

Northumbria Research Link

Citation: Fernando, Michael, Busawon, Krishna, Smith, Dave and Elsdon, Michael (2010) Fundamental issues in antenna design for microwave medical imaging applications. In: 7th International Symposium on Communication Systems Networks and Digital Signal processing (CSNDSP), 21-23 July 2010, Northumbria University, Newcastle upon Tyne.

URL:

This version was downloaded from Northumbria Research Link:
<https://nrl.northumbria.ac.uk/id/eprint/2688/>

Northumbria University has developed Northumbria Research Link (NRL) to enable users to access the University's research output. Copyright © and moral rights for items on NRL are retained by the individual author(s) and/or other copyright owners. Single copies of full items can be reproduced, displayed or performed, and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided the authors, title and full bibliographic details are given, as well as a hyperlink and/or URL to the original metadata page. The content must not be changed in any way. Full items must not be sold commercially in any format or medium without formal permission of the copyright holder. The full policy is available online: <http://nrl.northumbria.ac.uk/policies.html>

This document may differ from the final, published version of the research and has been made available online in accordance with publisher policies. To read and/or cite from the published version of the research, please visit the publisher's website (a subscription may be required.)

Fundamental Issues in Antenna design for Microwave Medical Imaging Applications

M. Fernando, K. Busawon, M Elsdon and D. Smith
School of Computing Engineering and Information Sciences,
Northumbria University, NE1 8ST, UK
e-mail: michael.fernando@northumbria.ac.uk

Abstract— This paper surveys the development of microwave medical imaging and the fundamental challenges associated with microwave antennas design for medical imaging applications. Different microwave antennas used in medical imaging applications such as monopoles, bow-tie, vivaldi and pyramidal horn antennas are discussed. The challenges faced when the latter used in medical imaging environment are detailed. The paper provides the possible solutions for the challenges at hand and also provides insight into the modelling work which will help the microwave engineering community to understand the behaviour of the microwave antennas in coupling media.

1. Introduction

Microwave imaging for medical application has been a subject of research for many years. In the last decade, however, there has been a renewed interest in the topic due to its viable and advantageous approach for many medical applications. Basically, microwave images are maps of electrical property distributions in the body. The changes in electrical property indicate the deposition of heat in the tissues [1]. Cancer detection using microwave imaging is based on such contrast in electrical properties. Recently, microwave imaging for breast cancer detection has gained attention due to advances in imaging algorithms, microwave hardware and computational power [2]. Microwave breast cancer detection is based on differences in electrical properties between healthy and malignant tissues at microwave frequencies [3, 4]. Breast cancer is a significant health issue for women and affects one in every seven women. Early detection and timely medical intervention is the key to successful treatment, long-term survival and quality of life for patients [5].

Currently, X-ray mammography is the most effective detection technique, and women are encouraged to participate in breast cancer screening programs that involve regular mammograms [6, 7]. A mammogram is a map of the densities of the breast, and has proven to be quite sensitive to the presence of lesions in the breast. According to the reports published on the X-ray mammography reviews by U.S. Institute of Medicine (IOM) [7], the limitations of the mammography includes missing up to 15% of breast cancers together with false negative rates ranging from 4% to 34% [8]. Mammography has a recall rate of 11% [9] and the diagnosis of suspicious lesions identified on mammograms often involves waiting for further imaging or biopsies. From a patient viewpoint, this modality also involves uncomfortable compression of the breast. X-rays

are also ionising and this poses limitations on the frequency of screening [10].

Microwave imaging of breast tumours offers an alternative approach to mammography. X-rays detect structural changes in tissue cells whilst microwaves detect changes in dielectric properties. Also microwaves do not have any ionisation properties and hence this technology is ideal for breast imaging that results in safer and more comfortable examinations [1]. It is also less expensive than MRI and nuclear medicine methods. The advantages of the microwave imaging system are that the process is very rapid, sensitive and specific. It has the ability to detect small tumours by measuring the difference in the electrical permittivity of malignant and normal tissues. The typical difference in the permittivity between the normal and malignant tissues is 10 – 20 % [11]. Different techniques are employed by different microwave research groups around the world in the hope of developing an efficient tool for early breast cancer detection. Three different methods of microwave breast imaging methods are discussed briefly below.

1. *Passive microwave Imaging*: Passive methods incorporate radiometers to measure temperature differences in the breast, detecting tumours based on their increased temperature compared to normal tissue. Microwave radiometry has been explored for breast cancer detection as an adjuvant to mammography [12-14]. Two examples of microwave radiometers are Oncoscan [14] and the system reported by S. Mouty et al. [15].
2. *Hybrid Microwave-Acoustic Imaging*: Hybrid methods use microwave energy to select and rapidly heat tumours and ultrasound transducers to detect pressure waves generated by the expansion of the heated tissues. Due to higher conductivity of malignant breast tissue, more energy is deposited in tumours, resulting in selective heating of these lesions. The tumours expand and generate pressure waves which are detected by ultrasound transducers. Two methods of image reconstruction proposed are Computed Thermo-acoustic Tomography (CTT) [16, 17] and Scanning Thermo-acoustic Tomography (STT) [18, 19].
3. *Active Microwave Imaging*: Active methods involve illuminating the breast with microwaves and then measuring transmitted or reflected microwave signals, and forming images with

these data. Active microwave methods for breast imaging can be classified as tomography and radar-based. Meaney et al. [20, 21] at Dartmouth College have successfully implemented a clinical prototype of tomography imaging for active microwave imaging of the breast. Hagness et al. [22] proposed the first radar-based breast cancer detection in 1998. Since then, two systems have been developed: Microwave Imaging via Space Time beamforming (MIST) developed by Hagness et al. [23, 24] in 2003 and Tissue Sensitive Adaptive Radar (TSAR) developed by Fear et al. [3, 25] in 2003.

So far in this section the development of microwave medical imaging for breast cancer detection was presented along with the different imaging approaches. All these microwave medical imaging approaches use microwave antennas to transmit and receive signals/energy. The characteristics of the microwave antenna differ considerably in freespace and coupling media. Most of the imaging techniques employ dielectric medium to nullify the reflections at the air-skin interface. So it is paramount to study the behaviour of the antenna used in relation to that of the lossy medium employed. The following sections detail the different types of microwave antenna employed and the design challenges they present in medical imaging application.

2. Microwave Antennas employed in Medical Imaging

Ever since engineers started using microwaves for medical applications, the search for a suitable microwave antenna has been underway. Various microwave antennas are used across the globe by different microwave medical imaging groups. This section details four such antennas which are either used in medical imaging applications or are identified as potential solutions to be used; namely: the monopole antenna, the vivaldi antenna, the bow-tie antenna and the pyramidal horn antenna. In what follows, a discussion on each of these antennas will be made.

2.1. Monopole Antenna

By using monopole antennas the entire imaging region can be illuminated by placing them close to the target, whereas in other antennas the distance has to be greater in order to provide sufficient illumination coverage. Space advantage offered by the monopole transmitters can prove to be very useful for systems using multiple transmit/receive channels. Meaney et al. [26] have designed a configuration which utilizes the monopole antennas to both transmit and receive elements. The monopole were constructed by having the centre conductor of a semi rigid cable of quarter wavelength (physical length was 2.5cm) exposed in a medium at 500MHz. The figure of a typical Monopole antenna constructed using semi rigid coax is shown in Figure 1. In a medium such as air or deionised water this type of antenna is notorious for producing exciting currents. Due to the lack of a balun arrangement, the characteristic

impedance of the monopole antenna in deionised water is uneven. Meaney et al. [26] capitalized on the high attenuation of the surrounding saline solution to limit this effect. The characteristic impedance of the monopole antenna in the saline solution (0.9%) is considerably different; it exhibits a nominal return loss of 9dB for the frequency range of 300–1100MHz [26].

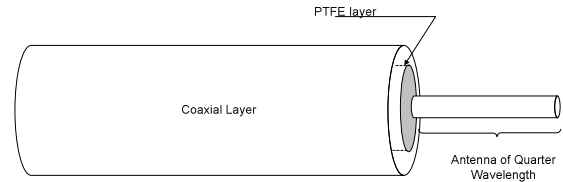


Figure.1 Monopole Antenna constructed using Semi Rigid Coax

Through this finding Meaney et al. [26] demonstrate that the isotropic radiation pattern of the monopole does not serve to degrade imaging performance in the near field context, rather it actually increases the image quality obtained. In order to realise a clinically viable system a fixed array data acquisition design may be desired. Because of the physical advantages offered by the monopole transceiver arrangement, by eliminating the more bulky waveguides, they can be conducive to a fixed array design thereby making this arrangement more suitable for medical applications.

2.2. Bow-tie Antenna

G. Bindu et al. [27] designed an efficient wideband coplanar stripline fed bow-tie antenna with improved bandwidth, low crosspolarisation and reduced backradiation. The new antenna is constructed by structurally modifying the conventional microstrip bow-tie antenna design; this is achieved by attaching an image plane. The antenna is designed as a patch on a single layered substrate with $\epsilon_r = 4.28$ and thickness of 1.6mm. The coplanar stripline is designed to have an input impedance of 50Ω in order to couple the antenna effectively with the measurement system. The parameters, such as the distance to the image plane, flare angle of the bow, and dimensions of the antenna, are found to affect the bandwidth. These parameters are optimised to enhance the performance.

The antenna exhibits unidirectional radiation pattern with enhanced bandwidth reduced backradiation and low crosspolarisation in the operational band and thus making it suitable for Confocal Microwave Imaging (CMI). A typical wideband bow-tie antenna with coplanar stripline feed for CMI is shown in Figure 2. CMI employs back scattering to locate breast cancer tumours, so the antenna employed is required to focus the microwave signal towards the target and collect the back scattered energy [4]. A 2:1 Standing Wave Ratio (SWR) bandwidth of 45.9% is obtained for the designed 4x4cm bow-tie antenna in air, which has a flare angle of 90° . The antenna operates in the band of 1850MHz - 3425 MHz with a return loss of -53dB. It is reported that in corn syrup the bandwidth is enhanced to 91% in the range of 1215 MHz

– 3810 MHz with resonant frequency of 2855MHz and return loss of -41dB[28].

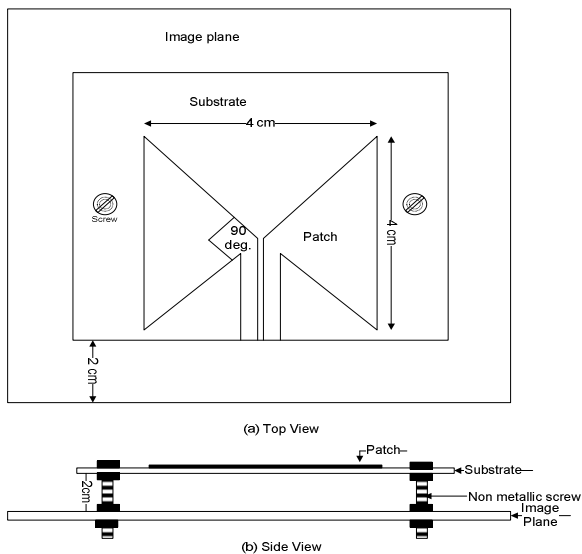


Figure.2 Wideband Bow-tie antenna

2.3. Vivaldi Antenna

The Vivaldi antenna, a form of the tapered slot radiator, has been shown to produce performance over a wide bandwidth limited only by the traditionally used slotline to microstrip transition [29]. Langley et al. [30] designed a Vivaldi antenna that satisfies the requirements for imaging systems in terms of bandwidth, gain and impulse response, albeit at the expense of significant volumetric size. In addition to the bandwidth requirement, the antenna supports the sub nanosecond pulse transmission with negligible distortion to achieve precision imaging without ghost targets. Later in 2006, Abbosh et al.[31] designed a Vivaldi antenna that reduced its physical dimensions such that it can be incorporated in a compact microwave imaging detection system whilst maintaining its distortionless performance.

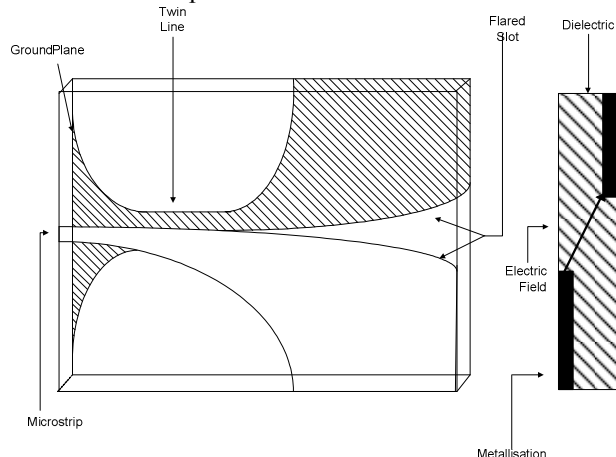


Figure.3 Antipodal Vivaldi antenna

A typical Ultrawideband Antipodal Vivaldi antenna is shown in Figure 3. The antenna operates over an Ultrawideband (UWB) from 3.1GHz to 10.6GHz with a peak gain of 10.2dBi at 8GHz. These characteristics show

that the Antipodal Vivaldi antenna has the potential to be used in medical imaging applications.

2.4. Pyramidal Horn Antenna

Horn Antennas are known for their higher aperture efficiencies but are constrained to certain applications due to their limited bandwidths. However, the bandwidth of the horn antennas can be increased significantly by adding metallic ridges to the waveguide and flared sections[32]. Numerical and experimental investigations of pyramidal horn antennas with double ridges have been reported[33]. E.T. Rosenbury et al.[34] designed a modified version of the ridged horn antenna in which the waveguide section is eliminated and one of the two ridges is replaced by a curve metallic plane terminated by resistors. Later in 2003 Susan C. Hagness and her team presented a complete numerical and experimental study of a specific realisation of this design, wherein the antenna is customized to centimetre scale dimensions for operation in the microwave frequency range 1 to 11 GHz[35].

The antenna consists of a pyramidal horn radiation cavity, a metallic ridge, and a curve metallic launching plane terminated with resistors. The pyramidal horn is connected to the outer conductor of the coaxial feed and serves as the ground plane, providing a current return path. Because of the coaxial feed, the ground plane configuration eliminated the need for a UWB Balun. The launching plane is a curved plane structure connected to the central conductor of the coaxial feed.

Termination resistors are attached between the end of the launching plane and the side wall of the pyramidal horn. Microwave energy is directed and launched by this curved plane into the surrounding medium. The termination resistors suppress reflections from the end of the launching plane. The top surface of the ridge curves toward the antenna aperture. The dimensions of the horn antenna are chosen according to the physical size required and operating frequency range.

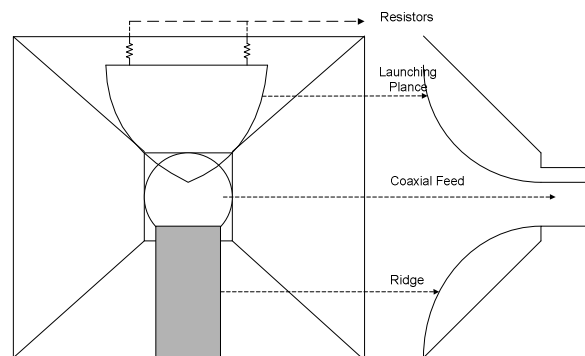


Figure.4 Ridged Pyramidal Horn Antenna

A typical Ridged Pyramidal Horn antenna is shown in Figure 4. The curvature and shape of the launching plane, the thickness and the contour of the curved side of the ridge and the termination resistors are the main factors influencing the input impedance of the antenna. The pyramidal horn has a depth of 13mm with a 25mm x

20mm aperture. The maximum width of the launching plane is 12mm and the thickness of the ridge is 2mm. This antenna yields VSWR of less than 1.5 over the frequency range and fidelity of approximately 0.96 in both the simulation and experiment[35]. The antenna has been tested under low loss immersion medium and achieved similar VSWR and fidelity. Overall it is evident that this type of antenna can be useful for biological sensing and imaging application.

3. Antenna Design Challenges in Medical Imaging Applications

In order to develop a clinically viable medical imaging system, it is important to understand the characteristics of the microwave antenna under coupling media. One of the major requirements of the microwave medical imaging is that the whole arrangement is to be immersed in a coupling medium in order to account for reflections at the air-skin interface. It is essential that the system designers take into consideration all the changes to the antenna characteristics used in comparison to its freespace behaviour. Most imaging systems work on the principle of transmitting and receiving signal/energy to and from the object. The signal propagation from the microwave antenna to the object and the reflected/scattered signal to the receiving antenna will be altered depending on the medium it propagates in relation with freespace propagation. The microwave signal propagation is characterised by a constant k , known as *the propagation constant*. In freespace the propagation constant k is related to the angular frequency ω , the permeability μ_o and permittivity ϵ_o of freespace and it is given in (1)

$$k = \frac{2\pi}{\lambda} = \omega\sqrt{\mu_o\epsilon_o} \quad (1)$$

The permittivity of the coupling medium ϵ_r is given as $\epsilon_r = \epsilon_r' - j\epsilon_r''$ where ϵ_r' and ϵ_r'' are the real part and imaginary part of the dielectric constant respectively. The conductivity σ of the coupling medium is given as $\sigma = \omega\epsilon_o\epsilon_r''$. Ideally for medical applications coupling media with no losses are preferred, i.e., the imaginary part in the permittivity equation will be zero and the propagation constant k_r will given as

$$k_r = \omega\sqrt{\mu_o\epsilon_o\epsilon_r}$$

However, practically it is impossible to have a coupling medium without any losses. Because of the conductivity values of the coupling medium the propagation constant k_r' will be a complex value and this will change the wavelength λ to λ_r in coupling medium. The propagation constant k for a lossy medium is given as (2)

$$k_r' = \omega\sqrt{\mu_o\epsilon_o(\epsilon_r' - j\epsilon_r'')} \quad (2)$$

In microwave antenna design, the size of the antenna (l) will always be specified in terms of wavelength, for example l can be $\lambda/4$ long (quarter wavelength). This relationship between the wavelength and size of the length will affect the length of the antenna in coupling medium when compared with freespace length. The input

impedance of the antenna will also be affected by the coupling medium.

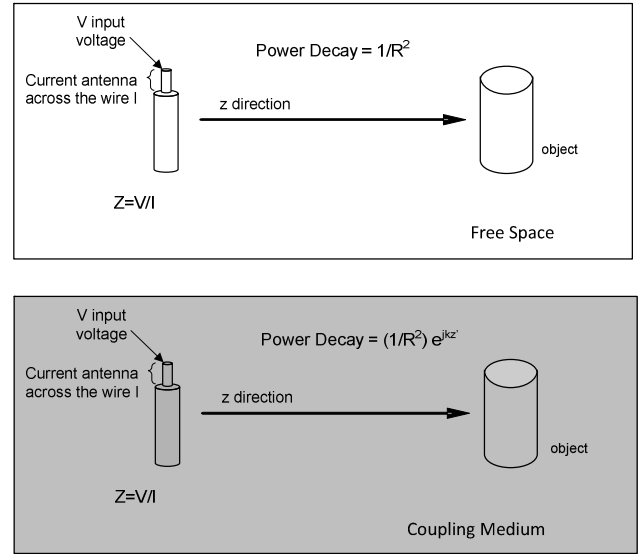


Figure 5 Illustration of the power decay component difference in freespace and coupling medium

The input impedance Z is normally derived as the ratio between the voltage applied and the current distribution along the antenna. The current distribution of the antenna in the coupling medium will depend on the new wavelength λ_r and thereby altering the input impedance of the antenna. In order to match the antenna properly in the coupling medium the designer needs to take into account the input impedance in the coupling medium. This variation caused by the conductivity values in the radiation pattern of the microwave antenna will affect the performance of the imaging system. In freespace the power decay in far field is proportional to $1/R^2$ where R is the distance between the origin and the observation point. However, in lossy media this decay factor will be increased by a factor e^{jkz} this exponential term accounts for the additional loss in the system because of the coupling medium. Thereby, the radiated signal from the antenna cannot illuminate the whole object or reach the required depth of penetration. Figure 5 shows the difference in the power loss in freespace and coupling medium. This presents the designer with the challenge to fully understand the antenna behaviour under the lossy medium and comprehend the situation by altering the algorithm to accommodate these changes or to modify the design parameters of the antenna to enhance its performance.

4. Proposed Solutions

As stated above one of the most important aspects of the proposed solution has to be the study of the antenna behaviour in coupling media. The study should involve analysing the difference in impedance and radiation pattern of an antenna in coupling media and freespace. However the traditional analysis for determining the impedance and radiation pattern become computationally cumbersome once we extend the surrounding beyond

freespace. This raises another challenge in determining the characteristics of microwave antenna in lossy media. The initial part of the solutions has to be the comprehensive study of the antenna in various materials of different dielectric properties. Understanding the behaviour of the antenna in low, medium and high conductivity materials is essential. As it helps the engineer to predict the characteristics of the antenna employed in medical imaging applications as generally the work environment involves coupling media to reduce the reflections from skin-air interface. The proposed solutions involve observing the behaviour of the monopole antenna in different dielectric materials such as water, saline solution and oil and compare the results with that of freespace.

The latter part of the solution involves developing a new mathematical model to analyse the antenna in surroundings other than freespace. Traditionally, the Pocklington integral equation [36] involving Method of Moment (MOM)[37] techniques are used to determine the characteristics of a monopole antenna in freespace. Because of the MOM technique involved, this technique becomes computationally tedious as we extend the analysis to coupling media such as oil and water. To address this issue a new mathematical model is proposed [38].

The new model aims to reduce the computational time and the tedious nature of the MOM equations. The expression for the new model is given in Equation 3 as:

$$I(z) = I_0 e^{-\alpha z} \sin(k(l-z)) + f(z, \tau) \quad (3)$$

Equation 3 consists of two parts; the first part,

$$I_0 e^{-\alpha z} \sin(k(l-z))$$

accounts for the damping in the current distribution curve of Figure 4. This characterises the effect of the surrounding medium of the wire. The current distribution curve in Figure 4 is of the wire of length $\lambda/2$ in free space. In this case the damping coefficient α is zero and its value changes as the surrounding medium changes. This is very effective for applications involving coupling medium with complex dielectric properties, such as medical imaging applications.

This part also provides the overall shape of the current distribution curve in Figure 6. This part of the equation is similar to that of the current distribution expression given in [36]. The final part of the expression is given by,

$$f(z, \tau) = \begin{cases} d_0 + \frac{\tau}{4} \sin(2k(l-z)) & \text{for } l = \frac{(2w+1)\lambda}{4} \\ d_0 + 2\tau \sin(2k(l-z)) & \text{for } l = \frac{2w\lambda}{4} \end{cases}$$

where d_0 is the dc component and w is a positive integer. This part accounts for the variation due to the radii of the wire; it acts like the dc term in the expression. It also provides the delay element in the current distribution curve in Figure 6.

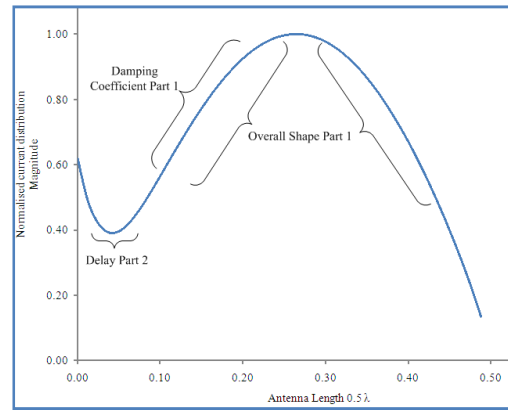


Figure 6: current distribution curve of the semi rigid coaxial wire of length $\lambda/2$.

This new mathematical model decreases the computational time as it depends on only three parameters; Initial current I_0 , damping coefficient α and radial parameter τ . Initial current I_0 is the current at the first segment of the wire, damping coefficient α characterises the conductivity of the surrounding medium. It is this parameter of the expression which makes this model suitable for predicting the current distribution of the wire in different surrounding media other than freespace. And finally, τ is a parameter related to the radius of the wire.

Finally, it is important to note that other closed form solutions for $I(z)$ can be derived by using polynomial approximation. However, this is a topic that is worth investigating.

5. Conclusion

A comprehensive survey on the evolution of microwave medical imaging has been presented. Cancer detection using microwave imaging techniques are documented. Various antennas which are used and have potential to be used in medical imaging application are discussed. The challenges and limitations these microwave antenna faces in medical imaging environment are detailed. The possible solutions for the challenges are suggested using the ongoing novel mathematical modelling work.

REFERENCES

- [1] Fear, E.C., P.M. Meaney, and M.A. Stuchly, *Microwaves for breast cancer detection?* IEEE Potentials, 2003: p. 12 - 18.
- [2] Fear, E.C., *Microwave imaging of the Breast.* Technology cancer Research Treatment, 2005. 4: p. 69-82.
- [3] Sill, J.M. and E.C. Fear, *Tissue Sensing Adaptive Radar for Breast Cancer Detection - Experimental Investigation of Simple Tumor Models.* IEEE Transactions on Microwave Theory and Techniques, 2005. 53: p. 3312-3319.
- [4] Fear, E.C., et al., *Confocal Microwave Imaging for breast cancer detection: localization of tumors in three dimensions.* IEEE Transactions on Biomedical Engineering, 2002. 49(812-822).

- [5] Society, A.C., *Cancer Facts & Figures 2005*, Atlanta, GA 2005. 2005.
- [6] Brown, M., *Screening mammography in community practice*. American J. Roentgen, 1995. **165**: p. 1373-1377.
- [7] Nass, S.J., C. Henderson, and J.C. Lashof, *Mammography and Beyond: Developing Technologies for the Early Detection of Breast Cancer*. Committee on Technologies for the Early Detection of Breast Cancer, Eds., National Cancer Policy Board, Institute of Medicine and Commission on Life Studies, National Research Council, 2001.
- [8] Huynh, P.T., A.M. Jarolimek, and S. Daye, *The False-Negative Mammogram*. Radiographics, 1998. **18**: p. 1137-1154.
- [9] Fletcher, S.W. and J.G. Elmore, *Mammographic Screening for Breast Cancer*. New England Journal of Medicine, 2003. **37**: p. 1672 - 1680.
- [10] Nilavalan, R., et al., *Numerical Investigation of Breast Tumour Detection using multi static radar*. IEE Electronics Letters, 2003. **39**(25).
- [11] Fear, E.C., et al., *Enhancing Breast Tumor Detection with near Field Imaging*. IEEE Microwave Magazine, 2002. **2**: p. 1527-1542.
- [12] Bocquet, B., et al., *Microwave Radiometric Imaging at 3 GHz for the Exploration of Breast Tumors*. IEEE Transactions on Microwave Theory and Techniques, 1990. **38**: p. 791-793.
- [13] Carr, K.L., *Microwave Radiometry: its Importance to the detection of cancer*. IEEE Transactions on Microwave Theory and Techniques, 1989. **37**: p. 1862-1869.
- [14] Carr, K.L., et al., *Radiometric sensing: An adjuvant to Mammography to determine breast biopsy*. IEEE International Symposium on MTT, Dig. , 2000. **2**: p. 929-932.
- [15] Mouty, S., et al., *Microwave Radiometric Imaging for the characterisation of breast tumors*. European Physics Journal: Applied Physics, 2000. **10**: p. 73-78.
- [16] Kruger, R.A., et al., *Thermoacoustic CT with radio waves: A Medical Imaging Paradigm*. Radiology, 1999. **211**: p. 275-278.
- [17] Kruger, R.A., et al., *Thermoacoustic computed tomography of the breast at 434 MHz*. IEEE International Symposium on MTT, Dig., 1999. **2**: p. 591-594.
- [18] Wang, L.V., et al., *Microwave Induced acoustic imaging of biological tissue*. Rev.Sci. Instrum., 1999. **70**: p. 3744-3748.
- [19] Ku, G. and L.V. Wang, *Scanning Thermoacoustic tomography in biological tissues*. Medical Physics, 2000. **27**: p. 1195-1202.
- [20] Meaney, P.M., et al., *A Clinical Prototype for Active Microwave Imaging of the Breast*. IEEE Transactions on Microwave Theory and Techniques, 2000. **48**(11).
- [21] Meaney, P.M., et al., *Initial Clinical Experience with Microwave Breast Imaging in woman with normal Mammography*. Acad Radiol: Author Manuscript PMC, 2007. **14**(2): p. 207-218.
- [22] Hagness, S.C., A. Taflove, and J.E. Bridges, *Two dimensional FDTD analysis of pulsed microwave confocal system for breast cancer detection: fixed focus and antenna-array sensors*. IEEE Transactions on Biomedical Engineering, 1998. **45**: p. 1470-1479.
- [23] Davis, S.K., et al., *Microwave Imaging via Space-Time Beamforming for Early Detection of Breast Cancer: Beamformer design in the Frequency Domain*. J. of Electromagn. Waves and Appl., 2003. **17**(2): p. 357-381.
- [24] Hagness, S.C., A. Taflove, and J.E. Bridges, *Three Dimensional FDTD analysis of Pulsed microwave confocal system for breast cancer detection: design of an antenna array element*. IEEE Transactions on Antennas and Propagation, 1999. **45**: p. 783-791.
- [25] Fear, E.C. and J.M. Sill, *Preliminary Investigations of Tissue Sensing Adaptive Radar for Breast Tumor Detection*. Proceedings of the 25th Annual Meeting of the IEEE Engineering in Medicine and Biology Society, 2003: p. 3787 - 3790.
- [26] Meaney, P.M., K.D. Paulsen, and J. Chang, *Near-Field Microwave Imaging of Biologically based materials using a monopole system*. IEEE Transactions on Microwave Theory and Techniques, 1998. **46**(1).
- [27] Bindu, G., et al., *Wideband Bow-tie antenna with Coplanar Stripline Feed*. Microwave and Optical Technology Letters, 2004. **42**(3).
- [28] Bindu, G., et al., *Active Microwave Imaging For Breast Cancer Detection*. Progress in Electromagnetics Research 2006. **58**: p. 149-169.
- [29] Gibson, P.J., *The Vivaldi Aerial*. 9th European Microwave Conference, Brighton, 1979: p. 101 - 105.
- [30] Langley, J.D.S., P.S. Hall, and P. Newham, *Balanced Antipodal Vivaldi Antenna for wide bandwidth phased arrays*. IEE Proceeding Microwave Antennas Propagation, 1996. **143**(2).
- [31] Abbosh, A.M., H.K. Kan, and M.E. Bialkowski, *Design of Compact Ultra Wideband Antipodal Antenna*. Microwave and Optical Technology Letters, 2006. **48**(12).
- [32] Walton, K.L. and V.C. Sundberg, *Broadband Ridged Horn Design*. Microwave Journal, 1964: p. 96-101.
- [33] Notras, B.M., C.D. McCarrick, and D.P. Kasilingam, *Two Numerical techniques for analysis of pyramidal horn antenna with continous metallic ridges*. Proceedings of IEEE Internationsl Symposium Antenna Propagation, Dig., 2001. **2**: p. 560-563.
- [34] Rosenbury, E.T., et al., *Low cost compatible wideband antenna*, U.S., Editor. 2002: U.S.
- [35] Li, X., et al., *Numerical and Experimental Investigation of an Ultrawideband Ridged Pyramidal Horn Antenna with Curved launching Plane for Pulse radiation*. IEEE Antennas and Wireless Propagation Letters, 2003. **2**.
- [36] Balanis, C.A., *Antenna Theory: Analysis and Design Second Edition*. 1997, New York: John Wiley&Sons, Inc.
- [37] Peterson, A.F., S.L. Ray, and R. Mittra, *Computational Methods for Electromagnetics*. 1998, Oxford: Oxford University Press.
- [38] Fernando, M.J., K. Busawon, and D. Smith, *A Novel Simplified Mathematical model for Antennas used in Medical Imaging Applications*. Proceedings of Conference on Electrical Impedance and Electromagnetic Inverse Problems , Manchester UK, 2009.