

# A Prototype System for Early-Stage Breast Cancer Detection

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## Abstract

The early detection of breast cancer is very important. The final goal of this study is to develop an inexpensive portable device for simply detecting the existence of breast cancer using microwaves. In this study, we proposed a detection algorithm and the system configuration of such a device. The feasibility of the proposed method was investigated by numerical simulation and actual measurement. A prototype sensing module was fabricated, and the measurement results for tumor phantoms were presented. The measurement results showed that the prototype sensing module worked well, and the simulation results revealed that the detection rate of the device could be about 60% for a 4 mm tumor and almost 100% for a 6 mm tumor. The proposed device can be used for the self-diagnosis of breast cancer. Further study is required to reduce the size of the sensing module.

**Key Words:** Breast Cancer, Detection Algorithm, Diagnosis, Microwaves.

## I. INTRODUCTION

The occurrence of breast cancer has rapidly increased in both developed and developing countries because of westernized food habits, low fertility, and avoidance of breastfeeding, among others. In Korea, the incidence rate of breast cancer is especially high. Breast cancer occurs not only in old age but also in a young age. Women in their 40s and 50s have the largest portion of the breast cancer incidence rate, and even those in their 20s and 30s have an incidence rate of 25%. Detecting breast cancer at an earlier stage is very important to lower the death rate.

Mammography and magnetic resonance imaging (MRI) are commonly used for the diagnosis of breast cancer. Mammography is the standard diagnostic device that uses X-ray radiation. Tumor tissue can be distinguished from normal

tissue by the difference in X-ray absorption depending on the density of the organ tissues. However, the images are superimposed in mammography, and identifying cancer tissues can sometimes be difficult. Moreover, X-ray is a harmful radiation, and the breast is compressed during the procedure so that the patient can feel some discomfort. MRI, as well as computed tomography (CT) or positron emission tomography (PET), can identify smaller tumor tissues, but they are expensive.

Due to the drawbacks of the existing diagnostic devices, research has been conducted recently to find efficient techniques that utilize microwaves. Two types of approaches are available: microwave tomography (MT) [1–10] and ultra-wideband radar techniques [11–15]. The techniques utilizing microwaves have the advantages of being inexpensive and safe. Microwaves are non-ionizing radiation, and the power required for such a system is lower than that required for mobile

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phones. The Electronics and Telecommunications Research Institute (ETRI) has been developing an MT system for breast cancer diagnosis, and similar studies have been performed in Korea [5–7, 10]. Recently, Z-tech Company proposed a simple system utilizing the property that current can flow more easily through tumor tissue than through normal tissue [16].

The objective of the current study is to develop an inexpensive breast cancer detection system at an early stage using microwaves that can also be used for self-test or self-diagnosis. The purpose of this system is to determine whether breast cancer exists or not.

Tumor detection at microwave frequencies is based on the significant contrast in dielectric properties between malignant tumors and normal fatty breast tissues [17]. In this study, the system configuration as and the detection algorithm of a simple breast cancer detection system was proposed, and the feasibility of the system was investigated. A prototype sensing module was fabricated, and the measurement results for tumor phantoms were presented.

## II. DETECTION ALGORITHM

The scattered signal from an object illuminated by a transmitting antenna to the receiving antennas, as shown in Fig. 1, can be described by the following wave Eq. (1) or the corresponding integral Eq. (2), where  $\mathbf{E}_i$  is the incident electric field and  $\mathbf{E}_s$  is the scattered field.

$$\nabla^2 \mathbf{E}_s + k^2 \mathbf{E}_s - \nabla(\nabla \cdot \mathbf{E}) = (k_{obj}^2 - k_1^2) \mathbf{E}_i \quad (1)$$

$$\begin{aligned} \mathbf{E}(\vec{r}) &= \mathbf{E}_i(\vec{r}) + \mathbf{E}_s(\vec{r}) \\ &= \mathbf{E}_i(\vec{r}) + \int \mathbf{G}(\vec{r}, \vec{r}') (k_{obj}^2(\vec{r}) - k_1^2) \mathbf{E}_i(\vec{r}') dr' \end{aligned} \quad (2)$$

where  $k_{obj}$  is the wave number of the object, and  $k_1$  is the wave number of the surrounding medium. When one of the antennas in Fig. 1 transmits a signal, all the other antennas receive the scattered signals to obtain the  $N(N-1)$  scattered signals.

In the MT system,  $\varepsilon_{obj}$  is reconstructed using the scattered signals received by the receiving antennas by minimizing the difference between the theoretical scattered signals  $\mathbf{E}_{s,ij}$  for the assumed distribution of  $\varepsilon_{obj}$  and the measurement signals  $\mathbf{E}_{s,ij}^m$ , as given below. The indices  $i$  and  $j$  represent the transmitting antenna and the receiving antenna, respectively.

$$\text{Minimize } \mathbf{F} = \left\| \mathbf{E}_{s,ij} - \mathbf{E}_{s,ij}^m \right\| \quad (3)$$

The minimization process requires many iterations for

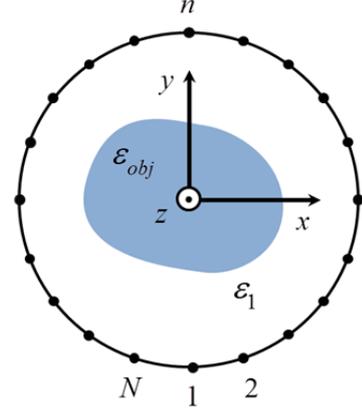


Fig. 1. Configuration of the breast cancer detection system.

image reconstruction by properly changing the distribution of  $\varepsilon_{obj}$ . Therefore, a long computation time is necessary for the reconstruction of the image (or the distribution of  $\varepsilon_{obj}$ ) because of the complicated reconstruction algorithm. Moreover, the hardware system is complicated, and the diagnosis cost is high.

In contrast to the MT system, the algorithm for a simple detection system, which can determine whether breast cancer exists or not, can be relatively simple. The equipment is also small, thus making it portable. The detection metric proposed in the current study is defined as the normalized variation of the scattering parameters between the transmitting antenna and the receiving antenna, as shown in Eq. (4).

$$\sum_{k=2}^n \left( \frac{|S_{ki} - S_{ki\_0}|}{|S_{ki\_0}|} \times 100 \right) [\%] \quad (4)$$

where  $S_{ki\_0}$  is the scattering parameter without tumor,  $S_{ki}$  is the scattering parameter with tumor when the  $i$ -th antenna transmits, and  $N$  is the total number of antennas. In a real situation, obtaining the reference value,  $S_{ki\_0}$ , would be difficult. However, we can overcome this difficulty, as shown in Fig. 2, if we use the left and right symmetries of the human breast. The reason is that having the same tumor size in both sides of breast is rare. Note that the metric based on the impedance variation is very small compared to the proposed metric, and thus it cannot be used for tumor detection.

As shown in the following, the proposed method works well

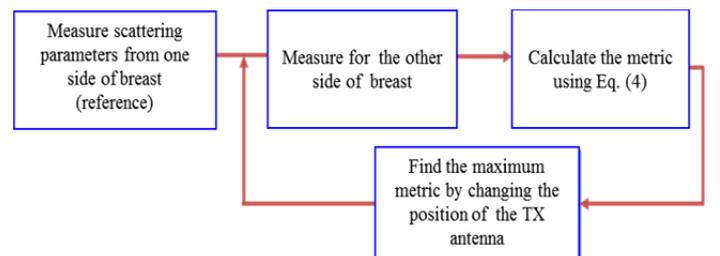


Fig. 2. Detection algorithm using the symmetry of the breast.

for a realistic contrast in the electrical properties of the breast and the breast tumor tissue. We also investigated the possibility of utilizing the variation of metric values for the breast when tumor tissue exists. It turned out that the proposed metric is better than the metric that utilizes impedance variation.

### III. ELECTRICAL PROPERTIES OF THE HUMAN BREAST TISSUE AND PHANTOM LIQUIDS

Prior to developing a breast cancer detection system, determining the electrical properties of breast and tumor tissues is necessary. The breast consists of fatty and fibro-glandular (FG) tissues. A two-port measurement probe was fabricated, and the electrical properties of human fat, FG, and breast tumor tissues at various frequencies were measured, as shown in Fig. 3 [17]. The human tissue samples were obtained from Samsung Medical Center in Seoul, Korea. The measurement results are presented in Fig. 4. As shown in the figure, the permittivity and conductivity of fat are relatively smaller than those of the tumor and FG.

To model the human breast, we have to determine the volume ratio of fat and FG. According to Lazebnik et al. [18], the volume percentage of fat is greater than 90% for 45% of American women. In Korea, such data are not known, but the FG content of Asian women is known to be higher than that of Western women. Therefore, we assumed the volume per-



Fig. 3. Two-port measurement to determine the electrical properties of human breast and tumor tissues: (a) measurement setup and (b) tissue in the probe.

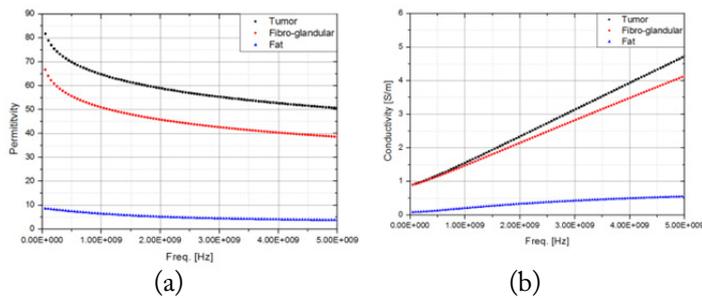


Fig. 4. Electrical properties of human fat, fibro-glandular, and tumor tissues: (a) permittivity and (b) conductivity.

Table 1. Electrical properties of the human breast and tumor tissue

Freq. (MHz)	Breast (20:80)		Tumor	
	$\epsilon_r$	$\sigma$	$\epsilon_r$	$\sigma$
900	15.67	0.44	65.65	1.47
1,300	14.61	0.54	62.68	1.80
1,500	14.18	0.58	61.48	1.96
1,700	13.80	0.63	60.41	2.12
2,000	13.32	0.70	59.03	2.35
2,500	12.67	0.81	57.09	2.74
3,000	12.13	0.91	55.45	3.14

Table 2. Electrical properties of the liquid phantoms

Freq. (MHz)	PG80		PG90		PG40		Distilled water	
	$\epsilon_r$	$\sigma$	$\epsilon_r$	$\sigma$	$\epsilon_r$	$\sigma$	$\epsilon_r$	$\sigma$
900	25.8	0.87	17.63	0.72	62.74	0.62	82.35	0.25
1,300	20.5	1.18	13.88	0.91	59.48	1.23	81.70	0.51
1,500	18.5	1.32	12.57	0.98	57.87	1.56	81.50	0.67
1,700	17.0	1.43	11.58	1.05	56.20	1.92	81.26	0.86
2,000	15.2	1.57	10.47	1.13	53.62	2.48	80.84	1.18
2,500	12.9	1.79	9.17	1.24	49.35	3.46	79.99	1.83
3,000	11.4	1.95	8.32	1.33	45.27	4.42	79.01	2.59

centage of 80% for fat and 20% for FG in this study. The electrical properties of the breast and tumor based on the measurement results are given in Table 1.

Phantom liquids were used for the measurement and the simulation. About 80% and 90% propylene glycol liquid (PG-80 and PG90) were used for liquid phantom for the bath and breast. Conversely, 40% propylene glycol liquid (PG40) and distilled water were used for liquid phantom for the tumor depending on the test. The electrical properties of the liquids were measured using the dielectric probe kit and the network analyzer (Agilent 85070E and E5071C). The measurement results are summarized in Table 2.

### IV. FEASIBILITY STUDY OF THE BREAST CANCER DETECTION SYSTEM

A feasibility study was performed by numerical simulation and preliminary test using the experimental MT system developed by ETRI [5, 6]. For the numerical simulation, the XFDTD tool of Remcom was used. The breast was simply modeled as a hemisphere with a radius of 5 cm, and a spherical tumor was inserted into the breast, as shown in Fig. 5. Dipole antennas were used for the simulation, and their phase centers were located 2.5 cm from the bottom of the breast.

As defined in Eq. (1), the variation of the metric values, which depend on the operating frequency, was investigated

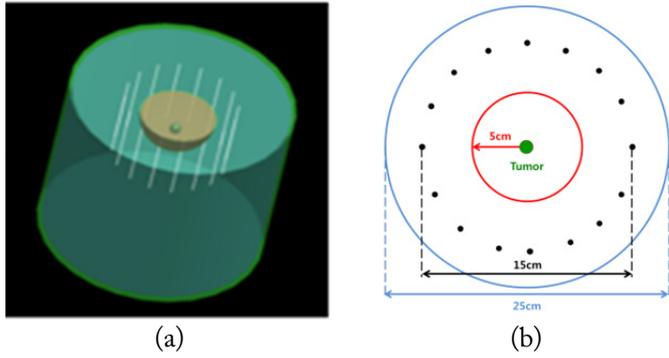


Fig. 5. Simulation setup and schematics for the feasibility study: (a) simulation setup and (b) simulation schematic.

first. The tumor tissue was located 2.5 cm on the symmetry axis of the breast, and the breast was placed inside the bath liquid (PG80), which was the same one used in the ETRI MT system. The electrical properties of the breast and tumor were the same as those presented in Table 1. The electrical properties of the bath for the given frequencies are given in Table 2. The simulation results are presented in Fig. 6. The metric values increase as the frequency increases. As the frequency increases, the scattered value also increases, but the reference signal (i.e., the received signal when a tumor is absent) decreases. However, transmission loss would be larger for higher frequencies, and thus signal reception would be difficult because of the limited receiver sensitivity. Therefore, the operating frequency should be determined properly in consideration of the size of the system, the transmitting power, and the receiver performance. In this study, the operating frequency of 1.5 GHz was chosen.

The effect of the number of antennas of the system on the metric value was also investigated. As shown in Fig. 7, the metric values are almost linearly dependent on the number of antennas. Therefore, the number of antennas should also be determined depending on the size of the system. The size of

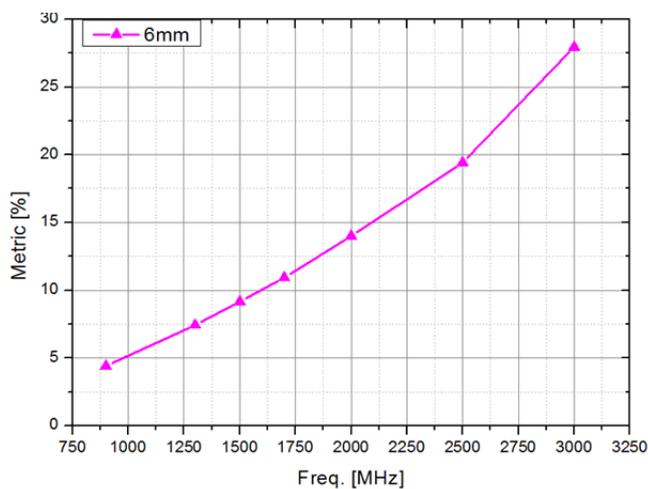


Fig. 6. Variation of the metric values depending on frequency.

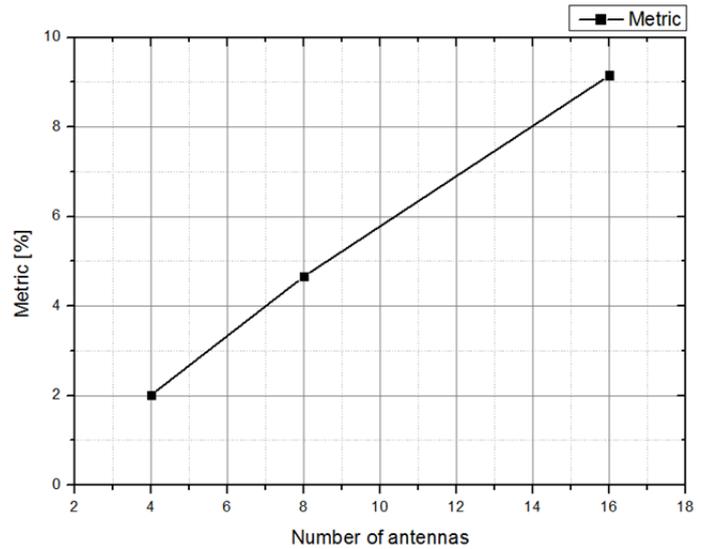


Fig. 7. Variation of the metric values depending on the number of antennas.

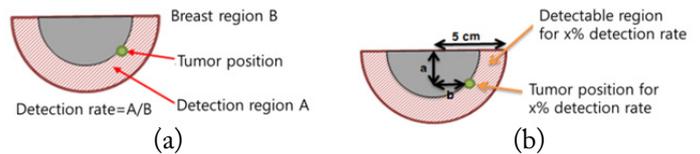


Fig. 8. Definition of the detection rate and cancer position for simulation: (a) definition of the detection rate and (b) position of the tumor for a given detection rate.

the antenna is also important, as the scattered signals from the metallic part of the antennas should be smaller than those from the tumor tissue. The coupling between antennas is also crucial in a real system.

A breast cancer detection system should be able to detect the tumor tissue located deep inside of the breast. This performance can be quantified by the detection rate, which is defined as the ratio of the volume of the detectable region to the whole breast volume, as shown in Fig. 8(a).

The detection rate was simulated at 1.5 GHz by changing the position of the tumor, as shown in Fig. 8(b). Fig. 9 shows the detection rate as a function of the metric values for tumors with a diameter of 2, 4, 6, 7, and 9 mm. The detection rate of a 4 mm tumor will be about 60% and that for a 6 mm tumor will be 100% if the hardware system can detect the detection metric value greater than 4%, which seems to be quite possible according to our analysis.

A preliminary test was conducted to confirm the feasibility of the breast cancer detection system using the experimental ETRI system [5, 6]. The transmitting power of the system was 10 dBm, and the minimum detectable level was  $-110$  dBm. The measurement setup is shown in Fig. 10. The bath liquid was PG80, and an acrylic hemisphere filled with PG90 liquid was used for the breast phantom. Cylindrical acrylic

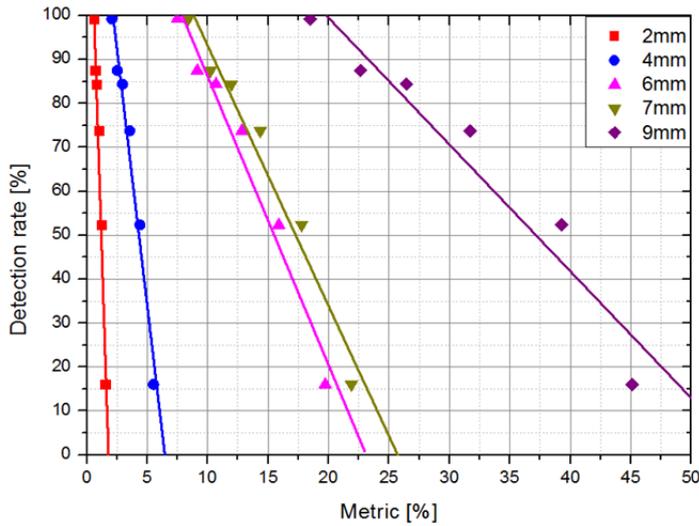


Fig. 9. Detection rate as a function of the metric value for a tumor size of 2, 4, 6, 7, and 9 mm.

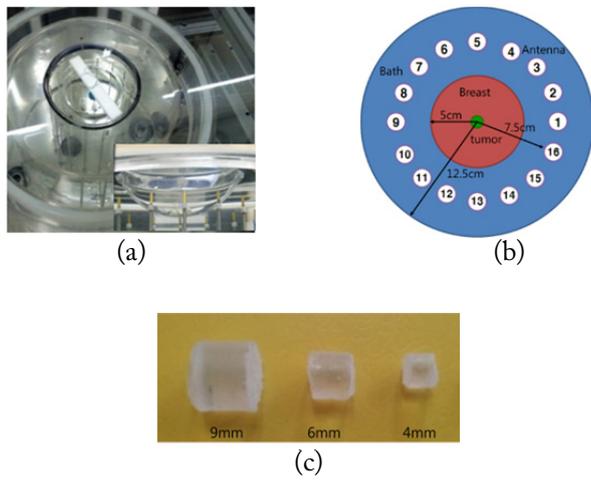


Fig. 10. Measurement setup and tumor phantoms for the feasibility test: (a) measurement setup, (b) configuration of the measurement setup, and (c) tumor phantoms.

tubes filled with distilled water were used as tumor phantoms to enhance the relative dielectric contrast of the tumor tissues. The inside diameter and the length of the tubes are the same. The electrical property of the distilled water is given in Table 2.

Fig. 11 shows the detected metric values for the tumor sizes of 4, 6, and 9 mm (62.83, 197.92, and 699.79 mm<sup>3</sup> in volume, respectively) at frequencies of 1,100, 1,300, and 1,500 MHz, respectively. Frequency dependency was similar to the simulation results, but the detected metric values were rather higher because of the higher contrast of the tumor tissue relative to the breast tissue. Moreover, the performance of the sensing module for the feasibility test seemed better than that of the simulated one. After the feasibility was tested, a prototype sensing module was designed and tested, as described in the next section.

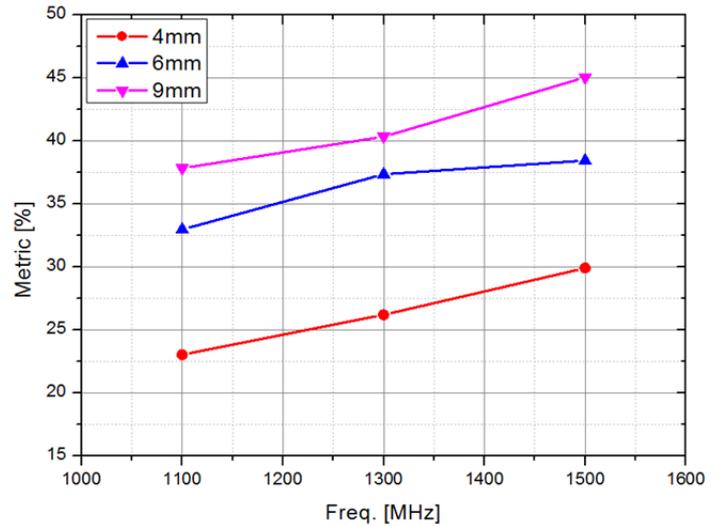


Fig. 11. Detected metric values obtained from the feasibility test.

## V. FABRICATION OF THE PROTOTYPE MODULE AND MEASUREMENTS

The key element of the proposed breast cancer detection system is the sensing module. It consists of a cylindrical cavity and a hemisphere (6 cm in radius) on top of it that will be in direct contact with the human breast. The inside of the cylindrical cavity was filled with bath liquid (PG80), and breast-equivalent liquid (PG90) was filled in the hemisphere. Inside of the cavity, eight antennas were placed around in a circle with a 12-cm diameter. The bath liquid was filled inside to match with the breast and to deflect the reflected waves from the outer walls and environmental signals. Fig. 12 shows the configuration of the sensing module and the physical dimension of the antenna. The antennas were designed using Microwave Studio 2013 of CST. They were optimized to obtain the best performance in the bath liquid of the sensing module. The resulting return loss at the operating frequency of 1.5 GHz was -25 dB.

Measurements were performed using the fabricated sensing module and the existing transceiver module in the ETRI mentioned previously. Fig. 13 shows the measurement setup. The tumor phantoms were cylindrical, and they had the same length as the inside diameters of 2, 4, 6, and 9 mm. The tumors phantoms were filled with PG40 at volumes of 9.42, 62.83, 197.92, and 699.79 mm<sup>3</sup>, respectively. The relative contrast in the dielectric constant of PG40 and PG90 was similar to that of a real human breast.

Fig. 14(a) shows the insertion loss when the signals are transmitted from each antenna, as shown in Fig. 14(b).  $S_{21}$  in the figure is the insertion loss between antenna  $(i + 1)$  and antenna  $i$  when the signal is transmitted from antenna  $i$ . All the other parameters could be read in such a way. The ma-

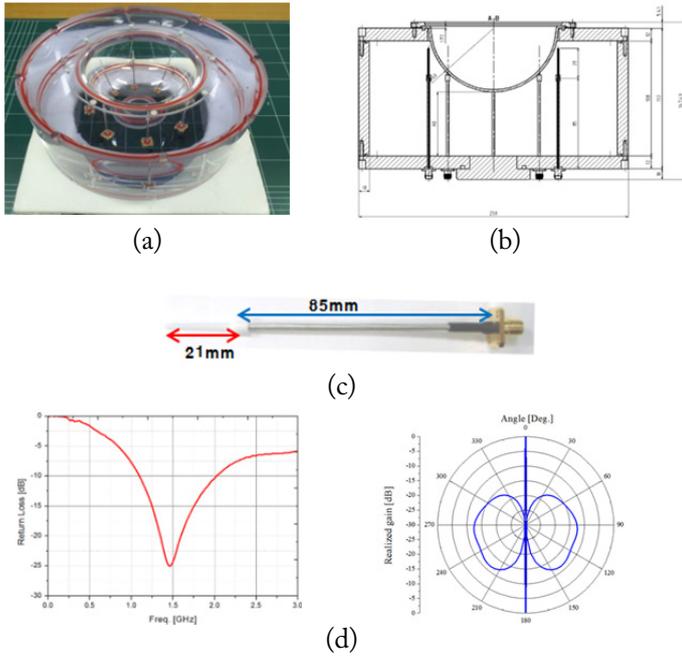


Fig. 12. The prototype sensing module: (a) sensing module, (b) physical dimensions of the sensing module, (c) antenna, and (d) return loss and radiation pattern of the antenna.

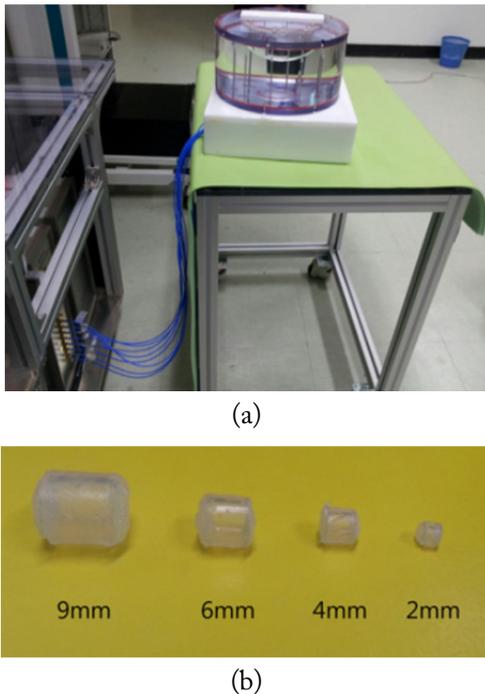


Fig. 13. Measurement setup for the prototype sensing module and tumor phantoms: (a) measurement setup and (b) tumor phantoms.

ximum insertion loss between the furthest antennas was  $-58$  dB, and no problem was encountered in detecting the scattered signals from the tumor phantoms.

The performance of the experimental sensing module was tested by measuring the  $S$ -parameters for the tumor phantoms

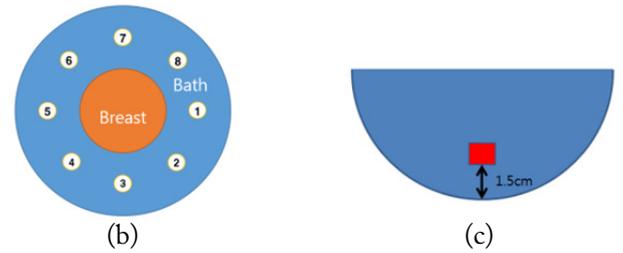
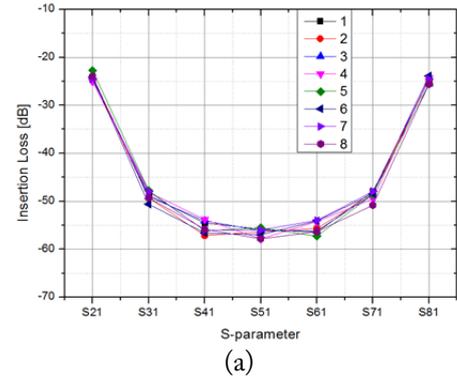


Fig. 14. Insertion loss of each antenna when a tumor is absent. (a) Insertion loss, (b) antenna position, and (c) position of the tumor phantom in the hemisphere.

located at a 4.5 cm depth along the center line of the breast, as shown in Fig. 14(c). The detection metrics defined in Eq. (1) were obtained for each tumor phantom. The detection metric values are shown in Fig. 15. The data in Fig. 15(b) are the metric values obtained when the specified antenna transmits, and the data in Fig. 15(a) are the average values. The average metric values for the tumor phantom sizes of 2, 4, 6, and 9 mm are 56.3%, 61.0%, 62.9%, and 80.9%, respectively. The prototype system was confirmed to work well, and the existence of even a small breast tumor was clearly detected.

The variation of metric values for the tumor size of 9 mm was also tested by changing the position of the tumor phantom along the center line of the breast phantom. The results are shown in Fig. 16. As expected from the simulation results, the detection rate quite large for the given size of the tumor.

## VI. CONCLUSION

The existing diagnostic devices for breast cancer, such as mammography and MRI, have some drawbacks. Recently, microwave technologies for breast cancer detection have been actively investigated. In this study, an efficient sensing method for the existence of breast tumor in the early stage was proposed, and the feasibility of the method was investigated by numerical simulation and method. A prototype sensing module was fabricated, and its performance was tested.

The test results show that the proposed system works well,

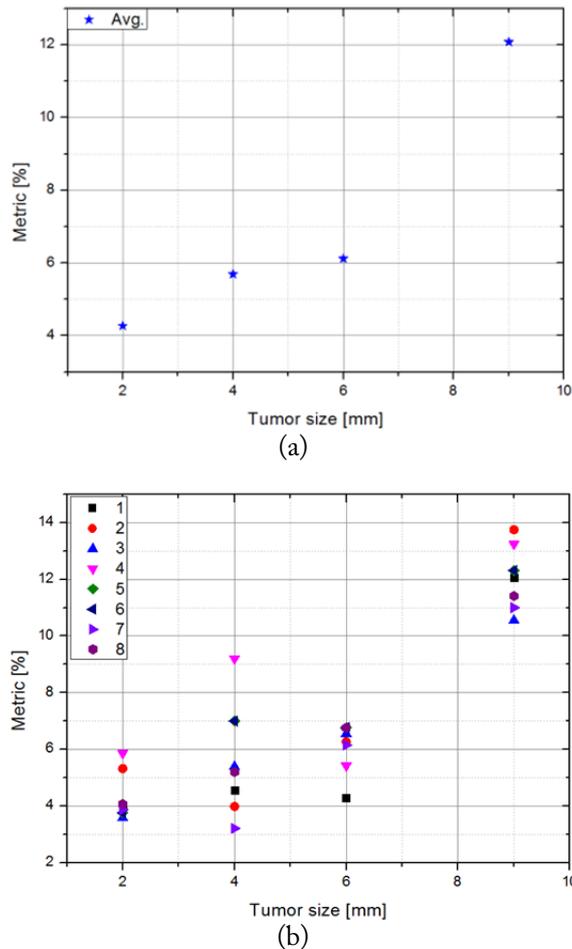


Fig. 15. Detection metric values for the tumor sizes of 2, 4, 6, and 9 mm. (a) Average detection metric values and (b) detection metric values for each transmitting antenna.

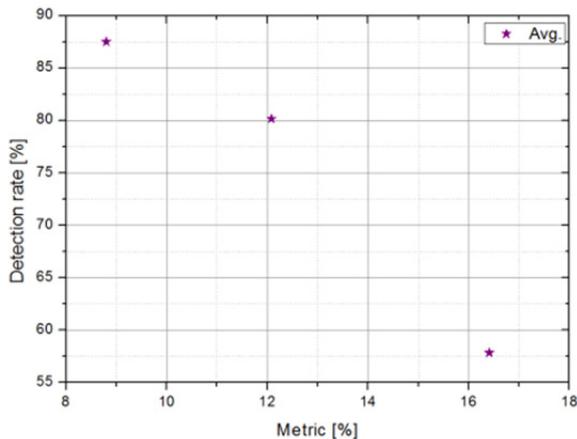


Fig. 16. Measured detection rate as a function of the metric value for a tumor size of 9 mm.

and even a small tumor phantom can be detected. We expect that the proposed system can be used for the self-diagnosis of the existence of breast tumor in the early stage. In a future study, we plan to focus on the reduction of the size of the

sensing module including some more improvements. For a commercial system, the development of a transceiver module and display module would also be necessary.

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## REFERENCES

- [1] P. M. Meaney, K. D. Paulsen, B. W. Pogue, and M. Miga, "Microwave image reconstruction utilizing log-magnitude and unwrapped phase to improve high-contrast object recovery," *IEEE Transactions on Medical Imaging*, vol. 20, no. 2, pp. 104–116, 2001.
- [2] Q. Fang, "Computational methods for microwave medical imaging," Ph.D. dissertation, Dartmouth College, Hanover, NH, 2004.
- [3] S. Y. Semenov, A. E. Bulyshev, A. Abubakar, V. G. Posukh, Y. E. Sizov, A. E. Souvorov, P. M. van den Berg, and Williams, "Microwave-tomographic imaging of the high dielectric-contrast objects using different image-reconstruction approaches," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 7, pp. 2284–2294, 2005.
- [4] T. Rubk, P. M. Meaney, P. Meincke, and K. D. Paulsen, "Nonlinear microwave imaging for breast-cancer screening using Gauss-Newton's method and the CGLS inversion algorithm," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 8, pp. 2320–2331, 2007.
- [5] S. Semenov, "Microwave tomography: review of the progress towards clinical applications," *Philosophical Transactions A: Mathematical, Physical and Engineering Sciences*, vol. 367, no. 1900, pp. 3021–3042, 2009.
- [6] S. H. Son, N. Simonov, H. J. Kim, J. M. Lee, and S. I. Jeon, "Preclinical prototype development of a microwave tomography system for breast cancer detection," *ETRI Journal*, vol. 32, no. 6, pp. 901–910, 2010.
- [7] K. C. Kim, B. D. Cho, T. H. Kim, J. M. Lee, S. I. Jeon, and J. K. Pack, "2D microwave image reconstruction of breast cancer detector using a simplex method with method of moments," *Journal of the Korea Electromagnetic Engineering Society*, vol. 10, no. 4, pp. 199–205, 2010.
- [8] A. Baran, D. J. Kurrant, A. Zakaria, E. C. Fear, and J. LoVetri, "Breast imaging using microwave tomography with radar-based tissue-regions estimation," *Progress in Electromagnetics Research*, vol. 149, pp. 161–171, 2014.
- [9] M. H. Khalil and J. Xu, "Inverse scattering in microwave

- imaging for detection of malignant tumor inside the human body," *International Journal of Signal Processing, Image Processing and Pattern Recognition*, vol. 7, no. 1, pp. 135–144, 2014.
- [10] J. Y. Kim, K. J. Lee, S. H. Son, S. I. Jeon, and N. Kim, "Temperature influence of matching liquid in a microwave tomography platform system," *Microwave and Optical Technology Letters*, vol. 56, no. 12, pp. 2978–2981, 2014.
- [11] S. C. Hagness, A. Taflove, and J. E. Bridges, "Three dimensional FDTD analysis of pulsed microwave confocal system for breast cancer detection: design of an antenna-array element," *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 5, pp. 783–791, 1999.
- [12] X. Li and S. C. Hagness, "A confocal microwave imaging algorithm for breast cancer detection," *IEEE Microwave Wireless Components Letters*, vol. 11, no. 3, pp. 130–132, 2001.
- [13] J. M. Sill and E. C. Fear, "Tissue sensing adaptive radar for breast cancer detection: experimental investigation of simple tumor models," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 11, pp. 3312–3319, 2005.
- [14] Y. Xie, B. Guo, L. Xu, J. Li, and P. Stoica, "Multistatic adaptive microwave imaging for early breast cancer detection," *IEEE Transactions on Biomedical Engineering*, vol. 53, no. 8, pp. 1647–1657, 2006.
- [15] T. Sugitani, K. Hashimoto, Y. Seo, H. Kono, and T. Kikkawa, "Time domain reflectometry using IR-UWB CMOS integrated circuits for breast cancer detection," in *Proceedings of IEEE International Conference on Ultra-Wideband (ICUWB)*, Paris, France, 2014, pp. 265–268.
- [16] R. S. Yoon, T. P. DeMonte, L. Organ, and M. L. G. Joy, "Study of current density distribution in a non-invasive breast cancer detection device," in *Proceedings of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Cancun, Mexico, 2003, pp. 494–496.
- [17] T. H. Kim and J. K. Pack, "Measurement of electrical characteristics of female breast tissues for the development of the breast cancer detector," *Progress in Electromagnetics Research C*, vol. 30, pp. 189–199, 2012.
- [18] M. Lazebnik, L. McCartney, D. Popovic, C. B. Watkins, M. J. Lindstrom, J. Harter, S. Sewall, A. Magliocco, J. H. Booske, M. Okoniewski, and S. C. Hagness, "A large-scale study of the ultrawideband microwave dielectric properties of normal breast tissue obtained from reduction surgeries," *Physics in Medicine and Biology*, vol. 52, no. 10, pp. 2637–2656, 2007.

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