

A 16-Element Wideband Microwave Applicator for Breast Cancer Detection Using Thermoacoustic Imaging

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Abstract— Microwave-induced thermoacoustic (TA) imaging is a hybrid technique that combines the high dielectric contrast of microwave imaging with the high resolution of ultrasound detection. This technique can achieve a penetration depth in excess of 5 cm, even in dispersive tissue. With all these capabilities, TA imaging is a suitable method for breast cancer screening, which requires a high contrast between cancer and benign tissues, and millimeter-level resolution. The most popular way to excite the imaging target is to employ a waveguide, which is limited in bandwidth and usually not well matched to the target for TA imaging. In this paper, a wideband and compact microwave applicator, which can efficiently excite the tissue in the near and quasi-near field range, is designed. A 16-element conformal phased array based on the proposed applicator focuses the microwave energy and controls the location of high specific absorption rate (SAR) region by tuning the phase of array elements. This architecture increases local SAR of the focus area and directly results in a higher signal-to-noise ratio (SNR) of the target region in the reconstructed image compared to uniform excitation. Full-wave electromagnetic simulations demonstrate the ability to localize and control the high SAR region across the target in the entire bandwidth.

1. INTRODUCTION

Microwave-induced thermoacoustic (TA) imaging [1–3] is a hybrid technique that combines the high dielectric contrast in the microwave range and the high resolution of ultrasound imaging. It can be used for frequent breast screenings [3] without posing ionizing radiation. In TA imaging, a short microwave pulse excites the tissue to generate a small differential temperature rise in the range of a millikelvin. The resultant thermal expansion generates pressure waves, which can be detected by the ultrasound transducer to reconstruct the image [4].

One challenge in TA imaging is the weak level of the generated pressure. A higher pressure level requires a higher local SAR which results from a higher microwave energy absorption. The majority of TA experiments utilize a waveguide as the RF excitation device [1–3, 5], but this method is not efficient in generating the desired SAR pattern in tissue. For breast cancer detection, for example, a high local SAR at the tumor site is desired to increase the generated pressure and SNR of the reconstructed image. To address this challenge, we propose to use a conformal phased array of applicators around the breast to increase local SAR at the target site. Using this method in the near and quasi-near field, we are able to move the focal point of the applicator array across the entire target by sequential beamforming. This sectionalized approach provides a high local SAR at

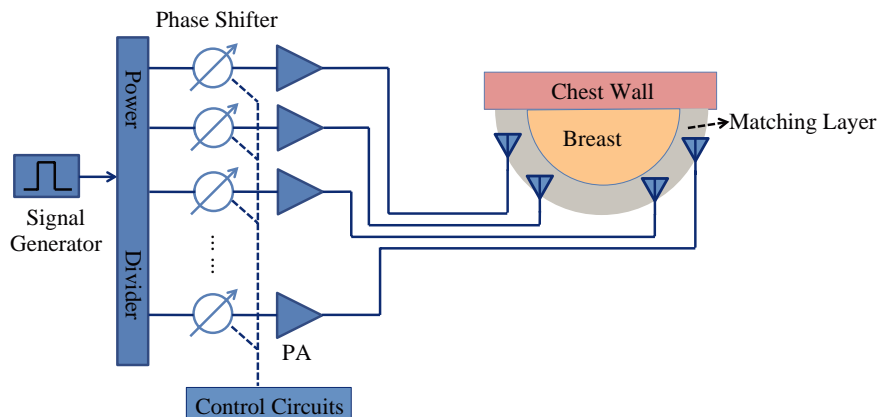


Figure 1: Block diagram of phased array TA system for breast cancer detection. The power amplifier (PA) boosts the microwave energy to the desired level.

the focus area and increases the generated pressure level. In addition, a relatively large frequency bandwidth is required to enable frequency spectroscopy [6] in TA imaging. This technique helps to characterize tissue properties in a wide frequency range and leads to better tumor classification. In this paper, we design a wideband dipole antenna as the microwave applicator in the phased array system.

A conceptual schematic of the proposed conformal phased array system is shown in Figure 1. The microwave pulse is divided into multiple channels for phase shift adjustments and power amplification. Then, the proposed applicator couples the microwave energy into the breast tissue. To improve coupling efficiency, we introduce a matching layer with appropriate dielectric property between the breast tissue and the applicator array.

2. APPLICATOR DESIGN

Figure 2(a) shows the bowtie dipole antenna [7] printed on Rogers 4350 dielectric. It is modified to obtain a large bandwidth and high efficiency required for the microwave applicator. As shown in Figure 2(b) (bottom side), the dipole is fed by a differential balun through via holes. Eventually, a coplanar waveguide (CPW) transition connects the balun to an SMA connector. Due to the trade-off between penetration depth and microwave absorption, the operating frequency between 1.5 GHz and 3.5 GHz is chosen.

The wavelength in the matching layer ($\epsilon_r \approx 6$) and the breast ($\epsilon_r \approx 5.1$) is about 5 cm at the center frequency of the bandwidth. Therefore the sample is in the mid-field of the dipole element. The dipole structure provides a desired microwave energy distribution in the mid-field, helping to concentrate energy in the target. Meanwhile, the applicator is able to maintain a low profile (4.5 cm in length and 2.9 cm in width) and fits a compact surface area.

The dielectric properties of involved tissues are obtained from the literature [8]. The simulated return loss of the antenna installed on the matching layer is shown in Figure 3(a). A 69% bandwidth from 1.6 GHz to 3.3 GHz is achieved for the return loss of better than -10 dB. The input impedance is shown in Figure 3(b).

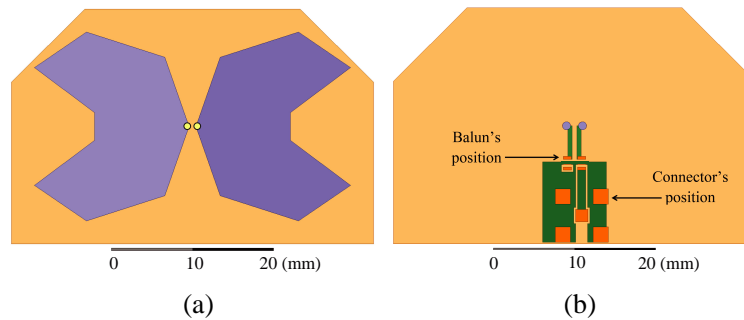


Figure 2: Geometry of the designed applicator. (a) Top side. (b) Bottom side.

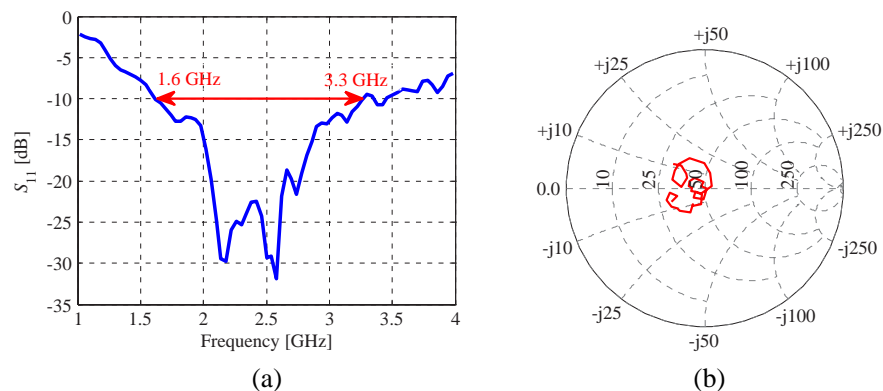


Figure 3: The simulated applicator S_{11} and input impedance. (a) S_{11} . (b) Simulated input impedance of the designed applicator in Smith chart, frequency range 1.6 GHz~3.3 GHz.

3. RESULTS AND DISCUSSION

For the phased array, we employ 16 applicators in a conformal architecture as shown in Figure 4. The array elements are arranged in two rows to enable movement of high-SAR region in both horizontal and vertical directions. All the elements are directed toward the center of the breast. Adjacent elements in the same row have 45 degree difference in the orientation. They are fed by synthetic short microwave pulses with specific delays controlled by the phase shifters. The pulse applied to each applicator has a peak power of 25 W and a pulse width of 1 μ s. The duty cycle is set to 1/1000. We use a matching layer between the applicator array and the breast tissue to improve the energy coupling efficiency. The breast is modeled as a half sphere with 5 cm radius. The chest wall is modeled as a thin layer of fat and a thick layer of muscle, as shown in Figure 4.

Figure 5 shows the SAR distribution when the focal point is at the center of the breast. It demonstrates the energy concentration capability of our proposed system at 2.5 GHz. As shown in Figure 5, the microwave power absorption in the matching layer is negligible. The breast tissue shows a high-SAR region in the center (shown as red color) which results from energy concentration from the applicator array. Most of the energy is absorbed by the breast region. The chest wall shows a very small absorption as desired. The tissue in the high-SAR region has an instantaneous local SAR higher than 1500 W/kg during the microsecond pulse, which contributes to an enhanced pressure generation in TA imaging. The average SAR is still limited to below 1.5 W/kg for safety concerns.

By adjusting the phase of each applicator, we can control the high-SAR region location. This capability enables spatial scan of the target, section by section. Figure 6 shows the simulation results at 2.0 GHz, 2.5 GHz, and 3.0 GHz, demonstrating that the designed system has the ability to control the high-SAR region within the bandwidth. The high-SAR region can move in the horizontal direction as shown in the figures of the same row, and in the vertical direction as shown in the figures of the same column. In some cases, a secondary high SAR region is generated due to the limited number of applicators in the array. At higher microwave frequencies, the high-SAR region is smaller in size because of smaller wavelength. However, the SAR value is also smaller due to larger attenuation.

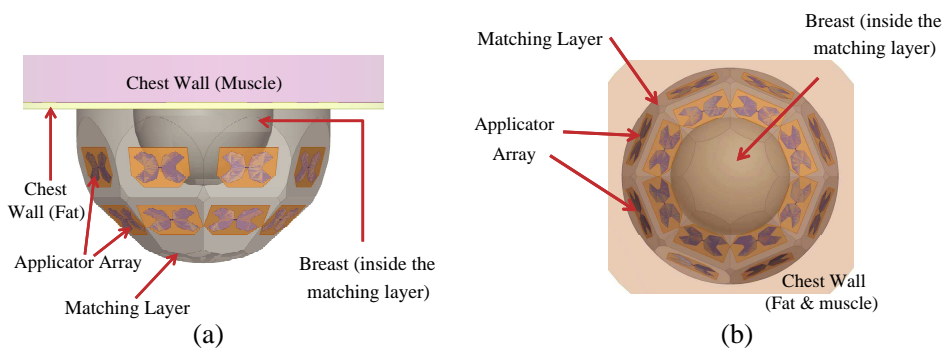


Figure 4: Setup of 16-element applicator array. For clarity, the matching layer is set to be transparent. (a) Front view. (b) Bottom view. Part of chest wall is outside this figure.

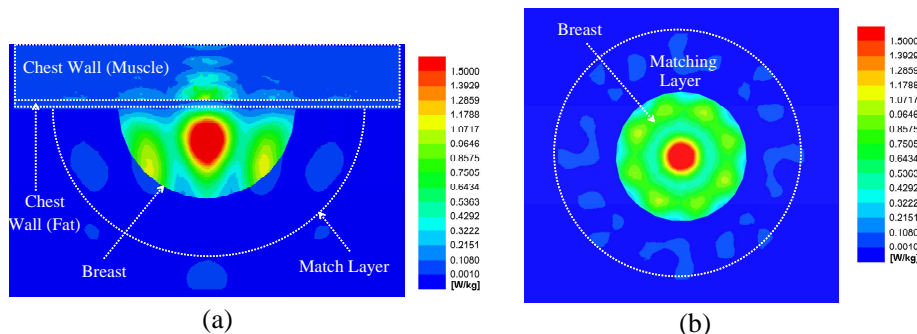


Figure 5: SAR (average value) distribution in the imaging target at 2.5 GHz. (a) Vertical cross section view. (b) Horizontal cross section view (2 cm from the surface of chest wall).

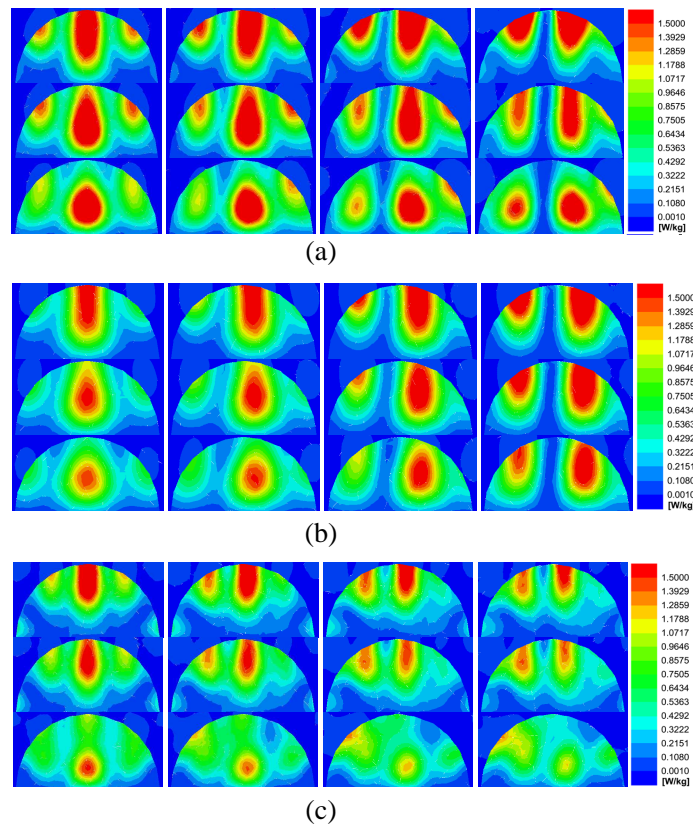


Figure 6: SAR (average value) in the breast tissue with different focal point locations by adjusting phase of each applicator. Vertical cross section view. (a) Microwave frequency: 2.0 GHz. (b) Microwave frequency: 2.5 GHz. (c) Microwave frequency: 3.0 GHz.

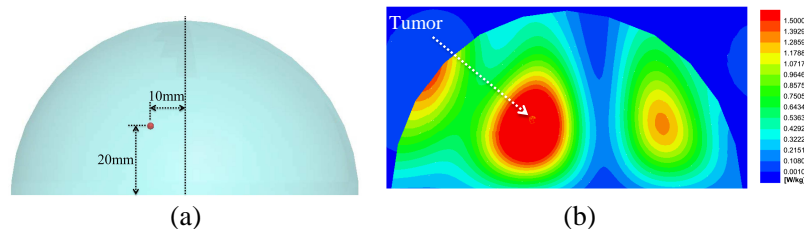


Figure 7: Microwave energy concentration at an example tumor location with 2.5 GHz microwave frequency. Vertical cross section view. (a) An example tumor in breast tissue. (b) SAR (average value) when high SAR region covers tumor.

Figure 7(a) shows an example tumor with 2 mm diameter in the breast tissue. By using 2.5 GHz microwave and adjusting phases of the applicators, we can concentrate the microwave energy on the tumor. Figure 7(b) shows the SAR distribution in the cross section of the breast tissue. We can see that the high-SAR region covers the target tumor. This increases the pressure generation of the target region and consequently improves the quality of the reconstructed TA image.

4. CONCLUSION

In this paper, we design a microwave applicator for localizing microwave energy on the tissue sample for TA imaging. The designed applicator has a high bandwidth and a high energy coupling efficiency. Using the designed applicator, we propose to use a 16-element phased array applicator system to excite the target for breast cancer detection. The proposed system can help concentrate the microwave energy on a small region that can be controlled in both the horizontal and vertical directions by tuning the phase of each channel. Full 3D EM simulations demonstrate this ability across the target and over the operation bandwidth.

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REFERENCES

1. Ku, G. and L. V. Wang, "Scanning microwave-induced thermoacoustic tomography: Signal, resolution, and contrast," *Med. Phys.*, Vol. 28, No. 1, 4–10, 2001.
2. Xu, M., G. Ku, and L. V. Wang, "Microwave-induced thermoacoustic tomography using multi-sector scanning," *Med. Phys.*, Vol. 28, No. 9, 1958–1963, 2001.
3. Nie, L., D. Xing, Q. Zhou, D. Yang, and H. Guo, "Microwave-induced thermoacoustic scanning CT for high-contrast and noninvasive breast cancer imaging," *Med. Phys.*, Vol. 35, No. 9, 4026–4032, 2008.
4. Xu, M., Y. Xu, and L. V. Wang, "Time-domain reconstruction algorithms and numerical simulations for thermoacoustic tomography in various geometries," *IEEE Trans. Biomed. Eng.*, Vol. 50, No. 9, 1086–1099, 2003.
5. Wang, X., D. R. Bauer, R. Witte, and H. Xin, "Microwave-induced thermoacoustic imaging model for potential breast cancer detection," *IEEE Trans. Biomed. Eng.*, Vol. 59, No. 10, 2782–2791, 2012.
6. Bauer, D. R., X. Wang, J. Vollin, H. Xin, and R. S. Witte, "Spectroscopic thermoacoustic imaging of water and fat composition," *Appl. Phys. Lett.*, Vol. 11, No. 3, 033705, 2012.
7. Raut, S. and A. Petosa, "A compact printed bowtie antenna for ultra-wideband applications," *Proceedings of European Microwave Conference*, 081–084, Rome, Italy, Sep./Oct. 2009.
8. Andreuccetti, S., R. Fossi, and C. Petrucci, "An internet resource for the calculation of the dielectric properties of body tissues in the frequency range 10 Hz–100 GHz," Website at <http://niremf.ifac.cnr.it/tissprop/>, IFAC-CNR, Florence, Italy, 1997, Based on data published by C. Gabriel, et al., in 1996.