The use of Microwave, Millimeter Wave and Terahertz Spectroscopy for the Detection, Diagnostics and Prognosis of Breast Cancer

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***Abstract*— We have analyzed the broadband dielectric properties of cancerous and non-cancerous tissues were analyzed at the microwave, millimeter wave, and terahertz frequencies. In-vitro measurements were obtained using the vector network analyzer-based coaxial probe (2 – 50 GHz), backward-wave oscillator-based free space quasi-optical spectroscopy (30- 120 GHz), and dispersive Fourier transform spectroscopy methods (60 -1.5 THz). All three techniques were modified to yield the complex real and imaginary permittivity, absorption coefficient, refractive index, and transmission data over an extended frequency range from 2 GHz to 1,500 GHz. The results reveal the characteristic signatures of breast tissues and display a significant difference in the electromagnetic response of cancerous (malignant) and non-cancerous (benign) tissues. All three techniques provide prospects for extending in-vitro measurements to in-vivo breast cancer detection and diagnostics.**

I. Introduction And Background

The electrical characteristics of human tissues have been of great interest since Schwan conducted early *in-vitro* studies on tissues and cells [1]. In recent years, Popovic, Okoniewski, Hagness, Souvorov, M. A. Stuchly, and S. S. Stuchly have developed several cancer detection techniques using confocal systems, capacitive sensors, antennas, and probes [2]-[3]. However, research limited to microwave spectroscopy or imaging has several disadvantages. Probe and sensor measurements are extremely sensitive to surface level modulations, the probe-sample interface, and external environmental conditions. Moreover, while microwave radiation provides deeper radiation penetration depths compared to terahertz and submillimeter signals, microwaves also suffer from a lack of resolution. This limits the utilization of microwave techniques for precise high resolution dielectric characterization of tissues. Hence, complete comprehension of human tissue spectroscopy must involve a broadband approach where microwave radiation can achieve penetration and low power millimeter, submillimeter, and terahertz waves can be utilized for resolution purposes. This study completes the first step in this process by examining the dielectric characteristics of tumorous and non-tumorous (normal) breast tissues at the microwave, millimeter wave, and terahertz frequencies.

Microwave measurements in this study were conducted with the use of a modified coaxial probe technique. This reliable method can potentially be used for *in-vivo* measurements and is thus important to utilize. Microwave measurements are supplemented with transmission data using the backward wave oscillator-based free space quasi-optical spectroscopic method from 35 GHz to 120 GHz. This technique provides relatively high output power for coherent millimeter wave radiation which can be advantageous while studying highly absorbing tissues.

Data for a large part of the frequency spectrum from 60 GHz to 1.5 THz was acquired by employing specialized Dispersive Fourier Transform Spectroscopy. This high-precision technique yields dielectric data with a sensitivity of 10^{-6} thus providing accuracy and resolution at extremely low powers. In addition, Dispersive Fourier Transform Spectroscopy can accommodate various tissue shapes, sizes, and compositions. Sample holders designed precisely to the dimensions of each tissue were constructed for the Fourier transform and free space quasi-optical spectrometers. Since the experimental setup and electromagnetic source power intensity vary at the microwave, millimeter wave, and terahertz ranges, our results for the different spectral ranges and techniques are not expected to “link up”; however, a general trend in the broadband dielectric behavior of the breast tissues is anticipated. This paper shall discuss the utilization of the vector network analyzer-based coaxial probe, backward wave oscillator-based free space quasi-optical spectroscopy, and Dispersive Fourier Transform Spectroscopy techniques for dielectric characterization of non-cancerous and cancerous breast tissues at high frequencies.

II. Measurement technique and experimental setup

Breast tissues were obtained courtesy of the Tufts-New England Medical Center. After being removed from the donors’ bodies, the tissues were fixed and preserved in 10% formalin containers and subsequently transported to the High Frequency Materials Measurement and Information Center for analysis. No information is currently available on the background of the tissue donors. The samples were cut to a size of one inch diameter. In the future measurement will be carried out on fresh tissues and results will be reported at the conference

A. Dielectric Permittivity Measurement by Coaxial Probe

Coaxial probe measurements from 2 to 18 GHz were acquired by connecting a 2.4 mm coaxial probe to an 8510C Vector Network Analyzer. Radiation supplied by the Vector

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Network Analyzer transmits and reflects through the specimen under test, providing the elementary reflection coefficients, ρ_1 and ρ_2. Using transmission theory, one can derive the reflection coefficient through the sample as:

$$\Gamma_L(\omega) = \frac{\rho_1 + \rho_2 e^{-2jkl}}{\rho_1 + \rho_1\rho_2 e^{-2jkl}} = \frac{\rho_1 + \rho_2 e^{-j\omega T}}{\rho_1 + \rho_1\rho_2 e^{-j\omega T}} \quad (1)$$

For the lossless case, T is the two-way travel time delay through a medium, η_1. Since a coaxial probe is being employed, a one-port measurement can be performed and Short-Open-Load terminations used to calibrate the machine. This technique only requires the acquisition of S_{11}. By using the infinite transmission line theory, the relationship between reflection coefficients Γ_L and S_{11} can be stated as $\Gamma_L = -S_{11}$. The load impedance normalized by the coaxial probe and input impedance seen by the Vector Network Analyzer may then be expressed as (2) and (3) respectively. After calibration, (3) can be simplified and the permittivity can be expressed as (4).

$$\frac{Z_L}{Z_{50}} = \frac{1+\Gamma_L}{1-\Gamma_L} = \frac{1-S_{11}}{1+S_{11}} \quad (2)$$

$$Z_i = Z_{50}\,\frac{Z_L + jZ_{50}\tan(kl)}{Z_{50} + jZ_L\tan(kl)} \quad (3)$$

$$\varepsilon_r = -j\left(\frac{120\pi}{50}\right)^2\left(\frac{1+S_{11}}{1-S_{11}}\right)\tan(kl) \quad (4)$$

It is important to mention that the phase of S_{11} is more than twice the phase of the tangent in equation (4). By using the appropriate Short-Open-Load calibration, we can acquire the highest reflection of S_{11}, which makes this technique superior to those that employ known references for the measurements.

B. Higher Power Backward Wave Oscillator-based Free Space Quasi-Optical Spectroscopy

Millimeter wave *in–vitro* transmittance measurements of non-tumorous and tumorous breast tissues were obtained by employing a free-space, quasi optical spectrometer. *Q*-, *V*-, extended *V*-, and *W*–band high-vacuum backward wave oscillators have been applied as sources of coherent radiation.

RESULTS

Fig. 1 exhibits the microwave measurements obtained in this research using a 2.4mm coaxial probe. BWO based transmission results can be seen in Fig.2. Here we can see much larger difference between tumorous and non-tumorous tissues. A promising idea is the expansion and development of the free space, quasi optical millimeter wave spectroscopy for *in-vivo* measurements and cancer diagnostics. In such a scenario, a human breast can be placed between two flat, plane-parallel, transparent windows to obtain transmission measurements and to detect the absorption level of the millimeter wave signal. This approach can be modified to develop a millimeter wave mammography system allowing non-invasive and non-destructive identification and detection of tumorous and non-tumorous breast tissues using the absorption coefficient and refractive index.

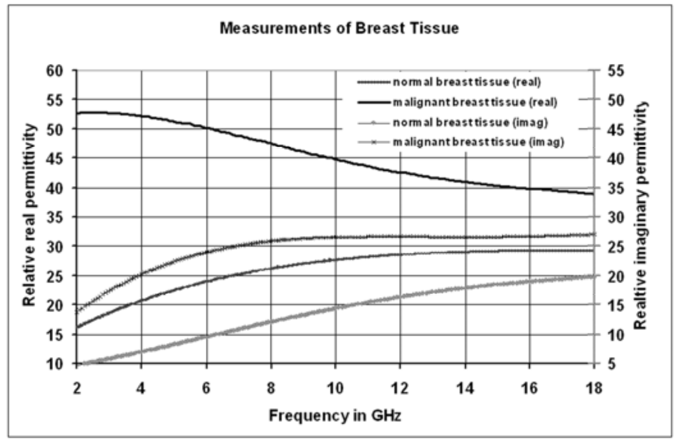

Fig.1 Complex permittivity measurements of normal (benign) and cancerous (malignant) breast tissue from human body

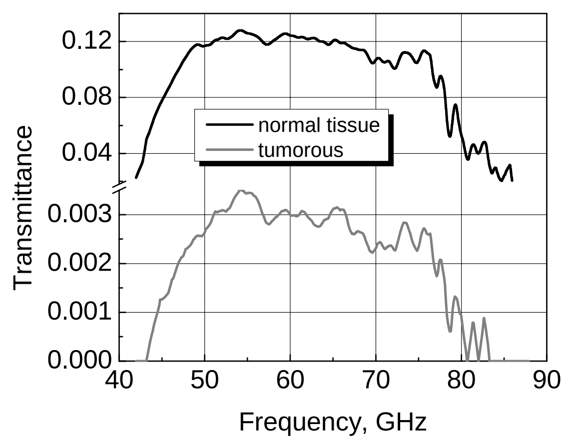

Fig. 2. The transmittance signal through non-tumorous (normal) and tumorous breast tissues as a function of frequency obtained using extended *V*- band backward wave oscillator-based free-space quasi-optical spectrometer. Note that the non-tumorous tissue is almost 40 times more transparent then the tumorous tissue.

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