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APTITUDE OF NONINVASIVE NEAR-FIELD MICROWAVE NONDESTRUCTIVE WAVEGUIDE-BASED TESTING TECHNIQUES FOR BREAST TUMOR DETECTION

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1. Introduction

The spread of breast cancer worldwide and the critical need for new technologies to improve detection, diagnosis and treatment of breast cancer present a challenge to the standard nondestructive testing (NDT) methods and their influence in medical applications [1-4]. Difficulties arise from the physical property inhomogeneities of the breast tissues, as well as the relative high absorption and scattering of the radiated signals. Microwave imaging and nondestructive testing of biological structures has been of interest for many years. Recently, microwave imaging and nondestructive testing has been applied to the detection of breast cancer [1-4]. The ability of microwaves to penetrate deeply inside dielectric materials like the breast tissue makes microwave nondestructive testing and evaluation (NDT&E) techniques very attractive for interrogating such structures [5-6]. The sensitivity of microwaves to the presence of dissimilar layers and tumor (inclusion) in the breast tissue allows for accurate measurement for tumor presence [7]. Microwave NDT techniques, when applied to breast tissues, are performed on a contact or non-contact manner.

Microwave imaging and NDT techniques offer several unique and appealing advantages over other techniques for inspecting tumors in breast. Microwave breast imaging is attractive because both ionizing radiation and breast compressions are avoided. Also, microwave imaging is noninvasive harmless and nondestructive screening tool. Microwave imaging is based on transmitting a microwave signal into a dielectric material and using the magnitude and/or phase information of the transmitted and/or the reflected signal to create a two or three dimensional image of the breast. The output signals of the open-ended waveguide microwave sensors are easy to interpret and minimal operator skills are required. Besides, when near-field microwave imaging and NDT technique is compared with ultrasonic, magnetic resonance imaging (MRI), mammograms, and biopsy methods, microwave techniques require no coupling agent, do not need surgical operation, do not suffer from high signal attenuation, are relatively inexpensive and they are not time-consuming. Microwave nondestructive testing (NDT) techniques may be exploited for regular examination of different tumors and may be adapted to on-line concurrent detection environments. These characteristics enhance the detection capability of breast cancer in its early stages and allow self-examination to be valid. Generally, a near-field microwave detection/inspection technique requires simple hardware and minimum operator expertise. The measurement system can be battery operated, handheld, used in an array fashion to quickly interrogate a large area and the measurements can be conducted on-line and in real time [4], [8-9].

2. Theoretical Formulations

Modeling the interaction between electromagnetic waves and multilayer dielectric media such as the breast is essential for tumor detection. Breast is made of layers, skin and tissue. Once irradiated by a microwave signal, the electric field in each layer may be expressed in terms of the media constitutive parameters for any stratified dielectric media terminated with a dielectric infinite half-space. In this work, the Fourier Transform matching technique will be utilized to express the electric field in a recursive model. Once the field coefficients are obtained, theoretical images can be formed by calculating the reflection coefficient at each scanned point. A general stratified structure

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of any number of dielectric layers (N) is considered. The n^{th} layer has complex relative dielectric constant ε_{rn} and thickness d_n. A waveguide with dominant mode excitation (TE_{10}) is used to illuminate the breast with electromagnetic waves at microwave frequencies. The waveguide aperture lies in the xy-plane and is centered at the origin as shown in figure 1. The breast is placed in the near-field region of the rectangular waveguide. The intention is to find the electric field's coefficients in each layer.

For TE_{10} mode, the excitation aperture fields are:

$$\overline{E}_{ap}(x,y) = \hat{y}(1+\Gamma)\frac{j\pi\varpi\mu}{ak_{c10}^2}\sin(\frac{\pi}{a}x) \tag{1}$$

$$\overline{H}_{ap}(x,y) = \hat{x}(1-\Gamma)\frac{j\pi\varpi\mu}{ak_{c10}^2}Y_o\sin(\frac{\pi}{a}x) \tag{2}$$

Where $k_{c10} = \frac{\pi}{a}$, and a is the broad dimension of the waveguide, $\omega=2\pi f$, and f is the frequency of operation, μ is the permeability of the media.

$Y_o = \frac{\sqrt{K^2 - k_{c10}^2}}{\omega\mu}$, is the admittance of the fundamental mode and $K^2 = \varpi^2\varepsilon_1\mu_1$ and Γ, is the effective reflection coefficient.

To model the interaction between the breast and the electric field, we need first to calculate the electric field distribution at every coordinate point (*x, y, z*). This requires finding field coefficients in each layer of the structure. Starting from Maxwell's equations, we can obtain the field solution by applying the Fourier Transform technique. This involves expanding the field in each layer in terms of the Fourier Integrals and applying boundary conditions at each interface. Having the solution for the field in the first layer, the reflection coefficient is calculated from the effective admittance at the waveguide's aperture [8-9]. The normalized admittance at the waveguide aperture is written as:

$$Y_s(x,y) = \frac{j}{4\pi^3\omega\mu Y_o\sin(\frac{\pi x}{a})}\left\{\begin{array}{l}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{C_{11}I^*}{1+g_{11}}(-1+g_{11})e^{j(k_x x+k_y y)}dk_x dk_y \ldots\ldots : x\in[x_1,x_2], y\in[y_1,y_2] \\ \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{C_{12}I^*}{1+g_{12}}(-1+g_{12})e^{j(k_x x+k_y y)}dk_x dk_y \ldots\ldots\ldots : otherwise\end{array}\right\} \tag{3}$$

The detailed expressions of the constants involved in this equation are given in [9]. The reflection coefficient is given by:

$$\Gamma = \frac{1-Y_s}{1+Y_s} \tag{4}$$

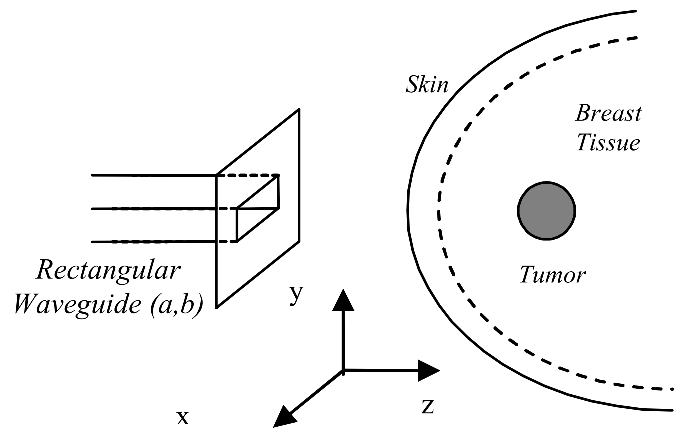

Figure 1: The schematic diagram of an open-ended rectangular waveguide sensor radiating into a breast with tumor.

3. Simulations and Analysis

The breast model used in this investigation consists of breast tissue surrounded by an outer layer of skin. The breast tissue consists of fat, muscle and blood. This model is used for feasibility studies of tumor detection in two-dimensional cross sections, for theoretical image formation and for experimental investigation. Skin of 2 mm thickness has a relative permittivity (ε_r) of 36 and conductivity (σ) of 4 S/m. Breast tissue of 60 mm thickness has a relative permittivity (ε_r) of 9 and conductivity (σ) of 0.4 S/m. A tumor of finite dimensions at certain depth located within the breast tissue has a relative permittivity (ε_r) of 50 and conductivity (σ) of 4 S/m [8-9]. These dielectric properties and this breast model will be adopted for all the simulation results. We assume TE_{10} excitation mode for the waveguide with propagation in the z-direction. Reflection coefficient has a phase and magnitude associated with it. Consequently phase and/or magnitude images may be obtained. Figures 2 and 3 show the magnitude and phase images for a 6×6×3 mm tumor 15 mm deep, respectively. These images were obtained using an X-band waveguide loaded with a dielectric material (ε_r =12.25) operating at frequency of 3.5 GHz. The resolution in x and y directions is 1 mm. The magnitude image has a dynamic range of 0.4 and phase image has 2 degrees. In practice, the magnitude and the phase dynamic ranges are relatively high. The presence of the tumor is clearly visible (the dark black area). Also, the resolution of the images is high such that the xy dimensions of the tumor can be estimated directly from the image. Effects of the waveguide's radiation pattern (side lobes, beamwidth, etc.) are also indicated on the images.

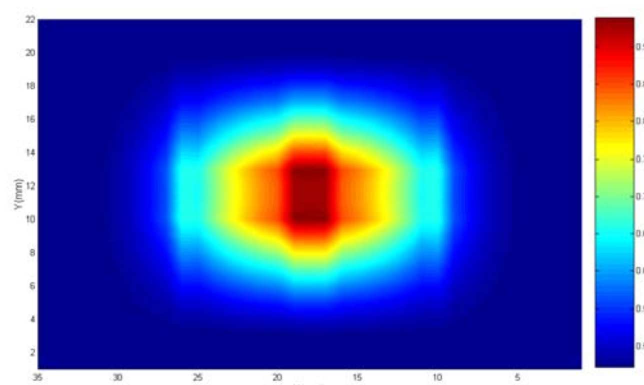

Figure 2: Magnitude image of the breast with 6x6x3 mm³ tumor at 15 mm depth at 3.5 GHz.

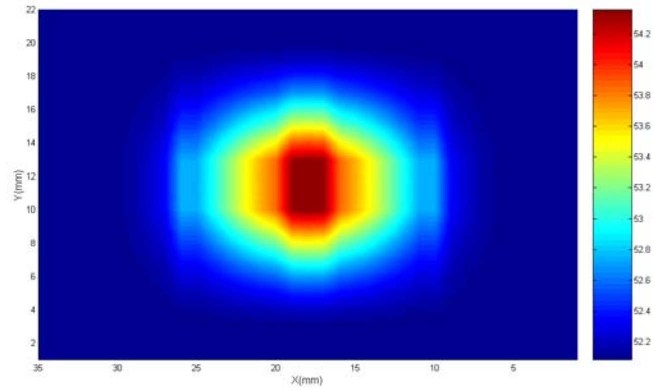

Figure 3: Phase image of the breast with 6x6x3 mm³ tumor at 15 mm depth at 3.5 GHz.

4. Conclusions

Near-field microwave nondestructive non-ionizing noninvasive harmless imaging systems utilizing open-ended rectangular waveguide sensors are coming of age and have proved to be a promising approach for breast cancer detection. Also, they will become a successful clinical complement to other conventional screening techniques such as x-ray mammography, ultrasound and MRI. In general, these systems are designed to detect and assess the effects of possible defects in opaque dielectric structures. One of their most critical applications is imaging of malignant tumors in the patient's breast. Radiation patterns and images of magnitude and/or phase of reflection coefficient for different tumor depths at multiple operating frequencies will be obtained and discussed. Based on these images, an optimal inspection system for tumor detection can be achieved and implemented.

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