MICROWAVE IMAGING FOR EARLY STAGE BREAST TUMOR DETECTION AND DISCRIMINATION VIA COMPLEX NATURAL RESONANCES

By

Fan Yang

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University of Technology, Sydney

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CERTIFICATION

I certify that this thesis has not already been submitted for any degree and is not being submitted as part of candidature for any other degree.

I also certify that this thesis has been written by me and that any help that I have received in my research work, preparing this thesis, and all sources used, have been acknowledged in this thesis. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate

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(Fan Yang)

In loving memory of my father, Zengke Yang (1951-2013)

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ABSTRACT

In this thesis, a new microwave imaging technique for early stage breast cancer detection is developed to achieve two key aims: (i) to reconstruct the radar image of the suspicious region within the breast and (ii) to decide whether a suspicious region has malignant or benign tumors by differentiating their morphological features in terms of their complex natural resonances.

For our investigations we employ both numerical and chemical tissue mimicking breast phantoms. The breast phantom is illuminated by UWB pulses radiated from antenna elements arranged in a multistate configuration surrounding the breast. An efficient pre-processing technique is proposed to process the received pulses for the removal of early-time artifacts. To reduce the interferences of the background tissue clutter in inhomogeneous breast environment, a new time-of-arrival (TOA) auto-calibration is presented to estimate accurate TOA for confocal imaging. For determining the suspicious region within the breast, a novel and efficient data independent beam former known as Modified Weighted Delay and Sum (MWDAS) algorithm has been proposed. Once the suspicious region is localized by MWDAS method, the waveform of late-time backscattered field will be estimated using a proposed two-stage waveform estimation method. The accuracy of the waveform improves the extraction of complex natural resonances (CNR) that will be used to discriminate of whether a suspicious tissue is malignant or benign. Basing on radar target discrimination, we propose that the CNRs extracted from the late-time resonant tumor response can be closely related their morphological properties: spiculated lesion has CNR poles that differ from CNR poles of a smooth lesion. To validate our proposal, we perform FDTD simulations on 2D and 3D numerical breast phantoms that have been developed based on MRI-derived tissue dielectric properties. These simulations have revealed that the CNRs from malignant tumors have significant lower damping factors than the benign ones. These simulation

results helped to reconfirm that it is possible to distinguish malignant and benign breast tumors based on their CNRs.

To validate the proposed method of tissue discrimination, we have developed an experimental UWB imaging prototype using novel UWB sensors and tissue mimicking chemical breast phantoms to carry out preliminary preclinical experiments. Three novel end-fire compact sized UWB antennas have been proposed. After thoroughly investigating their characteristics, a novel UWB horn antenna known as BAHA that offered superior UWB performance is chosen, fabricated and measured to confirm its characteristics. A prototype experimental imaging system that incorporates 32 BAHA antenna elements forming a hemispherical UWB array is fabricated and tested using a vector network analyzer. Tissues mimicking chemical phantoms with dielectric properties similar to human breasts have been manufactured to have both adipose-tissue dominated homogeneous phantom with a dielectric contrast of 4:1 and a low-adipose in-homogeneously dense phantom with dielectric contrast of 1.7:1. Experimental results obtained using the hemispherical array prototype and phantoms have shown that dielectric inserts (12mm diameter) that mimic malignant and benign lesions can be successfully detected from both high and low dielectric contrast scenarios. Tumor mimicking lossy dielectric inserts with both irregular and smooth patterns have also been fabricated using chemicals to represent malignant and benign tumors respectively.

Finally, measured data from experimental prototype have demonstrated that tissue shape can be discriminated via CNRs. The experimental results confirmed that the proposed UWB antenna array is capable of picking up undistorted late-time signals from embedded tumor-mimicking dielectric inserts with different morphological profiles to offer reliable CNR extraction. Matrix Pencil Method is employed to extract CNRs from late time responses. Our investigations have confirmed that damping factors of the extracted CNRs from both spiculated and smooth inserts can be used to differentiate their shapes which are quite promising for early stage breast cancer detection.

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List of Symbols

$E_{i,j}(t)$	Received raw data between *i*th to *j*th antennas
$\|\cdot\|$	Euclidean norm
$\boldsymbol{r}$	Confocal point used in confocal microwave imaging
H	Complex conjugate transpose
W_{BF}	Beamforming weight
dia	diameter
Δt	Time interval used in FDTD simulation
$\mathbf{a}(\theta)$	Steering vector of a narrow band signal
θ	The angle at which an incident narrow band signal arrive at antenna array
λ	wavelength
ε_r	permittivity
σ	conductivity
E	Expectation
G	Array gain
σ^2	Signal power
$\mathbf{R}$	Cross-spectral density matrix
∂	constraint parameter on steering vector
$\prod_{i=1}^{M} x_i$	Product over x_i from *i* to *M*
S_m	mth s-plane CNR pole
Z_m	mth z-plane CNR pole
α_m	mth damping factor of CNR
f_m	mth resonant frequency of CNR
C_m	mth complex amplitude of CNR
std(·)	Calculate the standard deviation of focused region
μ	TOA compensation factor
ρ	Constrain parameter to terminate the process of TOA autocalibration
β_{MMSE}	Scaling parameter used in minimum mean-square-error beamforming
n_{norm}	Normalized CNR error
$\mathbf{F}$	Antenna fidelity
S11	Reflection coefficients
S21	Transmission coefficients
$\boldsymbol{e_c}$	Antenna coupling efficiency

List of Abbreviations

BAHA	Balanced antipodal horn antenna
BAVA	Balanced antipodal Vivaldi antenna
CMI	Confocal microwave imaging
CNR	Complex natural resonances
CPML	Convolutional perfectly matched layer
DAS	Delay-and-sum
DCIS	Ductal carcinoma in situ
DFT	Discrete Fourier transform
DMAS	Delay-multiply-and-sum
FDTD	Finite-Difference Time-Domain
GPR	Ground penetrating radar
iFFT	inverse Fast Fourier Transform
IDAS	Improved delay-and-sum
LCIS	Lobular carcinoma in situ
MAMI	Multistatic adaptive microwave imaging
MIST	Microwave-imaging-via-space-time
MWDAS	Modified-weighted-delay-and-sum
MMSE	Minimum mean-square-error
MPM	Matrix pencil method
MVDR	Minimum variance distortionless beamformer
NFD	Near field directivity
NCR	Normalized CNR error
PEC	Perfect electric conducting
PML	Perfectly matched layer
RCB	Robust capon beamforming
RCS	Radar cross section
RMSE	Root-mean-square-error
SCB	Standard capon beamforming
SEM	Singularity expansion method
SNR	Signal-to-noise ratio
SCR	Signal-to-clutter ratio
TOA	Time-of-arrival
TG-RCB	Transmitter grouping robust capon beamforming
TSAR	Tissue sensing adaptive radar

UWB	Ultra-wideband
UWCEM	University of Wisconsin Computational Electromagnetics Laboratory
VNA	Vector network analyzer