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Analysis, Design and Realization of a Near-Field Focused RF Power Transfer System

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Abstract. This paper reports the analysis, design, prototyping and first measurement results of a linear array antenna consisting of Yagi-Uda elements, rotated and phased for focusing RF power in the near-field of the antenna. By employing Near Field Focusing more power may be transmitted before the EIRP limit is reached due to the inherent far-field difusing. A design based on four Yagi-Uda array elements is able to produce an average power density of 21.04dBm/m^2 at 2.45GHz in a box of 10x10x10cm^3 located 1m from the linear array face. The design has been verified through comparison with full-wave electromagnetic simulations. First measurements on a realized prototype confirm the functioning of the array.

1. Introduction

This paper describes the analysis, design and realization of a wireless energy transfer system that can be used for, e.g. remotely charging batteries at distances bridging about one to two meters (desk size). Since inductive [1] or non-radiative, resonant magnetic coupling [2] would require very large transmitting and receiving coils (diameters in the order of the distance to be bridged), we choose for radiative coupling. The system will be employed in the license-free 2.4 GHz Industry, Science and Medical (ISM) frequency band. Since in the ISM bands the allowed Effective Isotropic Radiated Power (EIRP) - i.e. the transmit power times the transmit antenna gain – is limited, the collection in the far-field of a few milliwatts DC-power will limit the bridging range to far below one meter. From the Friis transmission equation [3] it follows, for example, that a power density of 20dBm/m^2 at 2.45GHz, using an EIRP of 0.5W is obtained at a distance of 0.63m from the transmit antenna.

To overcome this distance-restriction we make use of the fact that EIRP is a parameter defined in the far-field of an antenna. By focusing the RF power in the near-field of a transmit antenna, the far-field of that antenna will diffuse and lead to a lower EIRP then when focused for the far-field. Thus, more power may be transmitted before reaching the EIRP limit. For focusing the RF power we use an array antenna and apply phase-shifts between the radiating elements to compensate for the different path lengths from the elements to the focal point.

In the following we will describe the basic theory of Near Field Focusing (NFF), the obtainable results and limitations and ways to overcome some of these limitations. Then we will discuss a linear NFF array design and will discuss measurement results.

2. NFF theory

For reasons of space reduction, we will work towards the design of a linear array. Figure 1 shows part a linear array antenna, positioned in the *xy*-plane of a rectangular coordinate system.

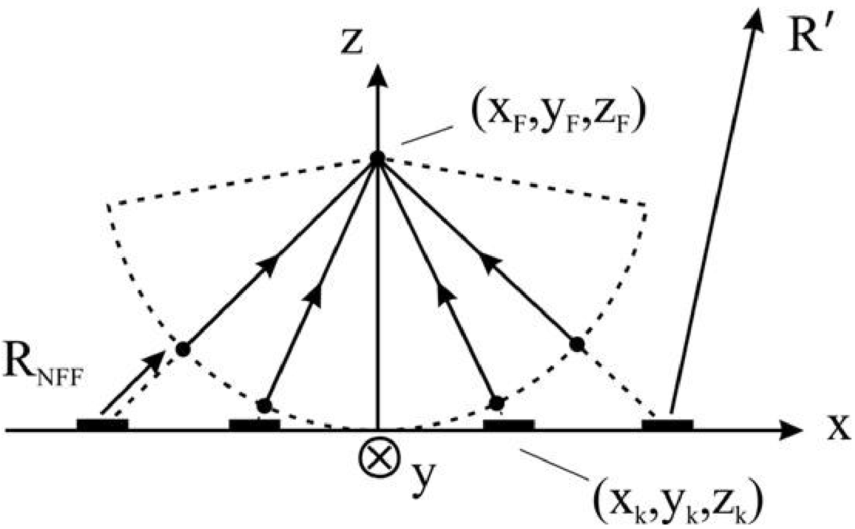

Fig. 1 – *Part of a linear array antenna to be focused at (x_F,y_F,z_F).*

The required phase shift for an element k for focusing the power (adding the signals in-phase) in the focal point (x_F,y_F,z_F) is given by [4]

$$\varphi_k = kR_{NFF_k} = \frac{2\pi}{\lambda}\left[\sqrt{(x_k - x_F)^2 + (y_k - y_F)^2 + (z_k - z_F)^2} - \sqrt{x_F^2 + y_F^2 + z_F^2}\right]. \tag{1}$$

The electric field at any position (x,y,z) in the far-field region of the individual (N) array elements is given by

$$\vec{E}(x,y,z) = \sum_{k=1}^{N} \frac{\vec{E}_k(\vartheta_k, \varphi_k)}{4\pi R'} e^{-jk\left(R_{NFF_k} - R'\right)}, \tag{2}$$

where (θ_k,φ_k) describes the local orientation of the element and where

$$R' = \sqrt{(x - x_k)^2 + (y - y_k)^2 + (z - z_k)^2}\ . \tag{3}$$

A similar expression may be derived for the magnetic field and the time averaged power density is then obtained from the vector (cross) product of the electric field and the complex conjugate of the magnetic field.

3. NFF analysis results

An example of the possibilities of NFF for a (0.5W) EIRP limited system consisting of a linear array of eight short dipoles, spaced apart one wavelength, is shown in Figure 2 for a frequency of 2.45GHz. Figure 2(a) shows that the power density around the focal spot at z=1m, produced by the NFF array is 5.5dB higher than that of a single element. The Figure also shows that that in this case the array antenna focused at infinity underperforms by -11dB compared to a single element. Figure 2(b) Shows the power density at a distance z=1m parallel to the face of the array. Figure 2(c) shows that the normalized far-field power density of a near-field-focused array is more diffuse than that of an array focused at infinity, leading to a lower directivity and thus allowing to transmit more power before the EIRP limit is reached.

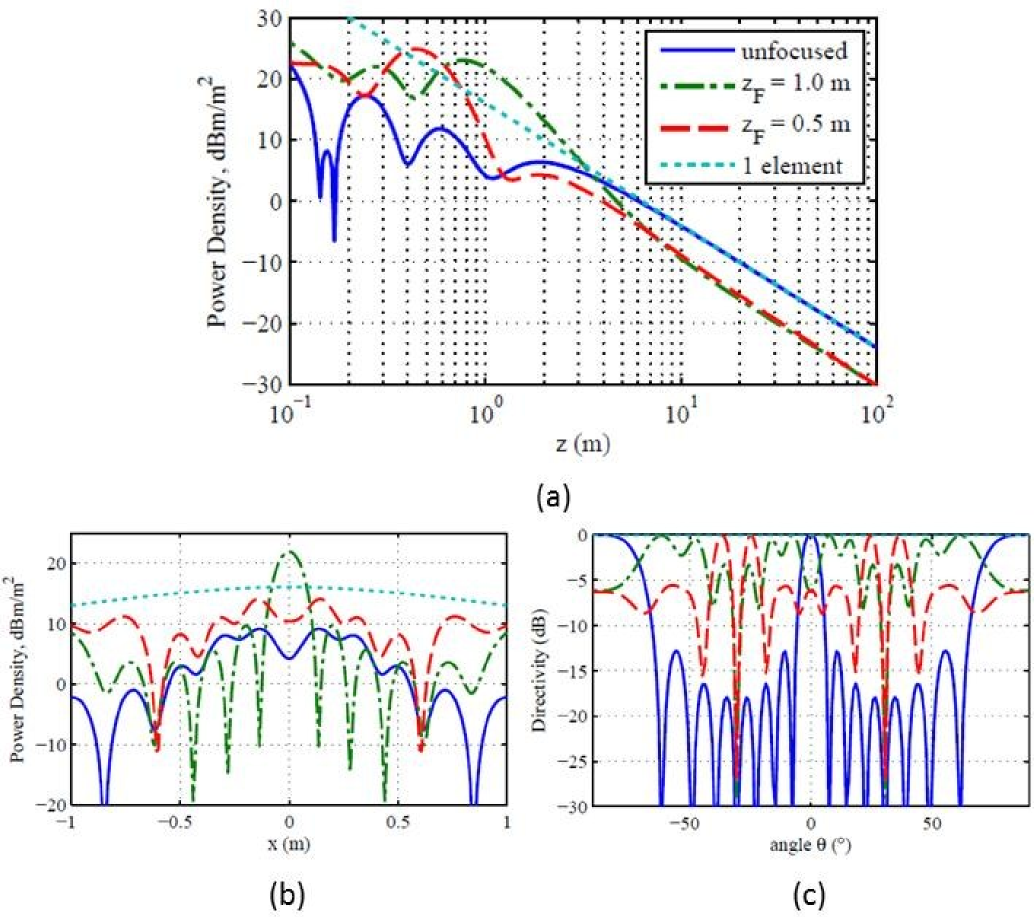

Fig. 2 – *Power densities along the axis perpendicular to the array face (a), parallel to the array face at a distance z=1m (b) and the normalized far-field in the xz-plane (c).*

For practical applications we do not need a sharp focal point but rather a focal area or volume in which a desired power density level can be guaranteed. Figure 3 shows the variation in power density averaged over a volume of 10x10x10cm^3 centered around z=1m for an eight-elements linear short-dipole array having different uniform element spacings.

4. Improvements

Although the results obtained with a 'standard' NFF array (employing realistic radiating elements) are satisfactory, we have been looking for ways to increase the focused power level. Several of the investigated methods, like amplitude tapering, the creation of multiple focal points, employment of orthogonal polarizations, employment of non-planar arrays resulted in the proposal to employ *rotated, highly directive array elements*.

The principle of this technique is shown in Figure 4. The antenna-elements are mechanically rotated towards a distance z_{rot}. The focal area is concentrated around z_F (z_F>z_{rot}). For a four-elements array consisting of 11.8dBi-gain Yagi-Uda elements, spaced 1.8 wavelengths apart, z_{rot} being 0.4m and z_F being 0.8m, the average power density in a 10x10x10cm^3 box is found to be 21.04dBm/m^2, see Figure 5. For the array focused at infinity this value is 10.8dB lower. For a single (Yagi-Uda) element the value is 5.04dB lower. The transmitted power for the focused array antenna is 46mW.

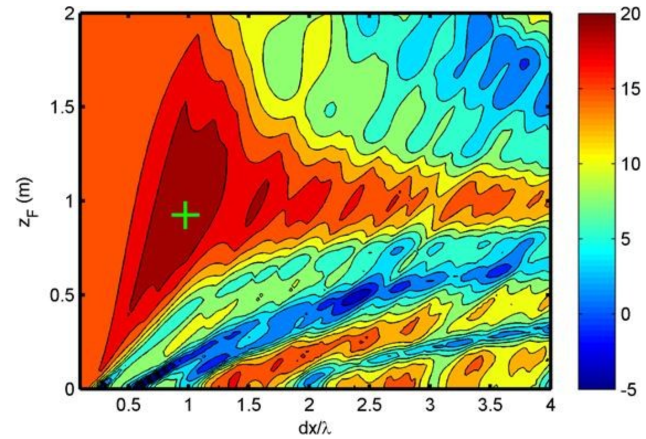

Fig. 3 – *Contourplot of the average power density in dBm/m² in a box of 10x10x10cm³ centered around z=1m for varying inter-element distance and focus distance. The array consists of eight short dipole elements. The green cross designates the maximum power density..*

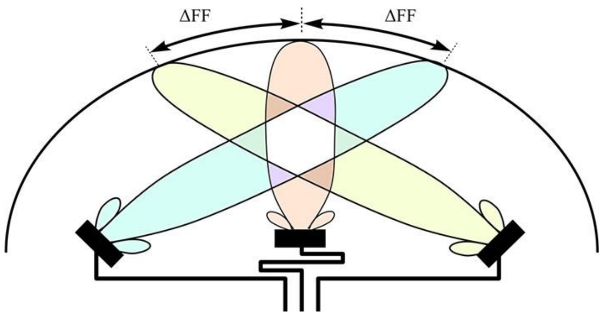

Fig. 4 – *Schematic of the rotated highly directive antenna elements. The power density increases in the target region, while simultaneously the far-field is difused.*

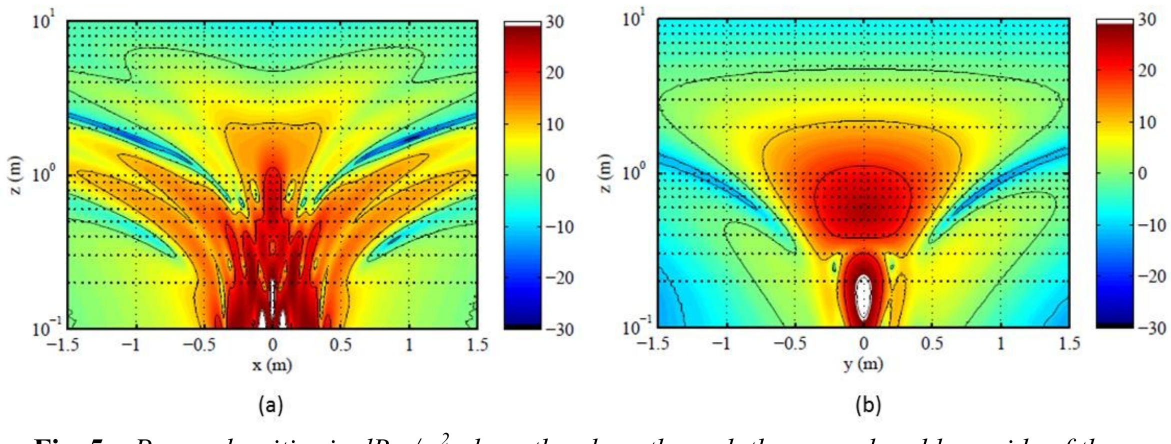

Fig. 5 – *Power densities in dBm/m² along the plane through the normal and long side of the array, i.e. the E-plane (a) and the plane through the normal and short side of the array, i.e. the H-plane (b).*

5. First measurements

The results for the array as shown in Figure 5 have been verified for several cuts through these figures with full-wave simulation results (CST Microwave Studio®). Finally, a prototype has been hand-made as shown in Figure 6. The Yagi-Uda radiating elements have been made out of copper strips on a High Impact Polystyrene (HIPS) substrate. The same substrate material has been used to create microstrip phase shifting elements for exciting the array elements.

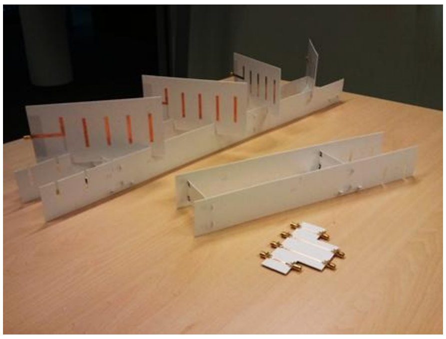

Fig. 6 – *Prototype NFF array with phase shifter elements. Feeding network not shown.*

Figure 7 shows the simulation results for the power density in the horizontal plane (corrected for the measured phase errors in the feeding) (a) and the *relative* power density measurements sampled in a number of regions in front of the antenna (b).

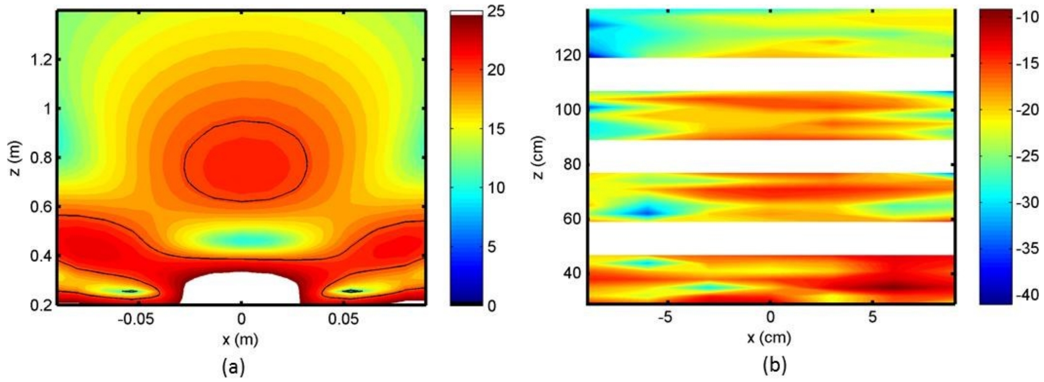

Fig. 7 – *Simulated (a) and measured power density (b).*

Given the limitations in the measurement setup, the measured results show an acceptable agreement with simulations.

6. Conclusion

Through near-field focusing, employing a (linear) array antenna, more power can be transferred over intermediate distances than will be possible by RF far-field power transfer when obeying the limitations in allowed EIRP. NFF array antenna optimization is currently going on.

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