Progress In Electromagnetics Research Letters, Vol. 11, 1–9, 2009

SPOKE TOP ANTENNA FOR TRANSIENT RADIATION

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Abstract—When an antenna transmits a short pulse of energy such as used for ultra-wide band applications, the pulse gets distorted upon transmission. To examine the properties of pulse transmission it is helpful to analyze the system in the time domain versus the frequency domain. Presented is a spoke top antenna for transient radiation. The spokes reduce the reflection from the open end of the antenna significantly reducing the trailing pulses commonly seen in the time domain. Comparisons are made with a dipole antenna. Both analytical, modeled and experimental results are presented.

1. INTRODUCTION

Most antenna theory presented in the literature rests on the assumption of harmonic waves, $e^{-j\omega t}$. Traditionally electric and magnetic fields are specified in the frequency domain. Common antenna specifications such as gain, voltage standing wave ratio (VSWR), efficiency are all specified for a particular frequency or band of frequencies. For transient, or pulse radiation, the short burst of energy in the time domain translates to very large bandwidth in the frequency domain. Therefore alternative analysis is necessary.

Analyzing the antenna in the time domain could provide greater insight and understanding of the antenna operation. Time domain analysis is analogous to a radiation from a point charge. A point charge radiates upon a change in velocity (bremsstrahlung radiation) and trajectory (synchrotron radiation) [1]. Using this analogy when one examines a pulse transmitted from an antenna the radiation can be shown to originate from the ends of the antenna or discontinuities in the antenna. Transient response distortion can be explained by

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the interference of the reflected signal from the abrupt discontinuities on the antenna. The pulses radiating from the discontinuities of an antenna arrive at the receiving antenna through paths of different length which cause a time delay hence distorting the pulse.

Ultra wide-band (UWB) is a form of communication based on the transmission and reception of pulses. UWB research began in the early 1960s from work in time domain electromagnetics, at this time it was commonly referred to as baseband radio. Recently UWB has emerged as a viable candidate for wireless networks. In February 2002 the FCC issued a First Report and Order [2] which authorized unlicensed commercial use of UWB in the 3.1–10.6 GHz band. One of the greatest challenges of UWB implementation is the development of a suitable antenna [3]. Antennas are inherently narrow band and do not operate over the entire frequency range.

2. TRANSIENT ANALYSIS DISCUSSION

For UWB transmission there are several different pulse shapes to select from [4]; the Gaussian pulse, the Gaussian monocycle (first derivative of a Gaussian pulse), the Gaussian doublet [5–7] as well as more complex such as Prolate Spheroid Wavefunctions or Hermite Polynomial functions [8]. The research presented here will be on the Gaussian pulse. Although the Gaussian pulse does not meet the power spectral density mask set by the FCC nor is it a transmittable pulse due to the DC component [9] its simple shape is beneficial for demonstrative purposes. The equation for a Gaussian pulse is:

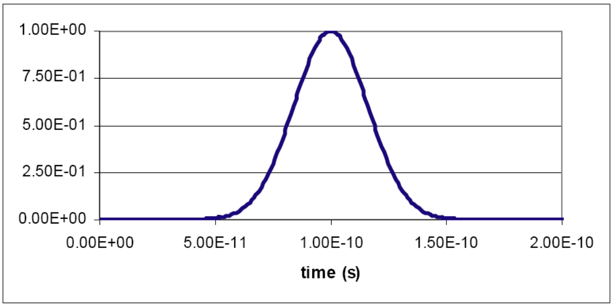
$$f(t) = \exp\left[-t^2/2\sigma^2\right] \tag{1}$$

where σ is the standard deviation of the Gaussian pulse in seconds. The pulse width, τ_p is related to the standard deviation as $\tau_p = 2\pi\sigma$. The bandwidth of a Gaussian pulse is roughly the inverse of the pulse width. So for a 10 GHz bandwidth the pulse width should be on the order of 100 pico seconds.

3. DIPOLE ANTENNA

A dipole oriented along the z-axis with standing wave current is a good example for discussion purposes. The typical frequency domain radiation is:

$$E_\theta(r,\omega) = j\eta \frac{I_0 e^{-jkr}}{2\pi r}\left[\frac{\cos\left(\frac{kh}{2}\cos\theta\right) - \cos\left(\frac{kh}{2}\right)}{\sin\theta}\right] \tag{2}$$



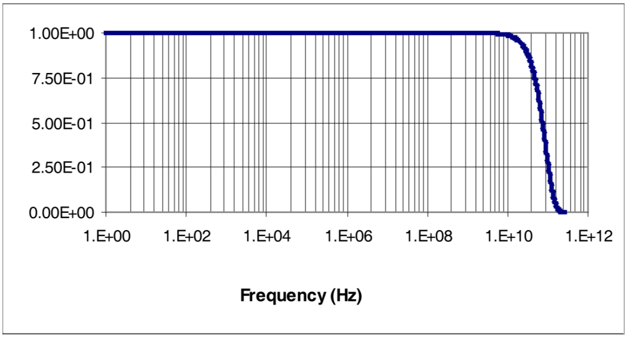


Figure 1. Gaussian signal and corresponding frequency spectrum.

where r is the distance, k is the wave number and h is the length of the antenna. The time domain analytical equation for a z directed dipole greater than one pulse length long is expressed below [10]:

$$E_\theta(r,t) = \frac{\mu_0 c}{2\pi r \sin\theta}\{I_s(t-r/c) + I_s(t-r/c-2h/c) \\ - I_s(t-r/c-(h/c)(1-\cos\theta) - I_s(t-r/c-(h/c)(1+\cos\theta))\} \quad (3)$$

where I_s is the input Gaussian waveform, r is the detection distance, h is the half length of the dipole, and c is the speed of light. Transient radiation originates from the source, reflections from either open end of the antenna and when the pulse enters back into the source region. This equation assumes that the source is absorbing and no other reflections occur. Most likely reflections from the source and open ends will occur until the energy decays completely.

The above Equation (3) is for a dipole in the z-direction. For general placement with the feed point translated by distance d and angle β and rotated through angle γ from the z azis, in spherical coordinates (r, θ, ϕ) the radiation can be defined as:

$$E(r,t) = \left[\frac{\mu_0 c}{4\pi r(1-\sin\gamma\cos\tau\sin\theta\cos\phi-\sin\gamma\sin\tau\sin\theta\sin\phi-\cos\gamma\cos\theta}\right]$$
$$\left[(-\sin\gamma\cos\tau\cos\theta\cos\phi - \sin\gamma\sin\tau\cos\theta\sin\phi + \cos\gamma\sin\theta)\hat{\theta}\right.$$
$$\left. + (\sin\gamma\cos\tau\sin\phi - \sin\gamma\sin\tau\cos\phi)\hat{\phi}\right]$$
$$[I_s\,(t-t_0-r/c+x_1\sin\theta\cos\phi/c+y_1\sin\theta\sin\phi/c+z_1\cos\theta/c)$$
$$-I_s(t-t_0-r/c+x_2\sin\theta\cos\phi/c+y_2\sin\theta\sin\phi/c+z_2\cos\theta/c)] \quad (4)$$

Work has been performed on impedance loading of antenna in order minimize the reflections from the dipole ends [11–14]. This however, simply dampens and spreads out the energy over time. In addition resistive loading decreases the antenna's overall efficiency.

Even though transient radiation can be traced to several radiation sites a dipole still does not radiate in the direction of the dipole, or for the z-directed dipole, in the $\theta = 0$ direction.

4. SPOKE TOP

The spoke top is a top-loaded antenna, a configuration commonly used for electrically short antennas. For this application the antenna is on the order of a wavelength long. The spoke top was analyzed for transient radiation due to several assumptions. Due to current division the energy reflected from the each of the ends is less. Also since the dipole does not radiate in the direction of its orientation the end radiation from the open ends of the spokes would be zero in the horizontal direction. In addition the radiation from the spokes cancels out in the 45 degree and 90 degree direction. All of these factors reduce the secondary point of radiation from the open end of the antenna.

Through simple algebraic manipulation the analytical form of the radiation can be shown where $E(r,t) = E_\theta(r,t) + E_\phi(r,t)$:

$$E_\theta(r,t) \;=\; \frac{\mu_0 c}{4\pi r}\left[\frac{\sin\theta}{(1-\cos\theta)}\left(I\,(t-r/c)-\frac{1}{4}I\,(t-r/c-h/c\,(1-\cos\theta))\right)\right.$$
$$-\;\frac{\cos\theta\cos\phi}{(1-\sin\theta\cos\phi)}\frac{1}{4}\,(I\,(t-r/c-h/c\,(1-\cos\theta))$$
$$-\;I\,(t-r/c-h/c\,(2-\sin\theta\cos\phi-\cos\theta)))$$
$$-\frac{\cos\theta\sin\phi}{(1-\sin\theta\sin\phi)}\frac{1}{4}\,(I\,(t-r/c-h/c\,(1-\cos\theta))$$

$$
\begin{aligned}
&- I\left(t-r/c-h/c\left(2-\sin\theta\sin\phi-\cos\theta\right)\right)\Big)\\
&+\frac{\cos\theta\cos\phi}{(1+\sin\theta\cos\phi)}\frac{1}{4}\Big(I\left(t-r/c-h/c\left(1-\cos\theta\right)\right)\\
&- I\left(t-r/c-h/c\left(2+\sin\theta\cos\phi-\cos\theta\right)\right)\Big)\\
&+\frac{\cos\theta\sin\phi}{(1+\sin\theta\sin\phi)}\frac{1}{4}\Big(I\left(t-r/c-h/c\left(1-\cos\theta\right)\right)\\
&- I\left(t-r/c-h/c\left(2+\sin\theta\sin\phi-\cos\theta\right)\right)\Big)\Bigg]
\end{aligned}
\tag{5}
$$

And since the spoke top has horizontal components there is an E_ϕ field component

$$
\begin{aligned}
E_\phi(r,t) \;=\; &\frac{\mu_0 c}{4\pi r}\Bigg[\frac{\sin\phi}{(1-\sin\theta\cos\phi)}\frac{1}{4}\Big(I\left(t-r/c-h/c\left(1-\cos\theta\right)\right)\\
&- I\left(t-r/c-h/c\left(2-\sin\theta\cos\phi-\cos\theta\right)\right)\Big)\\
&-\frac{\cos\phi}{(1-\sin\theta\sin\phi)}\frac{1}{4}\Big(I\left(t-r/c-h/c\left(1-\cos\theta\right)\right)\\
&- I\left(t-r/c-h/c\left(2-\sin\theta\sin\phi-\cos\theta\right)\right)\Big)\\
&-\frac{\sin\phi}{(1+\sin\theta\cos\phi)}\frac{1}{4}\Big(I\left(t-r/c-h/c\left(1-\cos\theta\right)\right)\\
&- I\left(t-r/c-h/c\left(2+\sin\theta\cos\phi-\cos\theta\right)\right)\Big)\\
&+\frac{\cos\phi}{(1+\sin\theta\sin\phi)}\frac{1}{4}\Big(I\left(t-r/c-h/c\left(1-\cos\theta\right)\right)\\
&- I\left(t-r/c-h/c\left(2+\sin\theta\sin\phi-\cos\theta\right)\right)\Big)\Bigg]
\end{aligned}
\tag{6}
$$

The radiation in the horizontal direction of the spoke top 40 mm high with four 40 mm length spokes compared to a 40 mm high monopole is shown in Figure 3. As can be seen there is no radiation from the ends of the spokes. There is radiation at the junction of the spokes where an abrupt change in direction of the current occurs.

5. MODELED RESULTS

A dipole and a 4-spoke and 8-spoke top dipole antenna were analyzed using CST Microwave Studio which is a Finite Difference Time Domain program. A Gaussian pulse 100 ps long was the input voltage. The dipole was 40 mm high, fed in the center (total of 80 mm high). The spoke top dipoles were 40 mm high as well, fed in the center, and

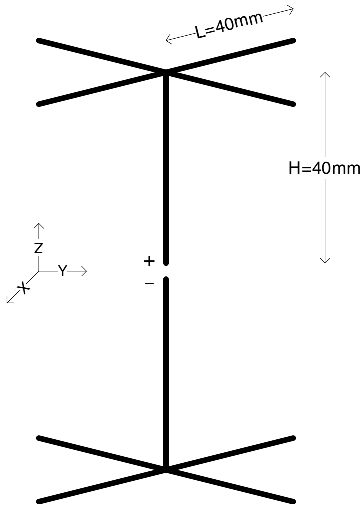


Figure 2. Diagram of the spoke top antenna.

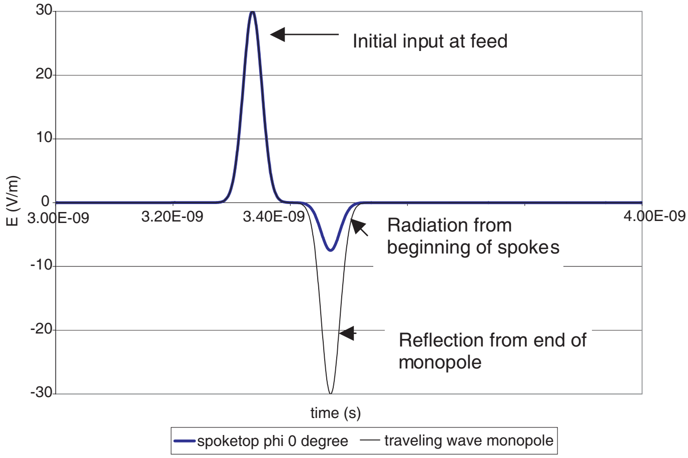


Figure 3. Comparison of analytical equations for a 40 mm monopole and a 40 mm high and 40 mm long 4 spoke top monopole.

the spokes were 40 mm long, as shown in Figure 2. The results are presented in Figure 4 below. Results are presented in the far field.

From the results presented in Figure 4 one can see much more reverberations than the analytical model. The analytical model assumed the ends are ideally absorbing, in reality there are reflections back toward the feed, then back towards the end and so on. The pulse is reflected at the open end of the antenna then travels back down to the

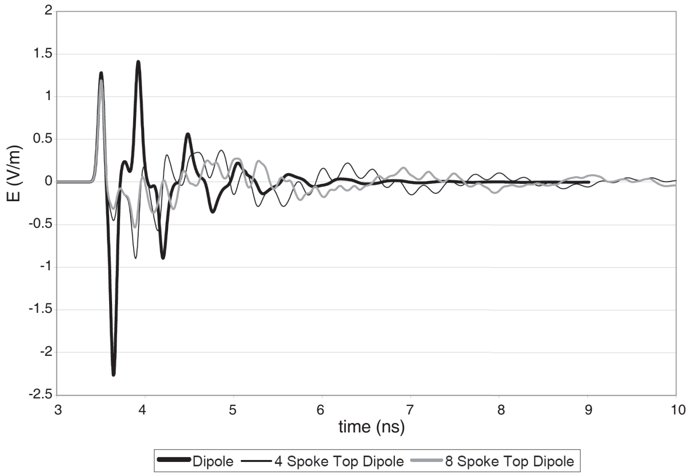


Figure 4. Comparison of time domain results for a 40 mm long dipole, 4 spoke and 8 spoke top dipole, with $\theta = 90°, \phi = 0°$ and $r = 1$ m.

aperture. From the plot shown above the subsequent pulse reflection are greatly reduced using the spoke top dipole. The greater the number of spokes, the greater the current division and therefore the reduction in the trailing pulses. The spoke top antennas do demonstrate that a greater period of time is required for the radiated energy to die out. This shows the charge remains on the antennas. This could be explained since the physical length of the spoke from coaxial aperture to open ends is twice as long compared to the dipole.

The length of the spokes is a critical parameter. If the length of the spokes is shorter than the height of the antenna then reflection will occur from the spoke ends and constructively sum resulting in a strong pulse traveling downward to the source. By making the spoke lengths the same as the height of the antenna the reflection from the spokes and the reflection from the source destructively interfere.

6. EXPERIMENTAL RESULTS

An experiment was performed using a pulse generator as a source for the antenna under test and a small receive probe attached to an oscilloscope. The source was only capable of producing a 1 ns pulse so the antenna was scaled accordingly. The monopole was 1 ft long over a ground plane. The 4 spokes were 1 foot long as well. The results are presented in Figure 5.

From Figure 5 one can see the spoke top dipole does reduced the magnitude of the trailing pulses. The negative pulse from the spoke

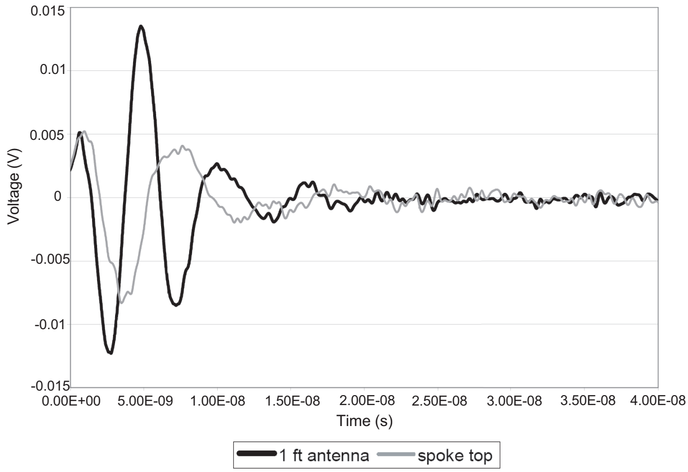


Figure 5. Experimental results for a 1 ns pulse with a 1 ft high monopole over a ground plane and the addition of 4 one foot spokes on the end.

top is a compilation of the reflection from the junction of the spokes and the radiation from the ends of the spokes.

7. CONCLUSION

By using a spoke top antenna for transmission of Gaussian or transient voltage signal the resulting radiated field is a closer representation of the input signal than that of a dipole antenna. In general when antennas transmit a transient signal reflection of the current occurs in the antenna resulting in a series of trailing pulses. The spoke top antenna significantly reduces the magnitude of the trailing pulses. The trailing pulses reduce the pulse repetition rate for UWB systems. Also pulse distortion could lead to processing errors in radar systems.

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