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RECONSTRUCTION OF EXTREMELY DENSE BREAST COMPOSITION UTILIZING INVERSE SCATTERING TECHNIQUE INTEGRATED WITH FREQUENCY-HOPPING APPROACH

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ABSTRACT

The Forward-Backward Time-Stepping (FBTS) inverse scattering technique is utilized for breast composition reconstruction of an extremely dense breast model at different center frequencies. A numerical extremely dense breast phantom is used and resized to suit the Finite-Difference Time-Domain (FDTD) lattice environment utilizing two-dimensional (2-D) FBTS technique. The average value of fibro glandular region for reconstruction with Frequency-hopping approach applied is much closer to average value of the actual image compared to the reconstruction without Frequency-approach applied. Hence, the composition of the extremely dense breast model can be reconstructed with Frequency-hopping approach is applied and the details of the reconstruction is also enhanced.

Keywords: breast imaging, frequency-hopping, inverse scattering.

INTRODUCTION

In developed country, breast cancer is a top ranked cancer although it is rare in men (DeSantis *et al.* 2014). Based on the findings, breast cancer ranks first among the women especially women aged between 20 to 59 years old. According to the breast cancer mortality trend, there will be 40,430 expected deaths caused by breast cancer which includes 40,000 women and 430 men as reported in Siegel *et al.* (2014). Therefore, annually breast screening is essential for early breast cancer detection and proper treatment to reduce the breast cancer mortality.

Clinical breast examination and mammography are the common breast screening methods for women at average risk. X-ray mammography is the standard screening method for breast tumour detection (Champaign and Cederbom, 2000). Based on the studies on mammography, radiologists recommended depicting the severity by using the American College of Radiology's (ACR) Breast Imaging Reporting and Data System (BI-RADS). BI-RADS becomes the standard in the mammographic density assessment (Liberman, 2002).

According to the studies in Tabar and Dean (2010), it indicated that the breast density is one of the risk factors causing missed cancers (false-positive and false-negative) in mammographic interpretations especially on dense breasts. The sensitivity of the X-ray screening mammography is lower for women with heterogeneously dense or very dense breasts according to Joy *et al.* (2005). In Kolb *et al.* (2002) stated that more than 11,000 women without clinical symptoms of breast cancer, the sensitivity of mammography was only 48% for the extremely dense breasts compared to the entire sample of women with 78% sensitivity.

The mentioned limitations have demonstrated a weighty challenge to the accuracy of early detection of breast cancer. It is also contributing to the alternative detection techniques by many researchers (Li and Hagness, 2001), (Hassan and El-Shenawee, 2011). The nonionizing microwave breast imaging is rationale due to the significant contrast in the dielectric properties of normal breast tissue and malignant tumours (Chaudhary *et al.* 1984). There are various types of active microwave approaches utilizing frequency-domain inverse scattering (Qianqian *et al.* 2004) and ultra-wideband (UWB) radar-based techniques (Li *et al.* 2004) for breast imaging. These approaches demonstrated that the tumours can be detected both in phantom experiments and numerical studies (Ping *et al.* 2009). Furthermore, time-domain scattering data contains more information as compared to frequency-domain scattering data. Hence, electromagnetic imaging in time-domain has the potential to reconstruct electrical profiles more accurately.

In this paper, there will be discussing the Forward-Backward Time-Stepping (FBTS) technique utilizing broadband microwave signals in order to overcome the inverse scattering problem in time domain. This technique was reported by Takenaka *et al.* (2000) for a simple one-dimensional case and has been extended for reconstruction of a two-dimensional (2-D) heterogeneous breast model (Johnson *et al.* 2008), (Ping *et al.* 2008). In this paper, research work is focused on 2-D FBTS utilizing the numerical extremely dense breast model in free space for breast composition reconstruction. FBTS technique possesses the ability to reconstruct the composition of the extremely dense breast.

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METHODOLOGY

Forward-backward time-stepping technique

The Forward-Backward Time-Stepping (FBTS) technique utilizes the broadband microwave signals to solve the inverse scattering problems in time domain. It possesses the potential to reconstruct images which provide useful quantitative information about the location, shape and the internal composition of the breast.

The aim of this technique is to determine the shape, location and electric properties of any electromagnetic inverse scattering problem. The electric properties include the permittivity, permeability, electric conductivity and magnetic conductivity. Figure-1 shows a typical configuration of an active microwave tomography setup for FBTS inverse scattering problem. The breast is assumed to be embedded in a free space. The breast is illuminated successively by M short pulsed waves generated by current sources $s_m(r,t)$ located at $r = r_m^t (m = 1, 2, ..., M)$.

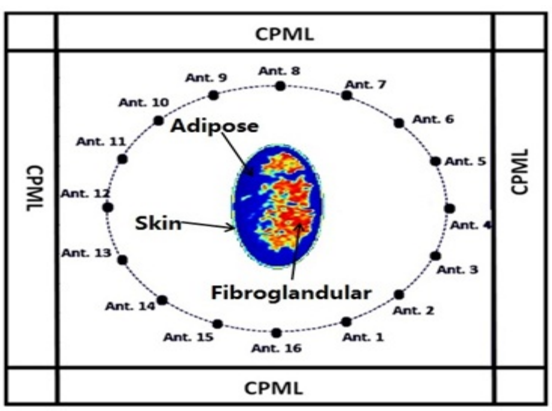

Figure-1. Configuration of the FBTS in 2-D FDTD scheme.

The major challenge in solving inverse scattering problem is reconstructing the electric properties' profile utilizing the knowledge of the transient field data measured at several observation points $r = r_n^r (m = 1, 2, ..., N)$ for each illumination. For the initial condition, the currents are assumed to be generated at time t=0 and there are no electromagnetic fields found before time t=0. Hence, the total electromagnetic fields $v_m(r,t)$ for the m^{th} current source $s_m(r,t)$ satisfy the following Maxwell's equation:

$$L v_m = s_m \quad (1)$$

Under zero initial condition for

$$v_m(r, 0) = 0 \quad (2)$$

To initialize the FBTS procedure, an optimization problem is formulated in the form of cost functional to be minimized.

$$Q(\boldsymbol{p}) = \int_0^T \sum_{m=1}^{M} \sum_{n=1}^{N} K_{mn}(t) |\boldsymbol{v}_m(\boldsymbol{p}; \boldsymbol{r}_n^r, t) - \tilde{\boldsymbol{v}}_m(\boldsymbol{r}_n^r, t)|^2 dt \quad (3)$$

where $\boldsymbol{p}$ is a medium parameter vector function as expressed in Equation (3), $K_{mn}(t)$ is a non-negative weighting function which takes a value of zero at time t=T (T is the time duration of the measurement), and $v_m(p; r_n^r, t)$ and $\tilde{v}_m(r_n^r, t)$ are the calculated electromagnetic fields for an estimated medium parameter vector $\boldsymbol{p}$ and the measured electromagnetic fields due to m^{th} source, respectively.

Frequency-hopping approach

Frequency-hopping approach is utilized to process multi-frequency microwave measurement data. This approach can be used to reconstruct larger dielectric bodies for microwave imaging with higher fidelity compared to a single-frequency reconstruction. This approach uses only data at a few selected frequencies leads to reduce data acquisition time in a practical system. The frequency of the illuminating field is increased for a better resolution of the reconstructed image. For large structures or high-contrast objects, they can be imaged at lower frequencies while higher frequency of the illuminating field are used for the reconstruction of high-contrast normal breast tissues by interpreting the initial guess from the resultant result of the reconstruction at lower frequency for the proceeding iterations. Hence, frequency-hopping approach can be used for the reconstruction of large structures or high-contrast normal breast tissues.

Numerical breast phantom

Numerical extremely dense breast phantom retrieved from University of Wisconsin-Madison Computational Electromagnetics (UWCEM) numerical phantom repository (UWCEM numerical breast phantoms repository, 2012) is utilized for this research. A series of T1-weighted magnetic resonance images (MRIs) of patients in a prone position are used to derived the numerical breast phantom. Each numerical phantom consists of a 3-D grid of cubic voxels with the size of 0.5mm x 0.5mm x 0.5mm for each voxel. The breast model includes an approximately 1.5mm thickness of skin layer, a 1.5cm thickness of subcutaneous fatty layer at the base of the breast model and a 0.5cm thickness of muscle chest wall. Debye parameters are used to describe the dispersive breast tissue dielectric properties and can be efficiently incorporated into FDTD scheme for microwave breast cancer detection. The voxel intensities within the 3-D numerical breast phantom are transformed into dispersive dielectric properties utilizing spatial distribution. The model is resized from 0.5mm x 0.5mm x 0.5mm to 1.0mm x 1.0mm x 1.0mm in order to satisfy the FDTD grid size. This can be done by interpolating the model linearly. Figure-2 shows the 2-D slices on the coronal plane are selected for the numerical simulations utilizing FBTS technique in FDTD lattice.

SIMULATION SETUP

Reconstruction of a 2-D numerical extremely dense breast model is done to demonstrate the validity of the FBTS technique to reconstruct the composition of extremely dense breast model. There are 16 antennas utilized in this work as shown in Figure-1. Each antenna will become transmitter sequentially to transmit a pulse while the remaining 15 antennas will become receivers to collect the scattered fields in the FDTD lattice environment. A sinusoidal modulated Gaussian pulse with different center frequencies f_c is excited by the transmitter into the FDTD lattice environment. The FDTD lattice environment is surrounded by Convolutional Perfectly Matched Layer (CPML) to prevent the reflection of the signal at the boundary of the environment.

The entire FDTD lattice environment is set as free space with relative permittivity, $\varepsilon_r = 1.0$ and conductivity, $\sigma = 0.0$. The breast model is then simulated at different center frequencies from 1GHz until 4GHz. The frequency-hopping approach is applied in order to enhance the resolution of the reconstruction of the breast model's dielectric properties.

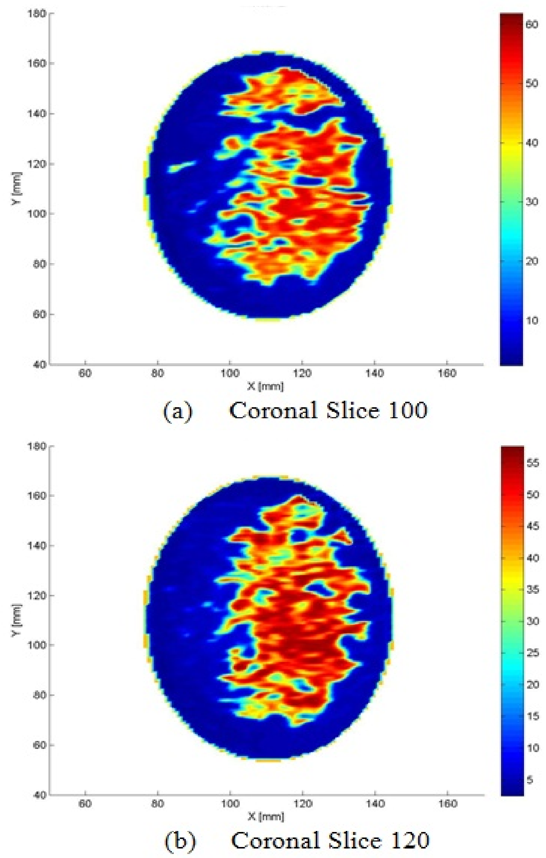

Figure-2. Actual relative permittivity of the numerical breast model.

RESULTS AND DISCUSSION

Figure-3 and Figure-4 show the reconstructed images of an extremely dense breast utilizing FBTS technique. The relative permittivity of this breast can be reconstructed roughly at center frequency of 1GHz as illustrated in Figure 3(a) and Figure 4(a), respectively. The average value of the relative permittivity for the fibro glandular region are ε_{r_a} = 37.287 (coronal slice 100) and ε_{r_a}= 37.663 (coronal slice 120), which are significantly lower than the actual values of ε_{r_a}= 40.061 (coronal slice 100) and ε_{r_a}=40.394 (coronal slice 120). In comparing Figure-3(a) to Figure-3(d), the fibro glandular region of the extremely dense breast model only can be estimated at center frequency of 1GHz. However, the finer details or smaller region of the fibro glandular region cannot be reconstructed. This shows that lower frequency only able to reconstruct the larger region of the extremely dense breast composition. Therefore, higher frequency is required in order to reconstruct the small region. However, the composition of the extremely dense breast was unsuccessfully reconstructed due to the effect of nonlinearity in the optimization procedure. Hence, the Frequency-hopping approach is applied to improve resolution of the reconstruction and overcome the effect of nonlinearity.

From the results obtained as in Figure-5(a) and Figure-6(a), Frequency-hopping approach is applied from 1GHz to 2GHz with the average values of the relative permittivity for the fibro glandular region are ε_{r_a} = 37.6143 (coronal slice 100) and ε_{r_a}= 38.1619 (coronal slice 120), which are closer to the actual values of ε_{r_a}= 39.513 (coronal slice 100) and ε_{r_a}=39.84 (coronal slice 120) compared to the reconstruction using single center frequency with average value of fibro glandular region of ε_{r_a}= 34.615 (coronal slice 100) and ε_{r_a}=31.487 (coronal slice 120), respectively.

As shown in Table-1 and Table-2, the average values for the fibro glandular region are getting closer to the actual images as the center frequency increases by applying the Frequency-hopping approach.

The composition of the extremely dense breast can be reconstructed significantly compared to the reconstruction using a single center frequency only. This shows that the effect of nonlinearity of the local optimization approach can be overcome by utilizing Frequency-hopping approach. This is also proven that Frequency-hopping approach enables the FBTS to estimate the large region of fibro glandular at lower frequency and estimate the smaller region of fibro glandular at higher frequency.

Previous works done by Takashi *et al.* 2008 and his co-researchers were utilizing a high contrast numerical breast model whereby the difference between the dielectric properties of the tumour and fibro glandular region is large. In this paper, the numerical breast model used is the low contrast numerical breast model. The difference

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between the dielectric properties of the tumour and fibro glandular region is small.

The results obtained in Figure-3 and Figure-4 show the images cannot be reconstructed with the center frequency above than 2GHz due to the huge difference of the dielectric properties of the fibro glandular tissues and fatty tissues. Hence, Frequency-hopping approach is needed to reconstruct the low contrast numerical breast model.

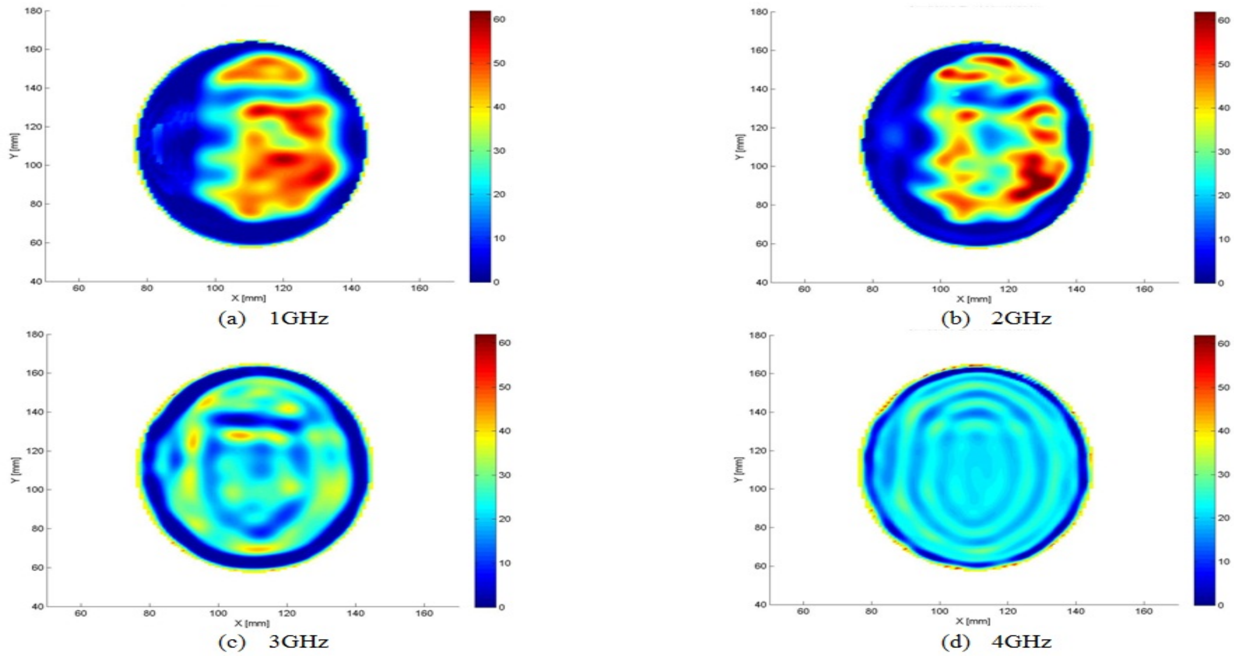

Figure-3. Reconstruction of relative permittivity using FBTS technique at different frequencies (Coronal Slice 100).

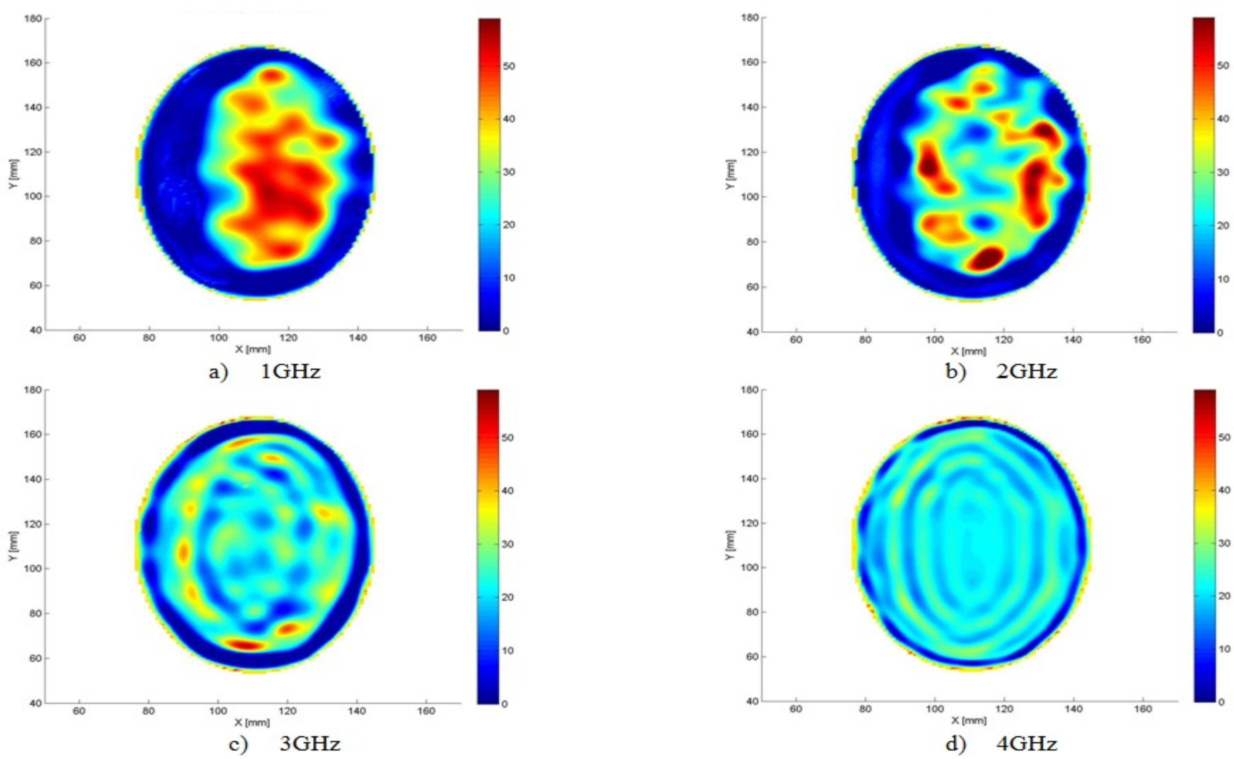

Figure-4. Reconstruction of relative permittivity using FBTS technique at different frequencies (Coronal Slice 120).

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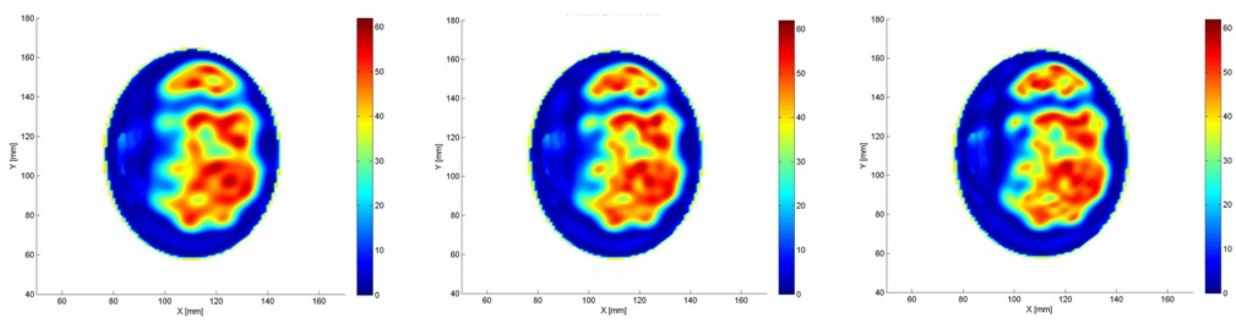
Table-1. The average value of reconstructed breast model (Coronal Slice 100).

	Fibroglandular $\varepsilon_{r\,avg}$	Fatty $\varepsilon_{r\,avg}$
Actual at 1GHz	40.061	4.781
Actual at 2GHz	39.513	4.748
Actual at 3GHz	38.644	4.697
Actual at 4GHz	37.516	4.631
Frequency-hopping from 1GHz to 2GHz	37.614	6.782
Frequency-hopping from 2GHz to 3GHz	37.255	6.204
Frequency-hopping from 3GHz to 4GHz	36.746	5.723

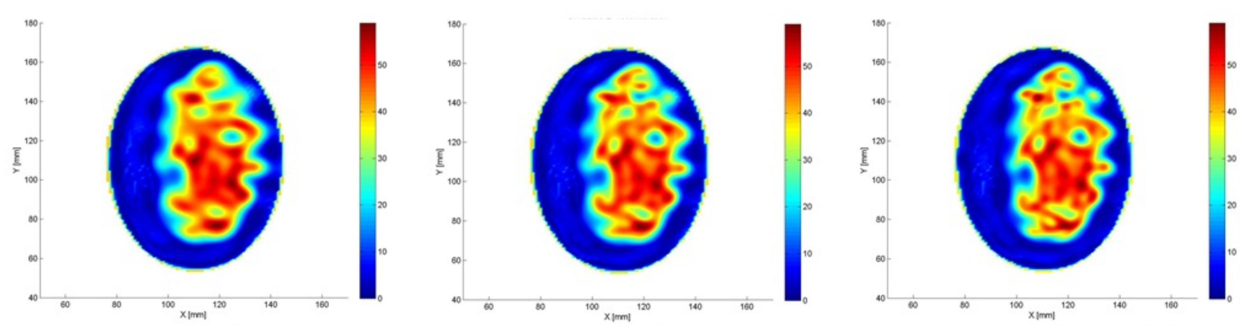
Table-2. The average value of reconstructed breast model (Coronal Slice 120).

	Fibroglandular $\varepsilon_{r\,avg}$	Fatty $\varepsilon_{r\,avg}$
Actual at 1GHz	40.394	4.815
Actual at 2GHz	39.840	4.782
Actual at 3GHz	38.964	4.730
Actual at 4GHz	37.826	4.663
Frequency-hopping from 1GHz to 2GHz	38.162	6.541
Frequency-hopping from 2GHz to 3GHz	37.704	6.082
Frequency-hopping from 3GHz to 4GHz	37.072	5.673



(a) From 1GHz to 2GHz (b) From 2GHz to 3GHz (c) From 3GHz to 4GHz

Figure-5. Reconstruction of relative permittivity using FBTS technique with Frequency-hopping approach applied at different frequencies (Coronal Slice 100).



(a) From 1GHz to 2GHz (b) From 2GHz to 3GHz (c) From 3GHz to 4GHz

Figure-6. Reconstruction of relative permittivity using FBTS technique with Frequency-hopping approach applied at different frequencies (Coronal Slice 120).

CONCLUSION

The iterative FBTS algorithm can be used to solve the inverse scattering problem using broadband microwave signal in time domain for breast composition reconstruction. The composition of an extremely dense breast model can be reconstructed with the integration of Frequency-hopping approach into iteration FBTS algorithm.

The iterative FBTS algorithm integrated with Frequency-hopping approach will be further investigated by implanting different size of tumour into the fibro glandular region of the numerical breast model.

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