

RADIATION EFFICIENCY OF UWB ANTENNAS

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ABSTRACT

This paper describes a version of the “Wheeler Cap method” modified for evaluating the efficiency of ultra-wideband (UWB) antennas and discusses the application of this method to a Time Domain Corporation BroadSpec™ Model 102 antenna. This antenna exhibits a radiation efficiency better than 90% from 1.5 GHz to above 6.0 GHz.

1. INTRODUCTION

“The radiation efficiency of an antenna is the ratio of the total power radiated by the antenna to the net power accepted by the antenna at its terminals during the radiation process [1].” Thus:

$$\eta_{IEEE} \equiv \frac{P_{rad}}{P_{accepted}}. \quad (1)$$

In the context of a narrow band antenna, this official definition makes sense. In principle, a narrowband filter could be devised so that essentially all of the applied power would be accepted.

In the case of an ultra-wideband (UWB) antenna, however, it is not typically possible to create a similarly UWB matching filter [2]. Particularly in the case of an antenna that does not use resistive loading, the mismatch reflected power can be the most significant loss term.

Consider an antenna that reflects 98% of applied power, and accepts 2% of applied power at a particular frequency. Suppose half the accepted power is radiated and the other half is dissipated in ohmic and dielectric losses. According to the official definition of antenna efficiency, this is a 50% efficient antenna.

A more reasonable definition of antenna efficiency would include mismatch reflected power as an explicit loss, and define efficiency as the ratio of the total power radiated by the antenna to the net power applied at the antenna terminals:

$$\eta_{UWB} \equiv \frac{P_{rad}}{P_{applied}}. \quad (2)$$

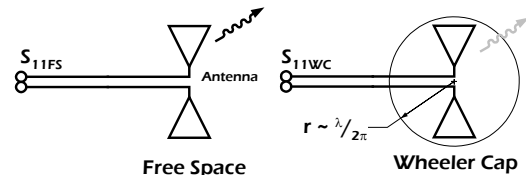


Fig. 1: The Wheeler Cap Method requires measurement of the scattering parameters of the antenna in free space, and inside a closed conducting shell or “Wheeler Cap.” The Wheeler Cap is sized to coincide with the radiansphere, the distance away from a small dipole antenna at which the near or reactive fields and the far or radiation fields are comparable in magnitude. This shorts out the radiation fields and inhibits radiation without significantly perturbing the reactive field in the immediate vicinity of the antenna feed.

One must either integrate power over the duration of the radiation process to obtain total energy, or average the power over an appropriate period. For a narrow band system, one may use the rms power; for a UWB or short pulse radiating antenna, one may calculate efficiency as a function of frequency, or determine the efficiency relative to a certain excitation of interest.

This paper describes a recently introduced method for assessing UWB antenna efficiency: a method that explicitly includes mismatch reflected power as a loss term. Then this paper discusses the efficiency of Time Domain’s BroadSpec™ Model 102 antenna. This antenna has a radiation efficiency better than 90% from 1.5 GHz to above 6.0 GHz.

2. UWB RADIATION EFFICIENCY

The “Wheeler Cap” method to evaluate antenna radiation efficiency was devised by H. A. Wheeler in the 1950’s, and has been revisited many times since then [3-5]. This technique compares the reflection coefficient of an antenna in free space (S_{11FS}) to the reflection coefficient (S_{11WC}) with the antenna placed in a “Wheeler Cap.” A Wheeler Cap is a closed conducting shell (or cap if the antenna is a monopole) with radius $r \approx \frac{\lambda}{2\pi}$ at the frequency of interest (see Figure 1).

A cylindrical geometry is sometimes used, but ideally, the Wheeler Cap should be a closed spherical

conducting shell with the antenna centered at the origin. This places the Wheeler cap at the surface on which the reactive and radiation field components are equal in magnitude: where radiated energy decouples from the near or reactive fields. Thus, the Wheeler Cap inhibits radiation without significantly influencing the reactive fields.

The difficulty with the Wheeler Cap method is that the size of the Wheeler Cap depends on the particular frequency of interest. The original Wheeler Cap method is thus not suitable for use with UWB antennas. Attempts have been made to modify the Wheeler Cap method for more broadband application, but these attempts rely on a significant amount of adjustment and tweaking to gather data at each frequency [6].

Recently, however, a new method has been developed for evaluating UWB antenna efficiency [7]. Instead of a closed spherical shell of radius $r \approx \frac{\lambda}{2\pi}$ at the frequency of interest, the “UWB Wheeler Cap” method uses a much larger spherical shell. Rather than inhibiting radiation from the antenna, the UWB Wheeler Cap allows the antenna to radiate freely, and then receive its own transmitted, reflected signal (see Figure 2).

The power budget for a transmit antenna may be expressed in terms of power fractions. A fraction of the incident energy is dissipated in losses ($\ell \equiv \frac{P_{loss}}{P_{in}}$), a fraction is reflected away due to mismatch ($m \equiv \frac{P_{reflected}}{P_{in}}$), and a fraction is radiated ($\eta \equiv \frac{P_{rad}}{P_{in}}$). Averaging over a suitable time interval and applying conservation of energy yields:

$$\ell + m + \eta = 1. \quad (3)$$

A number of interesting phenomena are manifest in the UWB Wheeler cap. The spherical shell surrounding the antenna under test enforces a near ideal time reversal of the transmitted signal. Thus the antenna receives the reflected signal with negligible structural scattering, and the antenna mode scattering term will be simply the mismatch fraction ($m = |S_{11-FS}|^2$). The receive and transmit efficiencies (η) are identical by reciprocity (see Figure 3). Of course, the transmit and receive antenna of Figure 3 are the same antenna operating in both a transmit and receive mode. The power fraction budget for the antenna is shown in Figure 4.

The scattering coefficient inside the UWB Wheeler Cap becomes:

$$\begin{aligned} |S_{11-WC}|^2 &= m + \eta^2 + \eta^2 m^1 + \eta^2 m^2 + \eta^2 m^3 + \dots \\ &= |S_{11-FS}|^2 + \eta^2 \sum_{n=0}^{\infty} |S_{11-FS}|^{2n} \\ &= |S_{11-FS}|^2 + \eta^2 \frac{1}{1 - |S_{11-FS}|^2} \end{aligned} \quad (4)$$

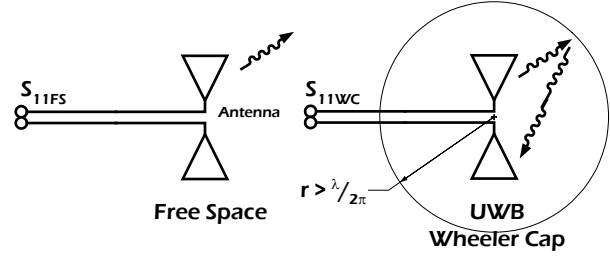


Fig. 2: A “UWB Wheeler Cap,” sized to be larger than the radiansphere dimension of the traditional Wheeler Cap. Instead of inhibiting radiation, a UWB Wheeler Cap allows the antenna to transmit and receive the reflected signal.

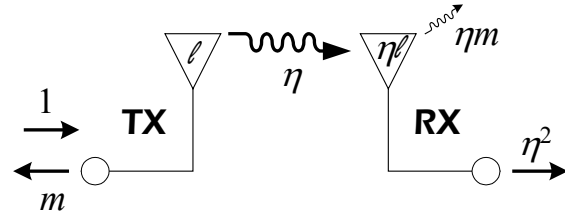


Fig. 3: Power budget for a TX-RX pair if all the transmitted power is available at the receive antenna.

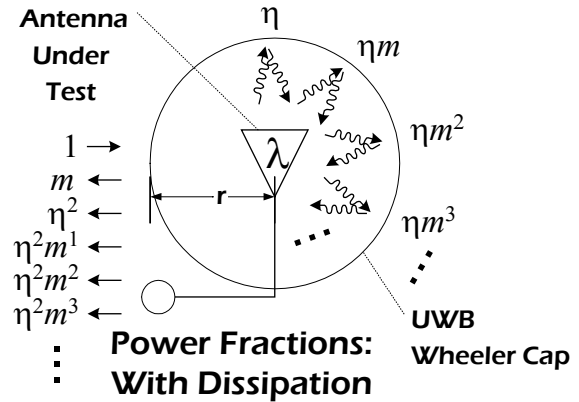


Fig. 4: Power fractions in a UWB Wheeler Cap assuming dissipation in the antenna.

which solves to yield the following result for the radiation efficiency:

$$\eta = \sqrt{(1 - |S_{11-FS}|^2)(|S_{11-WC}|^2 - |S_{11-FS}|^2)}. \quad (5)$$

This approach assumes that the various reflections inside the UWB Wheeler Cap are orthogonal to each other. This is a valid assumption provided the characteristic time required by the antenna to radiate or receive a signal is less than the time delay between transmission and reflection (in the case of a 30 cm diameter sphere, about 1 ns). The Wheeler Cap and experimental setup are shown in Figure 5a.

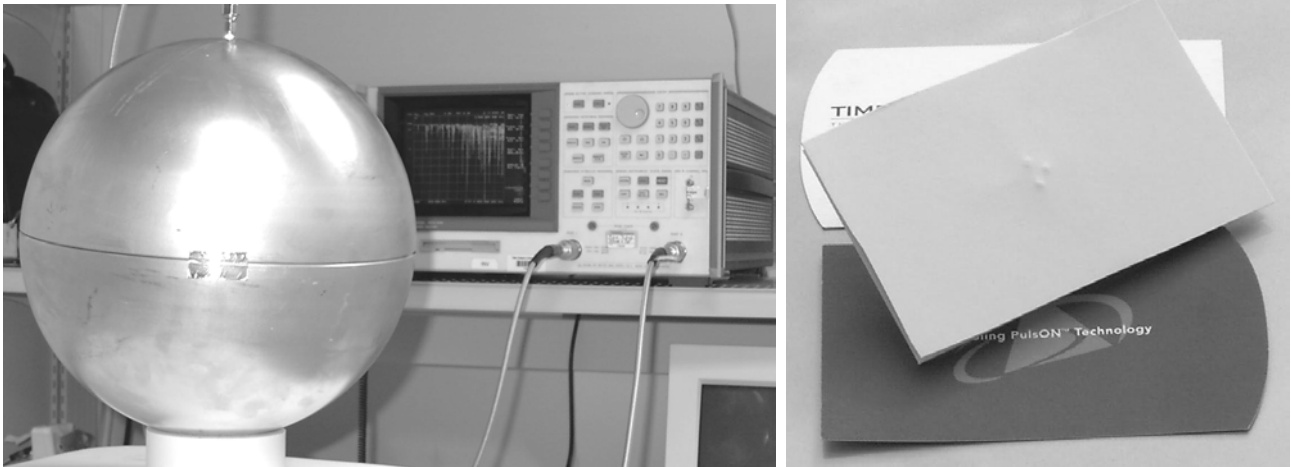


Fig. 5a (left): A 30 cm (1 ft) diameter UWB Wheeler Cap probed by an HP 8753D network analyzer.
Fig. 5b (right): Prototype BroadSpec™ 102 antenna. This UWB planar antenna is smaller than a standard business card, yet is a highly efficient radiator and receiver of UWB energy above 1.5 GHz.

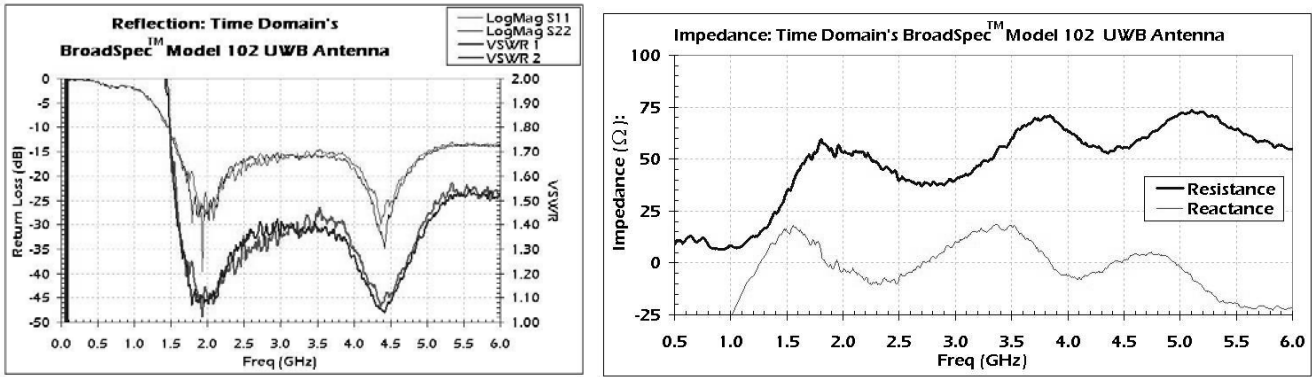


Fig. 6a (left): The BroadSpec™ 102 antenna is well matched as seen in these measurements on a matched pair. Maximum return loss is about -15 dB in the 1.7-4.5 GHz operating band.
Fig. 6b (right): This excellent matching is achieved from a near perfect $50 + j0 \Omega$ impedance in the 1.7-4.5 GHz operating band.

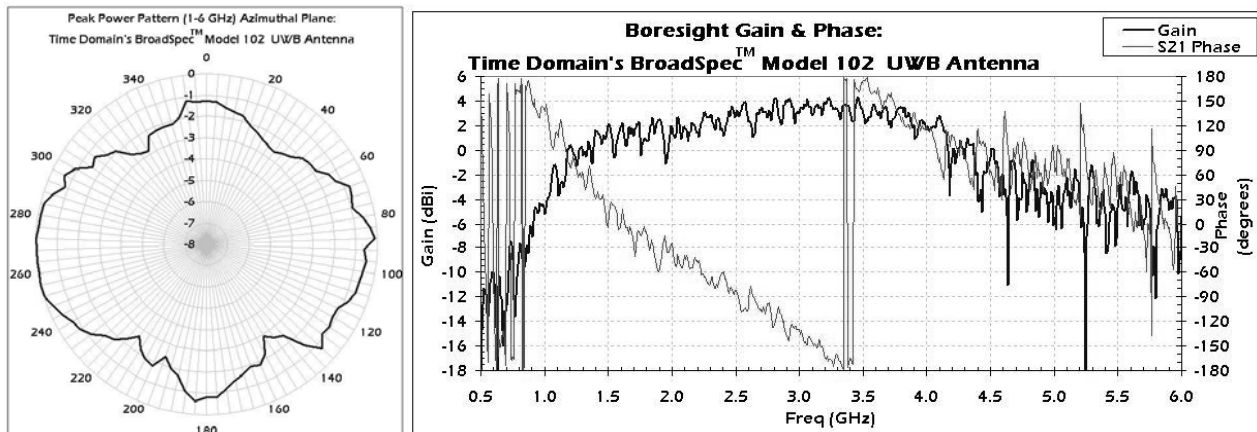


Fig. 7a (left): Peak power pattern of the BroadSpec™ 102 antenna at 3 GHz. This antenna has a dipole-like pattern with gain 0-3 dBi in the azimuthal plane.
Fig. 7b (right): Bore-sight gain and phase response of the BroadSpec™ 102 antenna. Bore-sight gain is nominally about +2 dBi and the phase response is very linear.

3. BROADSPEC 102 ANTENNA

The BroadSpec™ 102 antenna is a UWB planar dipole antenna (see Figure 5b). Smaller than a standard business card, this antenna is well matched from 1.7–4.5 GHz (see Figure 6a). The maximum return loss is about –15 dB in the 1.7–4.5 GHz operating band, and the VSWR is comfortably below 1.5:1.

The design does not employ resistive loading or lossy materials. Instead, careful element shaping holds the impedance at $50 + j0 \Omega$ to yield this excellent matching (see Figure 6b).

The antenna has a dipole-like pattern with gain between 0-3 dBi in the aximuthal plane. A peak power pattern is shown in Figure 8a. The boresight gain and phase response are shown in Figure 8b. The boresight gain is nominally about +2 dBi, and the phase response is linear as is preferred for distortionless transmission of pulses.

4. BROADSPEC 102 EFFICIENCY

UWB antennas are often resistively loaded to improve their impedance matching and reduce their reflection. This resistive loading introduces loss to the antenna and impairs radiation efficiency. A typical resistively loaded antenna will be no more than 50% efficient. The BroadSpec™ 102 antenna does not use resistive loading and thus achieves a remarkably high radiation efficiency. The antenna is fabricated from a high quality woven glass reinforced ceramic substrate: Rogers RO4003. This substrate has excellent high frequency performance and very little loss.

The results of the efficiency measurement are shown in Figure 8. At certain frequencies, spherical resonant modes are excited. These modes couple very strongly and tend to be dissipated in the cavity. This behavior manifests itself as sharp, narrowband decreases in measured antenna efficiency. The raw data has thus been smoothed by taking the largest value for the efficiency over an 80 MHz span. This yielded the “smoothed efficiency” result from the raw measurements.

The BroadSpec™ 102 antenna is a highly efficient radiator and receiver of UWB energy, exhibiting an efficiency of better than 90% from 1.5 GHz to above 6.0 GHz.

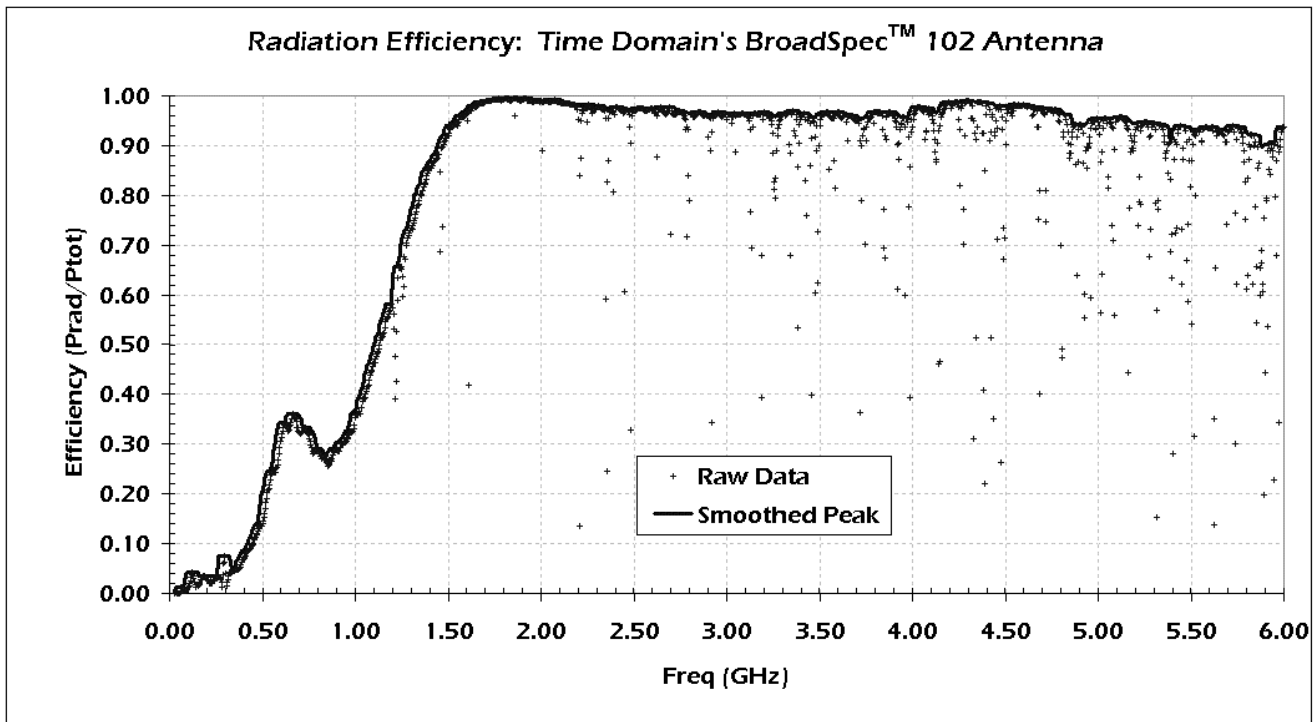


Fig. 8: Efficiency of the BroadSpec™ 102 antenna. This antenna has an efficiency better than 90% above 1.5 GHz.

5. CONCLUSION

The average transmit power of a typical commercial UWB system is on the order of a few tens of microwatts. These low power levels place a premium on radiating and receiving UWB signals with high efficiency. Designing a UWB antenna that combines good matching, and high efficiency can be a significant challenge.

A key element in meeting this challenge is the ability to assess the efficiency of prototype antennas. The techniques described in this paper extend the traditional Wheeler Cap method to allow evaluation of UWB antennas. Application of these techniques demonstrates that the Time Domain BroadSpec™ 102 antenna is a highly efficient UWB antenna.

6. REFERENCES

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