Progress In Electromagnetics Research C, Vol. 59, 117–126, 2015

Ground Slotted Monopole Antenna Design for Microwave Breast Cancer Detection Based on Time Reversal MUSIC

Mamadou H. Bah*, Jing-Song Hong, and Deedar A. Jamro

Abstract—In this manuscript, a reduced size, ground slotted monopole antenna, operating in the range of 3.1–10.6 GHz is designed and implemented for breast cancer detection using time reversal MUSIC. A homemade breast mimicking phantom has been experimentally designed to facilitate the detection implementation. The simulated and measured results are in good agreement. The slots and blending edges of the ground, along with the feed step are some techniques applied to the designed antenna in order to achieve a broad bandwidth and reduce considerably the reflection coefficient. The resulting dielectric constant from the breast phantom is relatively close to the real normal breast tissues. After the design has been completed, some techniques of time reversal MUSIC were employed to mimic the breast cancer detection. The experimental results show that both temporal and spatial images of the cancer (tumor) are well represented here.

1. INTRODUCTION

Breast cancer is, among others, one of the major causes of women mortality in the world [1]. In the recent decades, many investigations have been conducted and are still in progress in order to overcome this issue [2]. If detected in time and treated in earlier stage, this may increase the hope to long term survival from the disease [3–8].

The standard screening method for earlier breast cancer diagnosis is still the x-ray mammography which turns out with approximately 10 to 34% false positive and false negative cancer detection results [6, 7]. For this method, almost 70% of the breast cancer (tumor) is identified as benign [8]. It is characterized by a high false positive and negative rate. The limitations of x-ray mammography such as ionizing radiation and breast compression during the examination process are the most inspiring that brought many researchers groups to seek for a new and promising method to complement this method in the early stage breast cancer diagnosis [9].

Alternatively, microwave imaging is a low cost and improved safety technology system for breast cancer imaging. It is free of ionizing radiation and breast compression; it is also a non-invasive technique, which has been studied for more than a decade by different scientific research groups around the world. Due to the width applicability of microwave imaging system, it can be classified into passive and active microwave imaging, where many investigations have been made for both the imaging techniques in the case of breast cancer detection [9, 10]. — Passive microwave imaging referred to as radiometry [11, 12] uses the differences in temperature between healthy and timorous tissues. — For active microwave imaging, it relays upon the difference in dielectric properties of the human tissues [4, 7, 13].

People's exposure to electromagnetic waves from the electronic devices (especially in telecommunication system) has attracted the attention of several research institutes in order to evaluate the biological effect from the exposure. In the studies in literature, the permittivity of the cancerous

Received 29 August 2015, Accepted 28 September 2015, Scheduled 14 October 2015
* Corresponding author: Mamadou Hady Bah (sintaba@yahoo.com).
The authors are with the School of Physical Electronics, University of Electronic Science and Technology of China, Chengdu 610054, China.

tissues was found to be 10–20% higher than the normal (healthy) tissues [14]. With the increase of breast cancer mortality in the recent decades, many methods using breast phantoms have been studied and experimented by means of estimating the real breast tissues properties [2, 7, 14]. One of these examples is the use of oil in gelatin, which has been implemented by Lazebnik et al. in [14]. This method consists of mixing these two materials and adding surfactant liquids. Another example is experimentation carried out by Madsen et al. [15] in the domain of ultrasound imaging using breast tissues mimicking phantoms.

For this study, a mixture of some daily life use materials having different dielectric properties is considered as breast phantom. Even though microwave imaging system has big advantages in breast cancer detection, the EM wave propagation through biological tissues is characterized by some refraction and multipath properties. This can lead to the back-scattered signals to reach the detector by two or multipath. These conditions increase the limitation of the target identification and location during the detection. To overcome these limitations, Time Reversal Multiple Signals Classification (TR_MUSIC) is considered as one of the most encouraging methods. It has the ability to employ the multipath propagation to achieve good result in target detection such as breast cancer detection [1].

In this imaging system, antenna is a very important tool which facilitates the transmission and/or reception of the EM waves. Ever since engineers started using microwaves for medical applications, strong attention has been paid to the search for a suitable antenna. Many antennas have been used in microwave medical imaging. Among them, monopole is a compact and versatile design characterized by the potential advantages of low cost, light weight, easy design, broad bandwidth property and has greater availability.

2. MATERIALS AND METHODS

In this paper, our main goal is to design an ultra-wide band (UWB) monopole antenna which can be implemented in an experimental study on breast cancer detection based on time reversal (TR_MUSIC). For human safety purposes, the designed antenna and breast phantom are considered to operate within the range allocated by ISM (Industrial, Science and Medical) i.e., from 10 MHz to 20 GHz. For this research, all design and simulations were performed using computer simulation technology software (CST Microwave studio), Matlab and origin Pro. To confirm the results obtained through software, some measurements are performed, and more details can be found following sections.

3. GEOMETRY OF THE ANTENNA

This section describes the parametrical study of the designed rectangular shape monopole antenna. The stability in impedance bandwidth of rectangular monopole compared to circular and elliptical monopoles antennas [16] inspired us to choose the rectangular shaped monopole antenna, operating in the UWB range 3.1–10.6 GHz authorized by FCC. In this design, FR-4 was considered as substrate with a dielectric constant of 4.6 and a height of 1.2 mm. The initial length and width ($L_1 = 19$ and $W_1 = 22$) of the radiating patch are taking to be $\lambda/4$ at the lower frequency point. Figure 1 shows different steps of the design and the parametrical antenna model. $L = 32$ and $W = 35$ are the substrate's length and width, respectively. In its opposite face, a reduced and blended ground plane is placed. The radius of the blended edges is 16 mm. The parameters of the two L-shaped slots, horizontally and symmetrically placed on the ground plan, are shown in the parametric figure. The length and width of the feed-line are 10 and 3, respectively; $W_2 = 15$ is the width of the feed-step; and finally $WG = W = 35$ is the width of the ground. All dimensions are in millimeter (mm).

4. TR_MUSIC AND MULTI-STATIC IMAGING

Time reversal is a technique that has been experimented for the first time by the French scholar Fink and his team using acoustic waves [17]. Some other research groups and institutes such as the team of Carnegie Mellon University [18], and Yavuz and Teixeira, from the Ohio State University, have extended this concept to electromagnetic waves (microwaves imaging system) [19].

An electromagnetic wave is called time reversal if the wave can propagate backward. In such a case, the signal will refocus on the point source. In other words, time reversal is a new technique which

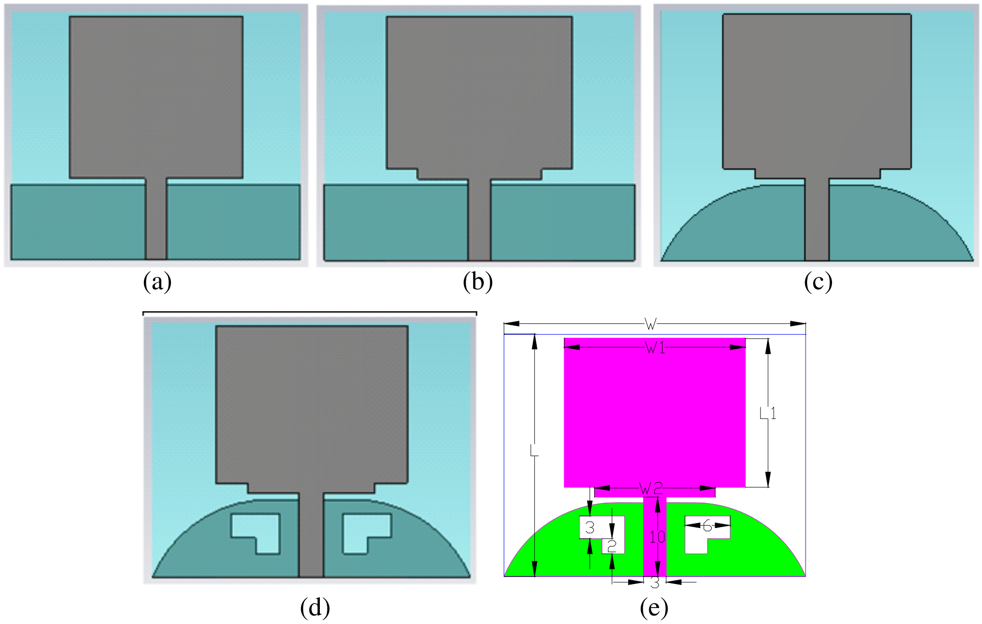

Figure 1. Antenna design steps and the design parameters.

satisfies the reciprocity theorem $E(t) = E(-t)$, meaning that if $E(r,t)$ is a solution of Equation (1), then the existence of another solution will be observed so-called time reversed $E(r,t) = E(r,-t)$. For simplicity, here we consider the electromagnetic wave equation in a uniform and loss free medium.

$$\Delta^2 E(r,t) - \mu(r)\varepsilon(r)\frac{\partial^2}{\partial t^2}E(r,t) = 0 \tag{1}$$

In this equation, $E(r,t)$ is the electric field; $\vec{r}$ is the vector position; μ, ε are permeability and permittivity respectively.

The reciprocity theorem governing this wave equation allows the scattered wave to reverse and propagate backwards to the original source. The TR wave will focus on the point source regardless of the nature of the medium. The basic idea about TR consist of recording the different received wave signals using an array of transducers, time reverse and send it back to the original point source. It can exploit the multipath effect to achieve good results [20].

TR microwave imaging techniques use the multi-static data matrix (MDM). Different imaging methods for microwave breast cancer imaging are investigated in [3, 4, 20] using time reversal. Among the well-known techniques, DORT and TR MUSIC are based on either the Eigen values or its equivalent singular value decomposition of the MDM matrix. Here, we propose the use of time reversal multiple signals classification (known as TR-MUSIC) technique to estimate the location of a tumor in a breast phantom. For that, let consider an N antenna elements located at r_j. To facilitate the localization of M targets in a two dimensional plane, we apply an excitation signal $e_j(\omega)$ to the j-th element of the antenna array with $j = 1, 2, 3, \ldots, N$. $e_j(\omega)$ is the excited energy signal with respect to the frequency domain. The electric field, after being propagated in the region under investigation, the scattered energy by the M-target is recorded by the l-th element of the array, and it can be expressed as shown in Equation (2). Here the electric field represents the scattering energy for the l–jth elements of the array.

$$E^S_{lj} = \sum_{m=1}^{M} G\left(X_m, r_l, \omega\right)\tau_m(\omega)G\left(r_l, X_m, \omega\right)e_j(\omega) \tag{2}$$

where $\tau_m(\omega)$ is the scattering potential, representing the back-scattering strength as a function of angular frequency; x_m & r_j represent the location of m-th target and the j-th receiving element; k is the wave propagation constant; G is the background Green's function of the medium. For simplicity, in the following section, we omit the frequency term in the mathematical formulation. The l, j-th element of the multi-static data matrix can be written as

$$K_{lj} = E_{lj}^S = \sum_{m=1}^{M} \tau_m g_r\left(X_m\right) g_t^T\left(X_m\right) \tag{3}$$

where the upper script T denotes transpose operation; g_r & g_t are vectors Green's function for transmission (subscripts t) and reception (subscripts r) respectively. g_r & g_t can be define as

$$g_r\left(X_m\right) = \left[G\left(r_1, X_m\right), G\left(r_2, X_m\right), \ldots, G\left(r_N, X_m\right)\right] \tag{4}$$

$$g_t\left(X_m\right) = \left[G\left(X_m, r_1\right), G\left(X_m, r_2\right), \ldots, G\left(X_m, r_N\right)\right] \tag{5}$$

By taking into account the reciprocity theorem in the propagation medium, the MDM becomes symmetric and can be expressed as $K_{lj} = K_{jl}$. The singular value decomposition, K, can be represented as

$$K = U\varphi V^H \tag{6}$$

After substituting the singular value decomposition K into the time reversal operator defined as $T = K^H K$, we will get $K = U\varphi V^H V\varphi U^H$ where the superscript H denotes conjugate transpose operation. Here U and V are both unitary matrixes, so finally the time reversal operator can be deduced as $T = \varphi^2$.

For DORT, every eigenvalue of φ^2 signifies the presence of cancer in the investigated region. The backpropagated corresponding eigenvectors facilitate identification of the targets in that region. There is a strong relationship between the eigenvectors (v) and the Green's (g) function vector of the medium [11, 21] as shown in (11).

$$v_m\left(\omega\right) \approx e^{j\varphi} \frac{g^*(x_m)}{\|g(x_m)\|} \tag{7}$$

where φ is the phase arising from singular value decomposition, and superscript star denotes conjugate operation. Consequently, the DORT imaging function that utilizes the signal subspace can be formulated as

$$I_{DORT}(r) = \sum_{n=1}^{M} \left|\langle v_n^* \mid g(r,\omega)\rangle\right|^2 \tag{8}$$

Due to the orthogonality between noise and signal subspaces, time reversal can make use of the singular value decomposition of the multi-static data matrix to separate them. Then the scattering object located at r will be estimated by the time reversal MUSIC pseudo-spectrum formulated in Equation (9).

$$I_{TR\_MUSIC}(r) = \frac{1}{\sum_{n=M+1}^{N} \left|\langle v_n^* \mid g(r)\rangle\right|^2} \tag{9}$$

This condition is satisfied only when the term $\langle v_n^* \mid g(r)\rangle$ is set to be null. Here v_n^* stands for n eigenvectors, and $g(r)$ is the vector Green's function.

5. EXPERIMENTAL SETUP

For our experimental study, after carrying out several simulations about antenna transmission in three different mediums, two antennas have been considered and placed symmetrically around the breast phantom that has been predesigned. For both simulation and measurement, the distance between the transmitting and receiving antennas was considered to be 200 mm. The images illustrating the simulated and experimental setups are shown in Figure 2(a), (b) and (c). The simulation consists of implementing the antennas coupling during its transmission in a lossless (free space) and in lossy mediums (see Figure 6), whereas the experiment consists of implementing the breast cancer detection based on Time Reversal MUSIC.

In biological tissues representation, an ideal tissue mimicking phantom should be cheap, safe, widely available, and conformable. It should also have similar dielectric properties as the tissues. However, one

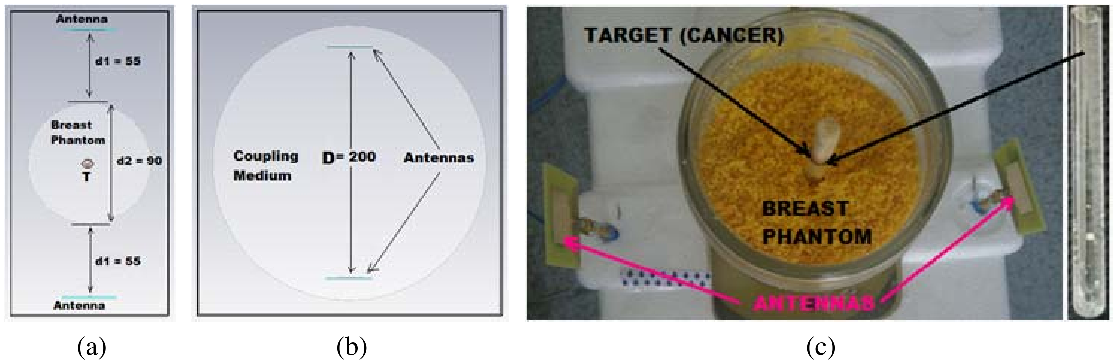

Figure 2. The simulated antennas coupling in different medium and the experimental set up. (a) Transmitting and receiving antennas in free space medium with the target placed in. (b) Transmitting and receiving antennas placed in a coupling medium. (c) Experimental set up: Transmitting and receiving antennas placed in a free space coupling medium, with the breast phantom placed in the middle having the tumor (target) imbedded in it.

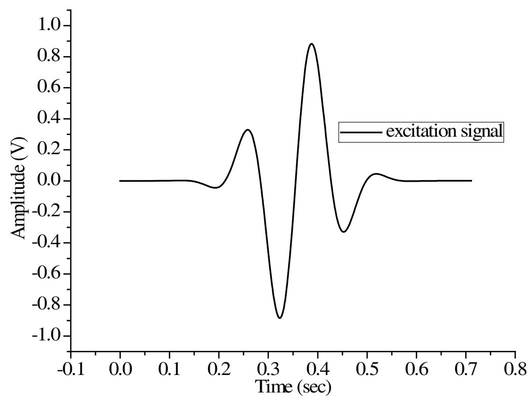

Figure 3. The excitation signal.

of the biggest challenges in the design is to find materials that can mimic different tissue properties in a wide range of frequencies and display similar characteristics. In the literature, many materials have been used to mimic the human tissue properties such as liquid, powder, semi-solid and solid (chemical and non chemical). It has been found that the chemical materials require more precaution from the modeling to the experiment, and their usability is more restricted, whereas the non-chemical materials are widely available and safe even with inhalation. Also due to human safety, before breast cancer diagnosis or treatments take place, there is a strong need of understanding the electrical properties of breast tissues. As microwave breast cancer imaging is based on dielectric contrast between normal and cancerous tissues, a study about dielectric constant of the breast tissues is required. This reason, in addition to what we have mentioned in the introduction, motivated us the most to use non-chemical, daily life used materials (with different dielectric constants) in our study about breast tissues mimicking phantom modeling. In Figure 2, the breast phantom is composed of three different materials: corn flour, soy bean oil and water in a ratio of $6.5:1.5:2$. These materials have been chosen because when they are mixed in the ratio giving here, it displays a dielectric constant $\pm 10\%$ similar to that of the real breast tissues. In the case of the breast cancer (tumor), due to the high dielectric constant of the malignant tissues (cancer or tumor), mineral water has been considered. It is poured in a unit cell glass and imbedded in the phantom (see Figure 2(c)). After the mimicking phantom has been modeled with respect to the ratio introduced here, the measurement is conducted (see Figure 7).

In TR MUSIC, generally, the multi-input multi-output (MIMO) antenna system is preferable in order to achieve a very good result. However, this requires a complete imaging equipment system with more antennas. On the other hand, in our experiment, due to the lacking of some equipment, we have chosen to adapt this work to the available equipment that uses single input and single output (SISO) imaging system, and this requires only two antennas. During the experiment, these antennas play both the roles of transmitting and receiving, whereas only one antenna transmits at a time. The antenna transmits a short pulse signal into the imaging medium, then after after this transmission, the backscattered signals are recorded by the receiving antenna. From there, we extract the received S-Parameters matrix, process the data by using a time reversal imaging algorithm built in Matlab, then resend back the signal to the original source where it comes from. At the point source, we observe the focusing signal amplitude which explains about how good the signal has responded. A maximum amplitude of the time reversed signal is observed at the point source (see Figure 8) which signifies that a good result has been achieved. Looking the image of the estimated target location, the process is almost the same; however here, after the multi-static data matrix (commonly known as K matrix) has been extracted from the obtained S-parameters using a vector network analyzer and then substituted into the Time Reversal algorithm and reprocessed again through Matlab, the program automatically generates a pseudo spectrum image of the estimated target location. This is a simple process which requires less time and simple equipment. Here, the particularity is that the more the signal is compressed at the origin, the stronger intensity the generated image has at the location of the target (Figure 9), and then the better the received signal is. The transmitted pulse (excitation signal) is shown in Figure 3.

6. SIMULATION AND EXPERIMENTAL RESULTS

In this section, we are going to explain, in detail, the results obtained from the simulation and measurement. In Figure 4, the result illustrates a broad bandwidth with a return loss less than -10 dB covering the entire frequency range.

For our designed monopole antenna with a reduced ground plane and without any feed step structure, the impedance is matched only at the lower and upper frequency limits. When reducing the radiating patch and creating a feed step in between the microstrip feed line and the radiator, the impedance bandwidth gets improved. However, the frequency band from 5.7 to 7.1 GHz is not covered. The blending edges on the ground plane contribute to matching the impedance at the center frequencies, therefore improving the bandwidth of the antenna. In the parametrical design figure, the slots made on the ground (see Figure 2(d)) play a very important role in improving the accuracy of the S-parameters, particularly at higher frequency.

In the UWB monopole antenna structure, the length of the ground is reduced to $\lambda/10$ over a width less than $\lambda/2$ at the low operating frequency. It is well known that a microstrip patch antenna fully ground bounded is more directional; however due to the confinement of the fringing fields in between the radiating patch and the ground plane in that case, the bandwidth of the antenna can be affected,

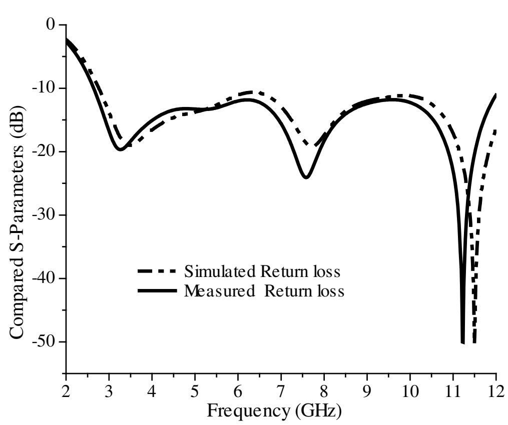

Figure 4. Compared return loss of the antenna.

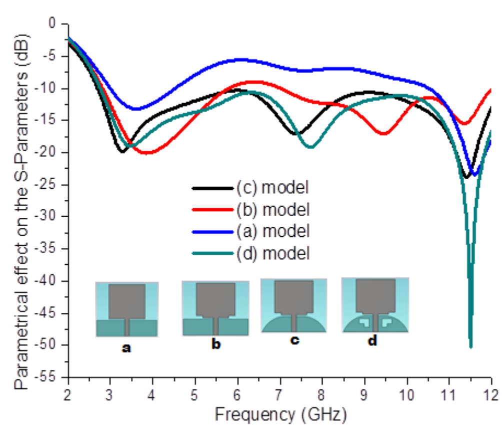

Figure 5. The effects on the step models of the designed antenna.

leading to a narrow bandwidth and increasing the size of the antenna as well. By taking into account the relationship between the skin depth and operating frequency (see Equation (10)), some techniques are applied to the design in order to achieve good penetration depth and high resolution as well.

$$k_p = \frac{c}{2\pi f \sqrt{2\varepsilon_r \left[\sqrt{1 + (\varepsilon_r'/\varepsilon_r)^2} - 1\right]}} \tag{10}$$

The slots made on the ground plane together with blending edges of the ground and the feed step on the radiator contribute to improving the bandwidth of the monopole antenna and its miniaturization as well. Figure 5 shows the different effects of all these parameters mentioned above. For the simulation, three different mediums were considered with different dielectric constants: one is free-space medium and the other two are Rogers ($E_r = 2.2$ and $E_r = 9$). From the result shown in Figure 6, we can notice that due to the high dielectric constant of the coupling medium, compared to the one used for the antenna design, the transmitted signal is strongly affected. On the other hand, in the coupling medium with lower dielectric constant, the effect is minimized. Furthermore, in the simulated model with free-space medium, the antenna coupling is minimized (see Figure 6). The experimental work on breast cancer detection was carried out using a vector network analyzer in order to extract the multi-static data matrix K (see Section 4). After the mimicking phantom has been modeled with respect to the ratio introduced here, the measurement is then conducted (see Figure 7). The result displays

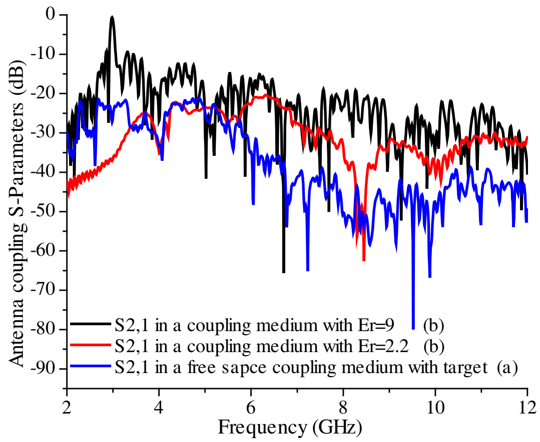

Figure 6. Antenna transmission in different coupling mediums.

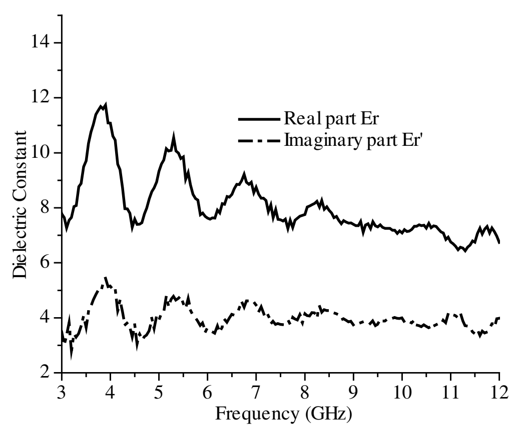

Figure 7. The dielectric constant of the breast phantom.

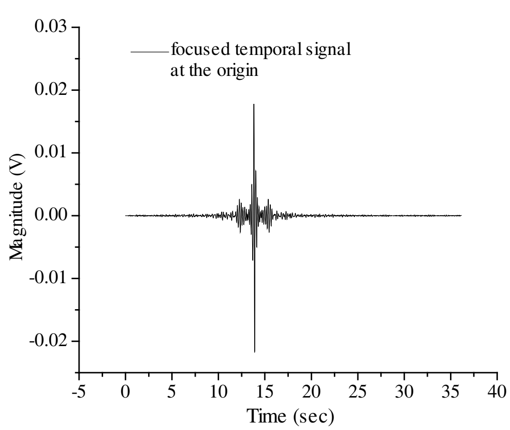

Figure 8. Time reversal focused signal.

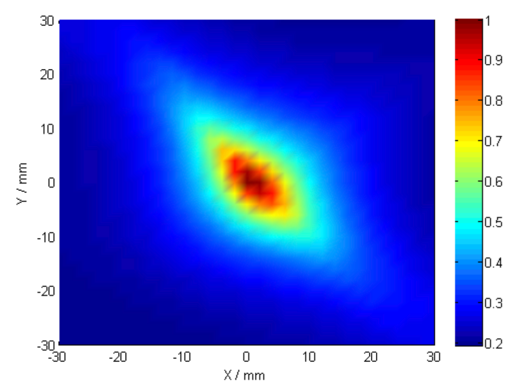

Figure 9. The location of the tumor (cancer) inside the breast phantom at 6 GHz.

two different curves representing a complex dielectric constant ($\hat{\varepsilon} = \varepsilon_r - j\varepsilon_r'$) which has the real part (ε_r), known as relative permittivity and the imaginary part (ε_r') known as loss factor. Here the relative permittivity is a measure of how much energy can be stored in the tissue, while the loss factor represents the scattering characteristic due to an external electric field applied to the specific part of the body. This experimental study about the electrical properties of the human body may help medical institutions to prevent the changes in human tissues through medical treatment and also contributes to facilitating patients' medication as well.

The dielectric constant of the breast phantom (Figure 7) and the resulting waveform with good temporal focusing signals (see Figure 8) are shown below. For this breast phantom, the experiment has been conducted using a very simple system which consists of a vector network analyzer connected at one side to a microstrip slub-line, and on the other side, it is directly connected to a computer in order to visualize the data. We have been able to achieve an average relative permittivity around 9 which is relatively close to the real normal breast tissues as presented in [7, 22]. This is due to the low water content in it. The loss factor also has an acceptable average value which is around 4.5. In Figure 8, the resulting waveform explains the ability of the time reversal technique to refocus the signals from the receiving positions back to the source. For more realistic results, a measurement is carried out in this study using TR-MUSIC algorithm formulated in (9). A good estimation of the target location is shown in Figure 9 with some surrounding noise due to instability of the mixture after one week of conservation.

7. CONCLUSION

In this manuscript, a ground slotted UWB monopole antenna operating in the standard UWB range from 3.1–10.6 GHz (according to FCC) is designed and implemented for breast cancer detection using time reversal MUSIC. A simulation of the antenna transmission was carried out through three different coupling mediums: one is free-space medium, and the other two are Rogers ($E_r = 2.2$ and $E_r = 9$). We have found that the simulated model with free-space coupling medium seems better than the other two mediums. Then we implemented the free-space medium in the experiment as shown in Figure 2(c).

One of the particularities of this antenna is that its size has been reduced to less than $\lambda/2$, without the use of high dielectric constant or high frequency which is the case in [10]. The antenna has a broad bandwidth. This satisfies the microwave imaging requirement. The designed antenna can be used for multiple applications using broadband in the UWB frequency range 2–12 GHz. Refering to [7, 22], we have been able to achieve a dielectric constant ±10% similar to the real normal breast tissues. The time reversal waveform shown in Figure 9 has a very narrow peak at the focusing point, meaning that the time reversed signals from the receiving points are well focused. This contributes to facilitating the detection and localization of the cancer (tumor) from the breast. Figures 8 and 9 explain about the capability of the antenna to transmit and receive a narrow pulse signal, which is very important in target detection such as breast cancer detection through medical imaging. In Figure 9, the measured result presents some noise; this is due to the migration of the water and oil from top to the bottom of the bottle during one week deposit after the mixing. This design shows that if it is improved, instead of employing surgery for cancer (tumor) treatment, with the rapid development of the imaging technologies, the antenna can be utilized in microwave imaging using time reversal techniques to locate, detect and even cure the tumor without touching the human body.

From this research, we can conclude that even though TR_MUSIC has a lot of advantages in breast cancer detection, the experimental work remains with some limitations such as carrying out an experiment with highly dense breast and a breast mimicking phantom resulting from mixed materials of different dielectric properties. Also we think that there is still a need for a more advanced method to complement the limitation of Time Reversal MUSIC in the case of very dense breast tissues.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (No. 61172115 and No. 60872029), the High-Tech Research and Development Program of China (No. 2008AA01Z206), the Aeronautics Foundation of China (No. 20100180003), the Fundamental Research Funds for the Central Universities (No. ZY-GX2009J037) and Project 9140A07030513DZ02098.

REFERENCES

1. Sajjadieh, M., F. Foroozan, and A. Asif, "Breast cancer detection using time reversal signal processing," *IEEE 13th International. Multi-optic Conference, 2009*, INMIC, 2009.
2. Nadine Joachimowicz, N., C. Conessa, T. Henriksson, and B. Duchêne, "Breast phantoms for microwave imaging," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 1333–1336, 2014.
3. Hossain, M. D. and A. S. Mohan, "Breast cancer localization in three dimensions using time reversal DORT method," *2012 International Symposium on Antennas and Propagation (ISAP)*, 471–474, 2012.
4. Jin, Y. W., J. M. F. Moura, and Y. Jiang, "Breast cancer detection by time reversal imaging," *5th IEEE International Symposium on Biomedical Imaging: From Nano to Macro, 2008. ISBI 2008*, 816–819, 2008.
5. Shao, W. and R. S. Adams, "Two antipodal vivaldi antennas and an antenna array for microwave early breast cancer detection," *Microwave and Optical Technology Letters*, Vol. 55, 670–674, Mar. 2013.
6. Huynh, P. T., A. M. Jarolimek, and S. Daye, "The false-negative mammogram," *Radiograph*, Vol. 18, No. 5, 1137–1154, 1998.
7. Fear, E. C., X. Li, S. C. Hagness, and M. A. Stuchly, "Confocal microwave imaging for breast cancer detection: Localization of tumors in three dimensions," *IEEE Trans. Biomed. Eng.*, Vol. 49, 812–822, Aug. 2002.
8. Elmore, J. G., M. B. Barton, V. M. Moceri, S. Polk, P. J. Arena, and S. W. Fletcher, "Ten-year risk of false positive screening mammograms and clinical breast examinations," *New Eng. J. Med.*, Vol. 338, No. 16, 1089–1096, 1998.
9. Fear, E. C., S. C. Hagness, P. M. Meaney, M. Okoniewski, and M. A. Stuchly, "Enhancing breast tumour detection with nearfield imaging," *IEEE Microwave Magazine*, Vol. 3, No. 1, 48–56, Mar. 2002.
10. Carr, K. L., "Microwave radiometry: Its importance to the detection of cancer," *IEEE Trans. Microwave Theory Tech.*, Vol. 37, 1862–1869, Dec. 1989.
11. Bocquet, B., J. C. van de Velde, A. Mamouni, Y. Leroy, G. Giaux, J. Delannoy, and D. Del Valee, "Microwave radiometric imaging at 3 GHz for the exploration of breast tumors," *IEEE Trans. Microwave Theory Tech.*, Vol. 38, 791–793, Jun. 1990.
12. Chaudhary, S. S., R. K. Mishra, A. Swarup, and J. M. Thomas, "Dielectric properties of normal and malignant human breast tissues at radiowave and microwave frequencies," *Indian J. Biochem. Biophys*, Vol. 21, 76–79, Feb. 1984.
13. Surowiec, J., S. S. Stuchly, J. R. Barr, and A. Swarup, "Dielectric properties of breast carcinoma and the surrounding tissues," *IEEE Trans. Biomed. Eng.*, Vol. 35, 257–263, Apr. 1988.
14. Lazebnik, M., E. L. Madsen, G. R. Frank, and S. C. Hagness, "Tissue-mimicking phantom materials for narrowband and ultra-wideband microwave applications," *Physic. Medicine Biology*, Vol. 50, 4245–4258, 2005.
15. Madsen, E. L., J. A. Zagzebski, and G. R. Frank, "Oil-in-gelatin dispersions for use as ultrasonically tissue-mimicking materials," *Ultrasound in Medicine and Biology*, Vol. 8, 277–287, 1982.
16. Abbosh, A. M. and M. E. Bialkowski, "Design of ultra-wideband planar monopole antennas of circular and elliptical shape," *IEEE Trans. Antennas Propag.*, Vol. 56, No. 1, 17–23, 2008.
17. Fink, M., "Time reversed acoustics," *Physics Today*, Vol. 50, 34, 40, 1997.
18. Jin, Y., Y. Jiang, and J. M. F. Moura, "Time reversal beamforming for microwave breast cancer detection," *IEEE International Conferences on Image Processing*, Vol. 5, V-13– V-16, San Antonio, Texas, Sep. 16–19, 2007.
19. Yavuz, M. and F. Teixeira, "Ultra wide band microwave sensing and imaging using time-reversal techniques: A review," *Remote Sensing*, Vol. 9, 466–495, 2009.
20. Yavuz, M. E. and F. L. Teixeira, "Ultrawideband microwave sensing and imaging using time-reversal techniques: A review," *Remote Sensing*, Vol. 9, 466–495, 2009.

21. Hossain, M. D., F. Yang, M. J. Abedin, and A. S. Mohan, "Time reversal microwave imaging for the localization and classification of early stage breast cancer," *Proceedings of the Asia-Pacific Microwave Conference*, 477, 2011-978-0-85825-974-4 © 2011, Engineers Australia, 2011.
22. Salvador, S. M. and G. Vecchi, "Experimental tests of microwave breast cancer detection on phantoms," *IEEE Trans. Antennas Propag.*, Vol. 57, 1705–1712, Jun. 2009.