Optimal Aperture Distribution of Near-Field Antennas for Maximum Signal Penetration

(article starts on next page)

Optimal Aperture Distribution of Near-Field Antennas for Maximum Signal Penetration

Aidin Razavi, Jian Yang and Tomas McKelvey
Dept. of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden
aidin.razavi@chalmers.se; jian.yang@chalmers.se; tomas.mckelvey@chalmers.se

***Abstract*—We present an investigation on the optimal aperture, both its size and current source distribution, for the maximum penetration of signals in near-field applications. The near-field beam radius is calculated for different size of the uniform Huygen's source distribution so that the optimal size of a uniform Huygen aperture is concluded. For a general aperture distribution, both analytical methods and optimization algorithm are applied.**

***Index Terms*—optimal near-field aperture, near-field beam radius, maximum penetration**

I. Introduction

Near-field microwave systems for detection and sensing find more and more applications in recent years [1]–[6]. However, how to characterize antennas in near-field is not well established as that in far-field case, and the question of what is the optimal antenna for a certain near-field application has not been addressed.

Efforts have been made to characterize antennas in near-field by the Penetration Ability [7] which is highly correlated to how much the propagated waves from the transmit antenna focus on the receive antenna in near-field. In this work, we aim to find an optimum aperture, in terms of both the size and the current distribution, in order to achieve the maximum signal penetration in near-field. In this study, a circular aperture with a Huygen's source distribution in a homogenous lossy material background is assumed, since the Huygen's source has a directional radiation.

A characterization parameter, the 3dB near-field beam radius, is used to quantify how signals focus. It is proposed from the results of this work that in order to get a high penetration ability, both the size and the aperture distribution of an antenna should be chosen depending on the spacing between the transmit and receive antennas.

II. Problem Formulation

Assume a y-polarized Huygen's source distribution over a circular aperture of radius a, where the current has only radial dependence (i.e. it is independent of angle). This circular aperture is shown in Fig. 1. The current distribution on the aperture is given by

$$\begin{aligned} \mathbf{J}_H(\rho') &= J(\rho')\widehat{\mathbf{y}} \\ \mathbf{M}_H(\rho') &= \eta J(\rho')(-\widehat{\mathbf{x}}) \end{aligned} \tag{1}$$

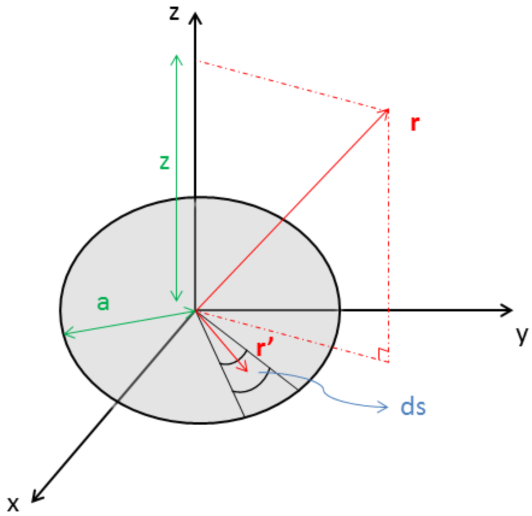

Fig. 1: The geometry of circular aperture.

The total electrical field caused by such aperture at any point in positive-z half-space can be calculated as [8]:

$$\begin{aligned} \mathbf{E}_{tot} &= \mathbf{E}_J + \mathbf{E}_M \\ &= C_k\eta \int_0^{2\pi}\int_0^{a} \Big[J(\rho')\,\hat{\mathbf{y}} C_{N1} - J(\rho') \left(\hat{\mathbf{y}}\cdot\hat{\mathbf{R}}\right)\hat{\mathbf{R}} C_{N2} \\ &\quad + J(\rho')\left(-\hat{\mathbf{x}}\times\hat{\mathbf{R}}\right) C_N \Big] \frac{e^{-jkR}}{R}\rho' d\rho' d\varphi' \end{aligned} \tag{2}$$

where $\mathbf{R} = \mathbf{r} - \mathbf{r}'$, η is the wave impedance, k is the wave number and

$$C_N = 1 + \frac{1}{jkR}, C_{N1} = 1 + \frac{1}{jkR} - \frac{1}{(kR)^2}$$
$$C_{N2} = 1 + \frac{3}{jkR} - \frac{3}{(kR)^2}, C_k = \frac{-jk}{4\pi}$$

III. Optimal Aperture Size with Uniform Distribution

It has already been observed in [7] that larger antenna does not necessarily lead to higher penetration in near-field. On the other hand, an antenna of a small size transmits RF signals into wider area, which leads to a lower penetration. Hence determining the optimum size of an antenna for the maximum

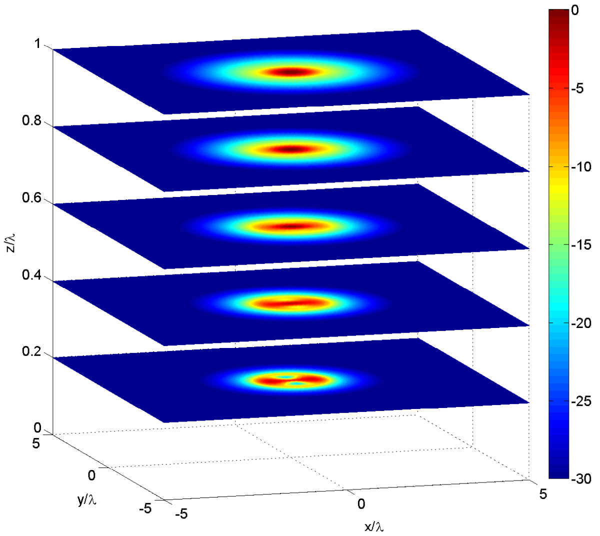

Fig. 2: Near-field co-polar component of a uniform aperture $a = \lambda$.

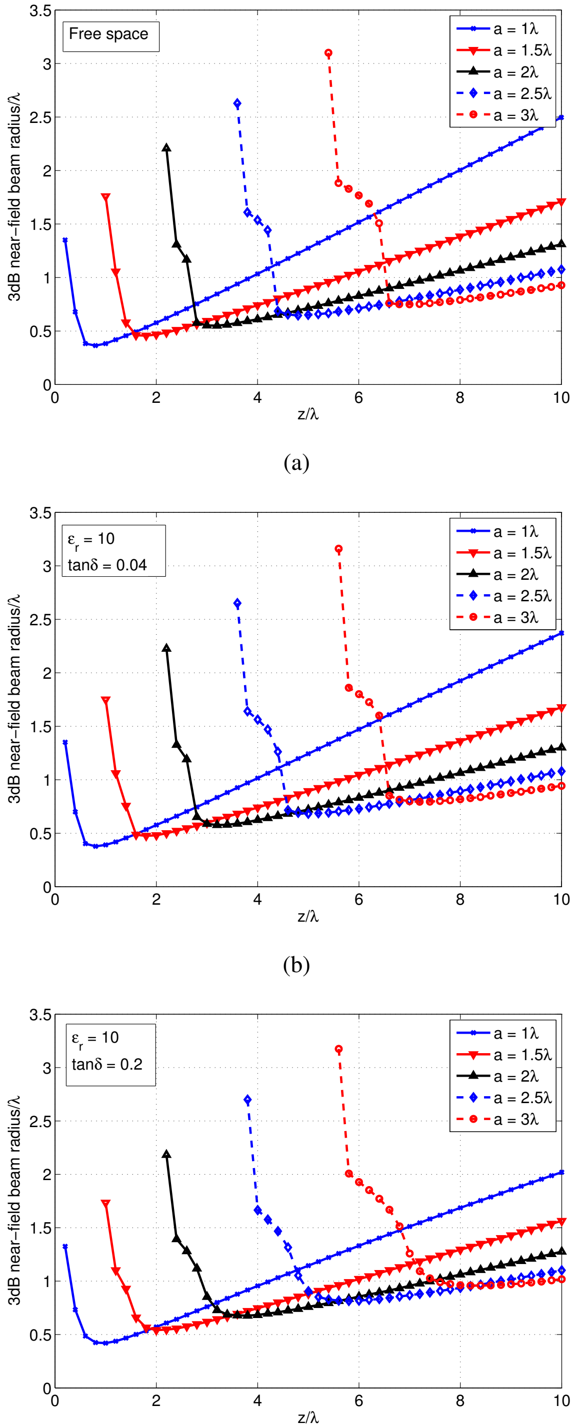

Fig. 3: 3dB near-field beam radius of a uniform aperture in different mediums (a) Free space (b) $\epsilon_r = 10$, $tan\delta = 0.04$ (c) $\epsilon_r = 10$, $tan\delta = 0.2$

penetration at certain distance in near-field is crucial for near-field antenna design.

As the first step, the optimal circular aperture size with uniform current distribution is investigated. It is assumed that the lossy material has a linear ohmic loss effect on the signal. Therefore, a high penetration ability at a certain distance is proportional to how much the signal is focused at that distance. In other words, the narrower near-field beam radius at a certain distance means the higher penetration ability at that distance.

Simulations are carried out by using (2) to calculate the near-field of a number of circular apertures with radii starting from one wavelength λ (the results up to three wavelengths are shown in this paper). Co-polar field component of each aperture is calculated at distances of 0.2–10 λ from aperture with steps of 0.2 λ, on square planes with dimensions $10\lambda \times 10\lambda$.

A sample of results for case of aperture with radius equal to $a = \lambda$ is shown in Fig. 2. In order to characterize the energy focusing ability at each cutting plane orthogonal to the propagation direction, the **3dB near-field beam radius** at a certain cutting plane is defined as the radius of the smallest circle on that plane, with its center at the maximum field strength point, including all points where co-polar component of the field has at least half the power of the maximum point on the same cut. Note that unlike far-field beam width which has the unit of angle, the 3dB near-field beam radius is measured in a unit of length, such as millimeter or wavelength, since the angle unit has not much meaning in our case. Note also that we use “beam” in the definition though there is no beam really formed in the near-field of antennas.

Fig. 3 shows the 3dB near-field beam radius when the circular aperture has different radius from 1λ to 3λ when the space is filled homogenously with three different materials. The material properties are set as i) free space, ii) $\epsilon_r = 10$, $tan\delta = 0.04$ and iii) $\epsilon_r = 10$, $tan\delta = 0.2$. It is observed that for a certain size of aperture there is a certain distance

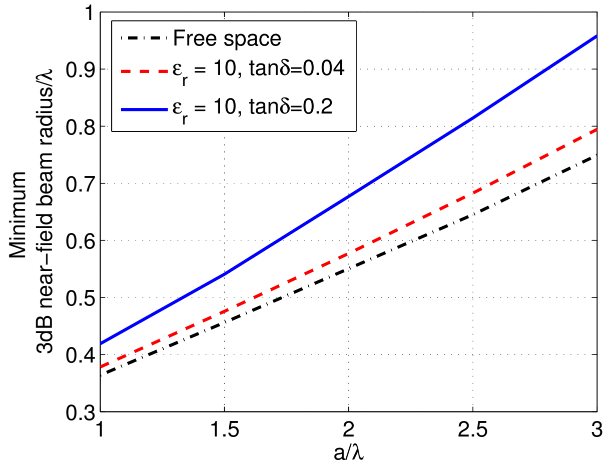

Fig. 4: Minimum 3dB beam radius vs. aperture radius.

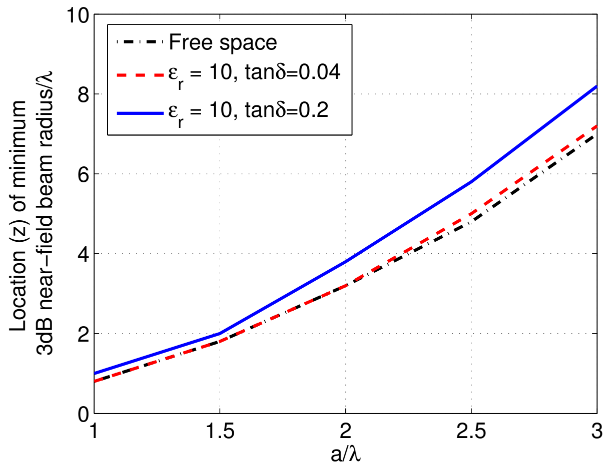

Fig. 5: Distance of the minimum 3dB near-field beam radius from the aperture vs. aperture radius.

where the 3dB near-field beam radius is minimum, and this minimum-3dB-radius distance increases with increase in the aperture radius. It is also observed that the minimum beam radius itself increases with the increase in aperture size. Plots of minimum beam radius, and the distance of minimum beam radius from the aperture in different mediums are shown in Figs.4 and 5, respectively. It is clear in the figures that the loss in medium will increase the minimum beam radius and push it further from the aperture. On the other hand, it is evident that the loss will affect larger apertures more.

IV. Desired Aperture Distribution

For a more general case, the optimal aperture (in terms of both the size and the distribution) for the maximum penetration is investigated by two approaches: optimization and direct solving.

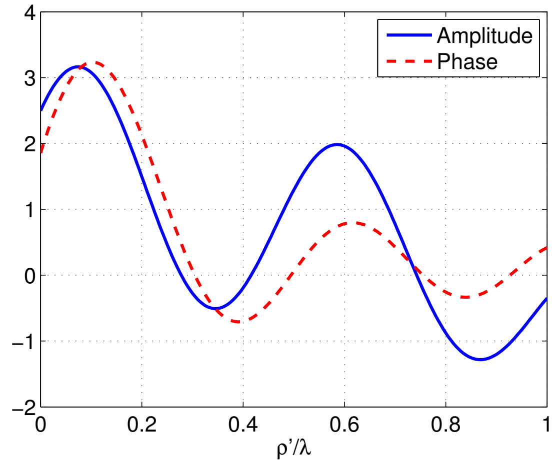

Fig. 6: Amplitude and phase of current distribution from GA.

A. *Optimization*

Global optimization algorithms (such as Genetic Algorithm, Particle Swarm, Pattern Search, etc.) are widely used in electromagnetic problems. Genetic algorithm (GA) is applied to find the optimal aperture distribution in this work.

To find the optimal aperture in this case, it is assumed that the aperture radius is fixed and only the distribution is optimized. For different aperture distributions of the same radius, 3dB near-field beam radius is calculated at a range of distances. This range is selected around expected best focus distance from the case of uniform aperture. Then, the minimum 3dB near-field beam radius in this range is selected as the fitness function which will be minimized by the means of GA. As for parameter to be tuned, low-order Fourier coefficients of current distribution are chosen. The purpose of this choice is to ensure the continuity and smoothness of resulting distribution.

A sample of GA results, by using the above assumptions is presented here, for an aperture of radius equal to one wavelength (i.e. $a = \lambda$) in free space. In this case a population of 20 genes is used and the algorithm converges after 51 generations. The amplitude and phase of resulting current distribution is shown in Fig. 6. Near-field co-polar component produced by such distribution is demonstrated in Fig. 7 at distances between 0.4λ and 0.8λ, also the 3dB near-field beam radius of this current distribution is plotted in Fig. 8.

It can be observed in Fig. 8 that although the distance of minimum near-field beam radius has moved closer to the aperture in this case compared to a uniform aperture with the same size, the minimum beam radius itself is significantly smaller than that of uniform aperture. Even at the distance where uniform aperture has minimum beam radius, though the beam radius there is not the minimum, the radius is still smaller compared to uniform aperture at the same distance. It can be concluded that GA can be used to minimize the near-field beam radius. It should be noted again that the uniform

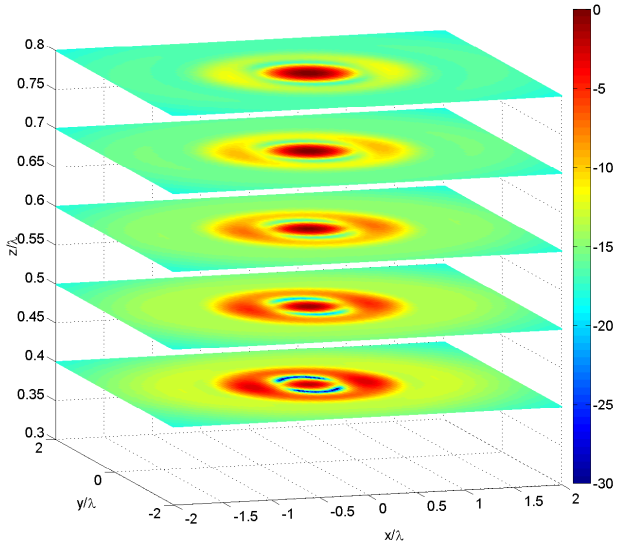

Fig. 7: Near-field co-polar component of GA optimized aperture.

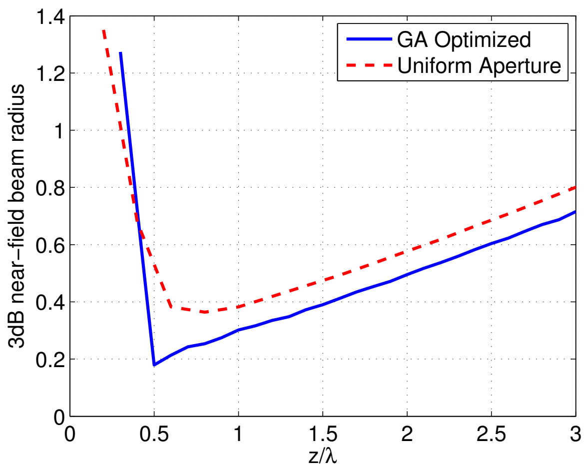

Fig. 8: 3dB near-field beam radius of GA optimized aperture.

aperture does not necessarily result in optimal beam radius but it can be considered as a reference point.

B. Direct Solving

Due to the linear nature of the problem, it is also possible to solve directly for the aperture distribution to have a desired field distribution at one or more z-cuts in the space. In order to do this, following approach is adopted.

First, a discrete aperture distribution $J_{dis}(\rho)$ and a desired field $\mathbf{E}_{\text{goal}}$ are selected.

$$J\left(\rho'\right) \approx J_{dis}\left(\rho'\right) = \sum_{n=1}^{N} J_n \psi_n\left(\rho'\right) \tag{3}$$

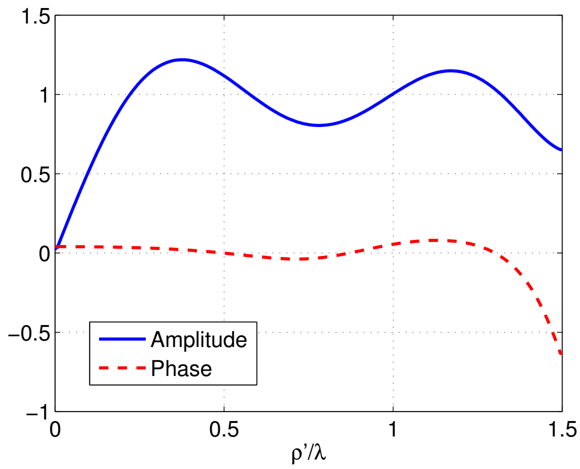

Fig. 9: Calculated amplitude and phase of current distribution by using the direct solving method.

where ψ_n are properly chosen basis functions. Then

$$\mathbf{E}_{\text{dis}} = C_k \eta \sum_{n=1}^{N} J_n \iint_{S'} \mathbf{V} \psi_n \frac{e^{-jkR}}{R} \rho' d\rho' d\varphi' \tag{4}$$

where

$$\mathbf{V} = \hat{\mathbf{y}} C_{N1} - \left(\hat{\mathbf{y}} \cdot \hat{\mathbf{R}}\right) \hat{\mathbf{R}} C_{N2} + \left(-\hat{\mathbf{x}} \times \hat{\mathbf{R}}\right) C_N \tag{5}$$

By selecting appropriate weighting functions (w_m), the equations can be solved for J_n as follows:

$$\iint_S w_m\left(\mathbf{r}\right)\left[\mathbf{E}_{\text{dis}} - \mathbf{E}_{\text{goal}}\right] ds = 0 \tag{6}$$

which is expanded as

$$\begin{aligned} \iint_S w_m \left[C_k \eta \sum_{n=1}^{N} J_n \iint_{S'} \mathbf{V} \psi_n \frac{e^{-jkR}}{R} \rho' d\rho' d\varphi' \right] ds \\ = \iint_S w_m \mathbf{E}_{goal} ds \end{aligned} \tag{7}$$

This final equation can easily be re-written in matrix form and solved for J_n.

To utilize this method an exact knowledge of both amplitude and phase of the desired field distribution is needed, which is not always the case. However to demonstrate the possibility, an example will be presented, where the field produced by an already known aperture distribution is used as the desired field.

Co-polar field component produced by a uniform aperture of radius $a = 1.5\lambda$ at a distance $z = \lambda$ is calculated and used as the desired field $\mathbf{E}_{\text{goal}}$. Step functions are used as basis ψ_n and Dirac delta functions are used as weighting w_m to facilitate point matching. In this case the matrix of the problem is highly ill-conditioned. However, by employing singular

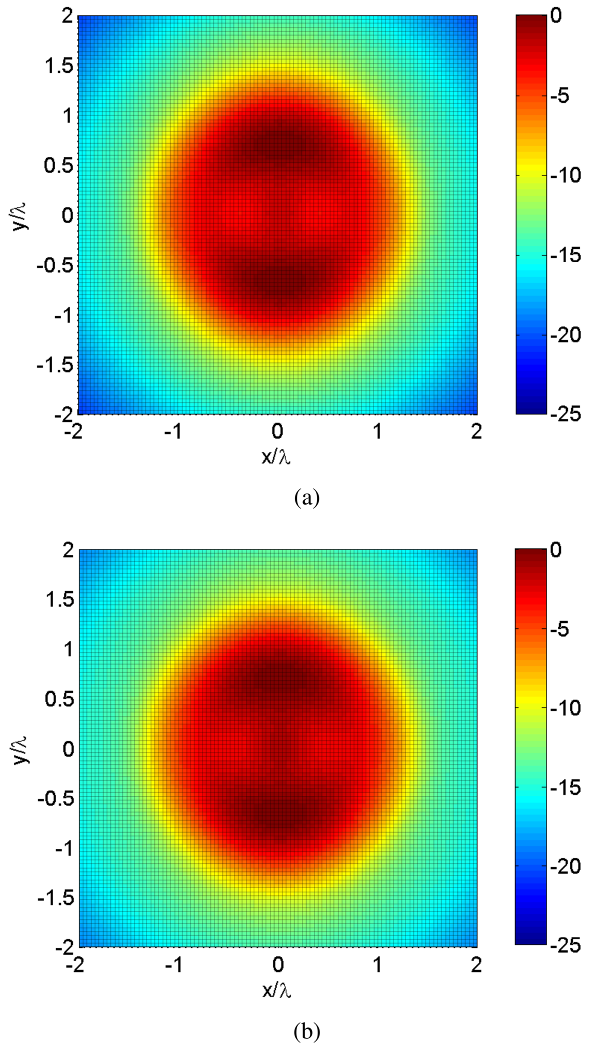

Fig. 10: Near-field co-polar distribution produced by (a) Uniform distribution (b) Current distribution calculated by direct solving

value decomposition and the use of pseudo inverse [9], some interesting results can be achieved. For example if only 4 highest singular values are used, the calculated amplitude and phase of resulting current distribution will be as shown in Fig. 9. It can be observed that the calculated current is quite close to the original uniform distribution. The field produced by uniform distribution and that produced by this distribution are shown in fig. 10. It can be observed that the two have a good agreement and indeed the error in dB is less than 1.8dB everywhere while comparing the field distributions, and the error in 3dB near-field beam radius is negligible. These results display that it is feasible to use the direct solving method in cases where the desired field is known. More investigation on this method is ongoing.

V. Conclusion

It has been shown that the optimal aperture size for near-field sensing applications depends on the spacing between the transmit and the receive antennas and the material properties of the medium between the two, as the minimum near-field beam radius varies with both aperture size and loss for a uniform aperture distribution. For a more general case, the optimal aperture can be determined by two approaches: optimization algorithms and direct solving. The optimization algorithms are more useful when just the 3dB near-field beam radius is required to be small and there is no restriction on the actual field distribution. On the other hand, direct solving method can be used in cases where the field distribution also matters for the specific application.

Acknowledgement

This work has been supported by a Swedish Research Council VR frame project.

We would like to express our appreciation to Profs. Per-Simon Kildal and Thomas Rylander for their comments and discussions on this work.

References

[1] X. Li, E. Bond, B. Van Veen, and S. Hagness, "An overview of ultra-wideband microwave imaging via space-time beamforming for early-stage breast-cancer detection," *IEEE Antennas and Propagation Magazine*, vol. 47, no. 1, pp. 19–34, 2005.

[2] J. Yang and A. Kishk, "A novel low-profile compact directional ultra-wideband antenna: the self-grounded bow-tie antenna," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 3, pp. 1214–1220, 2012.

[3] S. Abtahi, J. Yang, and S. Kidborg, "A new compact multiband antenna for stroke diagnosis system over 0.5–3 GHz," *Microwave and Optical Technology Letters*, vol. 54, no. 10, pp. 2342–2346, 2012.

[4] Y. Yu, J. Yang, T. McKelvey, and B. Stoew, "A compact UWB indoor and through-wall radar with precise ranging and tracking," *International Journal of Antennas and Propagation*, vol. 2012, 2012.

[5] S. Fayazi, H. Lui, and J. Yang, "Microwave imaging of near-field object using ultra-wideband synthetic aperture radar algorithm," in *2012 IEEE Antennas and Propagation Society International Symposium (APSURSI)*. IEEE, 2012, pp. 1–2.

[6] S. Fayazi, J. Yang, and H. Lui, "UWB SAR imaging of near-field object for industrial process applications," in *7th European Conference on Antennas and Propagation, (EuCAP 2013)*, Gothenburg, Sweden, 8-12 April 2013.

[7] A. Razavi and J. Yang, "Investigation of penetration ability of UWB antennas in near-field sensing applications." Prague, Czech Republic: 6th European Conference on Antennas and Propagation, (EuCAP 2012), March 2012.

[8] P.-S. Kildal, *Foundations of antennas: a unified approach*. Studentlitteratur, 2000.

[9] A. J. Laub, *Matrix Analysis for Scientists and Engineers*. Society for Industrial and Applied Mathematics, 2005.