that an efficient 3-10 GHz 1-mm-scale UWB device may be feasible.

Although highly speculative, the nanoantenna concept does not appear to violate any laws of physics. Nevertheless, ultimate validation of the nanoantenna concept will rely on on construction and testing of a proof-of-concept prototype.

References

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