Experimental Investigation of a Retro-Focusing Microwave Hyperthermia Applicator: Conjugate-Field Matching Scheme

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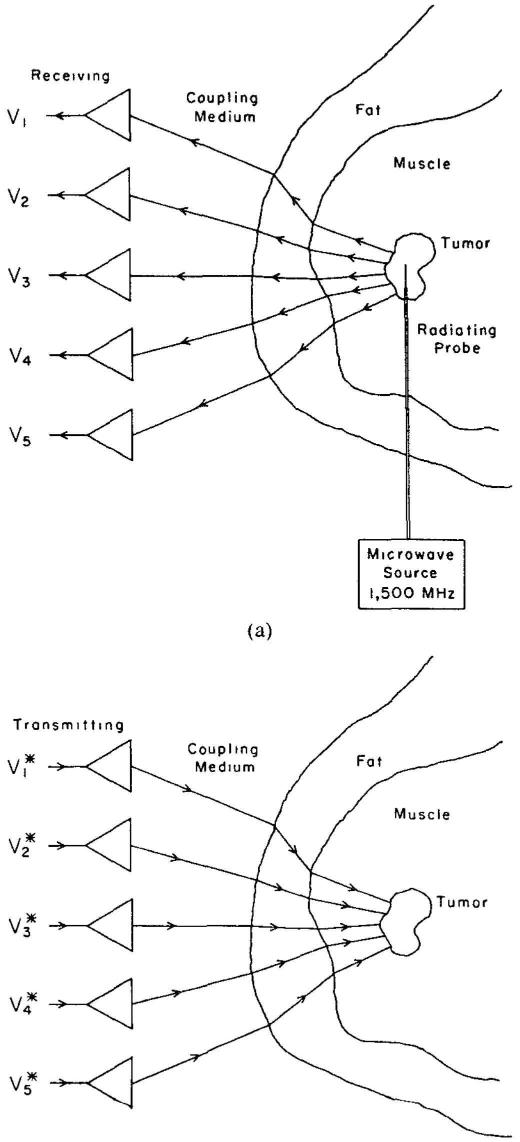
Abstract —**A seven-element array of dielectric-loaded open-ended waveguides totally immersed in a water tank is tested as a possible hyperthermia applicator. Experimental results show a substantial increase in focusing ability of the array if a conjugate matching scheme is used to adjust the phase of each element excitation. This scheme could offer a practical procedure for operating a focused hyperthermia applicator in a living patient.**

I. INTRODUCTION

MICROWAVE HYPERTHERMIA is one of the more promising new techniques for treating cancers. In the past two years, several focused phased-array applicators have been reported in the literature [1]–[6]. In comparison with earlier applicators made of single waveguide horns, the focused applicator offers the obvious advantages that

i) the spot size of the radiated beam is smaller, and its location can be moved electronically; and
ii) microwave energy is delivered more efficiently to the tumor; therefore, surface and spillover heating are reduced.

Although the principle of the phased-array applicator is well understood, its implementation in an actual biological medium is by no means trivial. The main problem is to determine the (relative) phase of the excitation in each individual element of the array so that the microwave energy is focused to a prescribed tumorous region. If the array were situated in a homogeneous medium, the phase determination could be easily accomplished by tracing geometrical rays. However, actual biological media are highly inhomogeneous, and ray tracing becomes impractical, if not impossible.



(a)
(b)

Fig. 1. Conjugate-field concept. (a) Receiving. (b) Transmitting.

It is the purpose of this paper to offer an experimental method of determining the excitation phases of an array. The method is based on the conjugate-field matching concept [7]–[9]. This idea is not new. The retro-focusing array was first reported and implemented in adaptive antenna systems more than two decades ago [10], [11]. The same concept applied to focused hyperthermia is described below. We first insert a small probe at the tumor and let it radiate, as shown in Fig. 1(a). At this time, the phased-array applicator is used as a receiving antenna. The received voltages from the array elements are denoted by $\{V_1, V_2, \cdots, V_N\}$. Next, we feed the array with excitations proportional to $\{V_1^*, V_2^*, \cdots, V_N^*\}$, as in Fig. 1(b). By

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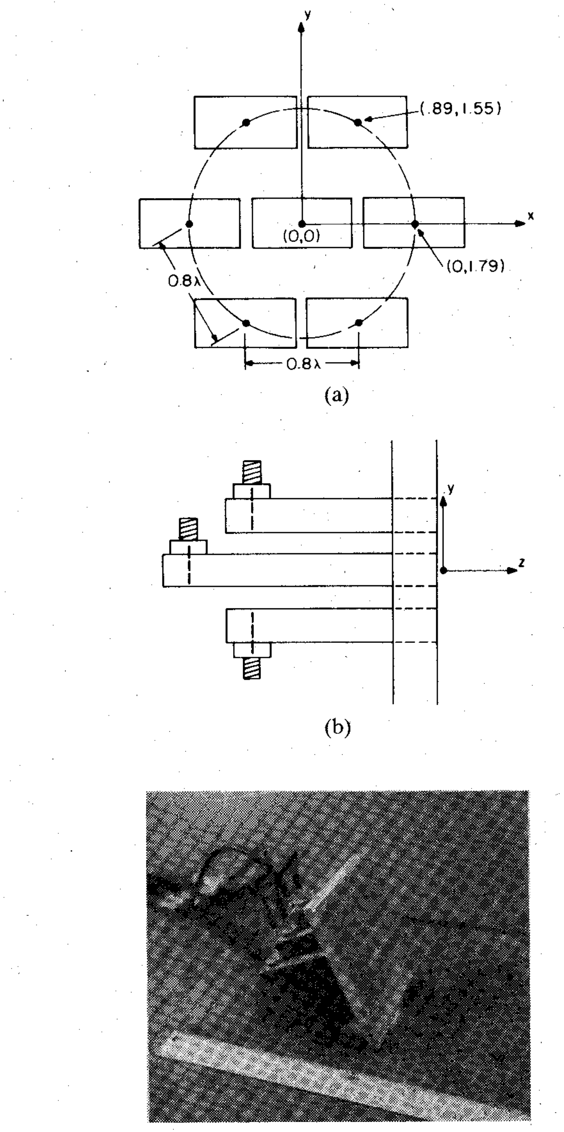


(a)

(b)

(c)

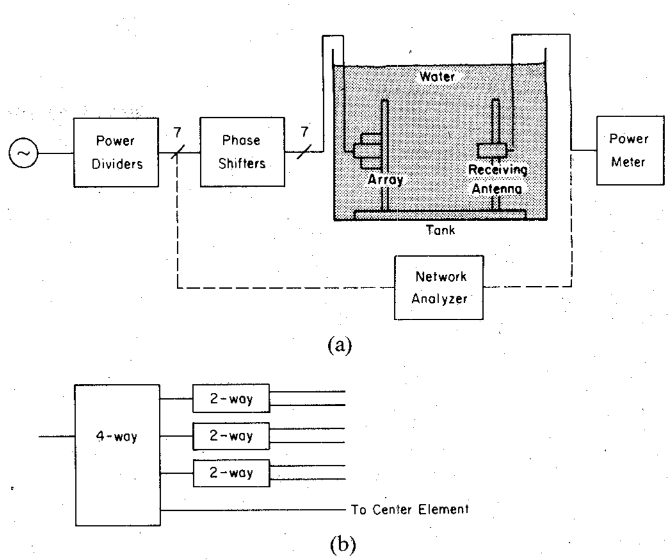
Fig. 2. Hexagonal array geometry. (a) Front view (x, y in cm). (b) Side view. (c) Photograph of the array (seven elements used).

reciprocity, the radiated field from the array is focused exactly at the tumor. The method works regardless of the inhomogeneity of the medium or differences between elements.

II. Experimental Description and Results

A. Setup

A seven-element hexagonal planar array of open-ended waveguides has been built for underwater operation at 1.5 GHz. Sections of standard *Ku*-band guide were tightly packed full of magnesium calcium titanate powder and then submerged, allowing water to seep in between the grains. The relative permittivity of the dielectric when wet is approximately 65, a sufficiently good match to room-temperature water with $\epsilon_r \cong 78(1 - j0.25)$. In 20°C water, $\lambda \cong 2.25$ cm and the loss is about 6.7 dB/λ. The cross section inside the waveguides is about 0.64 $\lambda \times 0.32$ λ, and the elements are packed as closely as possible so that the array geometry is that of a regular hexagon with 0.8 λ in water between centers, as sketched in Fig. 2(a). A side view of the array is shown in Fig. 2(b); each element is excited by a pin at an experimentally determined match point. A photograph of the array is given in Fig. 2(c).



(a)

(b)

Fig. 3. Experimental setup. (a) Block diagram. (b) Power dividers.

A block diagram of the complete setup is given in Fig. 3(a), which shows the array immersed in a tank of tap water. The receiving antenna is a short section of waveguide fed exactly like the array elements, oriented in the same polarization as the array. Multiple reflections from the moving probe during measurements can be ignored due to high medium loss. A network analyzer RF generator provides a sufficiently powerful source. The power divider network, expanded in Fig. 3(b), feeds the center element with twice the power of any other element. The phase shifting is accomplished by adding appropriate lengths to each (coaxial) line.

The problem of phasing the received element fields was solved by connecting the network analyzer to measure s_{21} between each element line and the receiving antenna. The outputs of the power divider network were assumed to be isolated in-phase sources, allowing for an extra 130° in the center element line length to compensate for the lack of a two-way divider there. A reference phase was chosen for s_{21} between one element and receiver, and then each remaining line length was adjusted in turn to obtain the same s_{21} phase. In reality, all phases could be set to within about $\pm 7°$ at best, due to the noise level and the finite lengths of line added. Even so, and although the elements were not perfectly matched, results showed that this method worked well in practice.

B. Array Calibration

We first checked the mutual coupling between elements in the array. Between adjacent elements coupling was on the order of -30 dB, presumably low due to medium losses. Impedance measurements showed that the elements were not uniform, which was to be expected since the small feed pins were quite sensitive and costly machining tech-

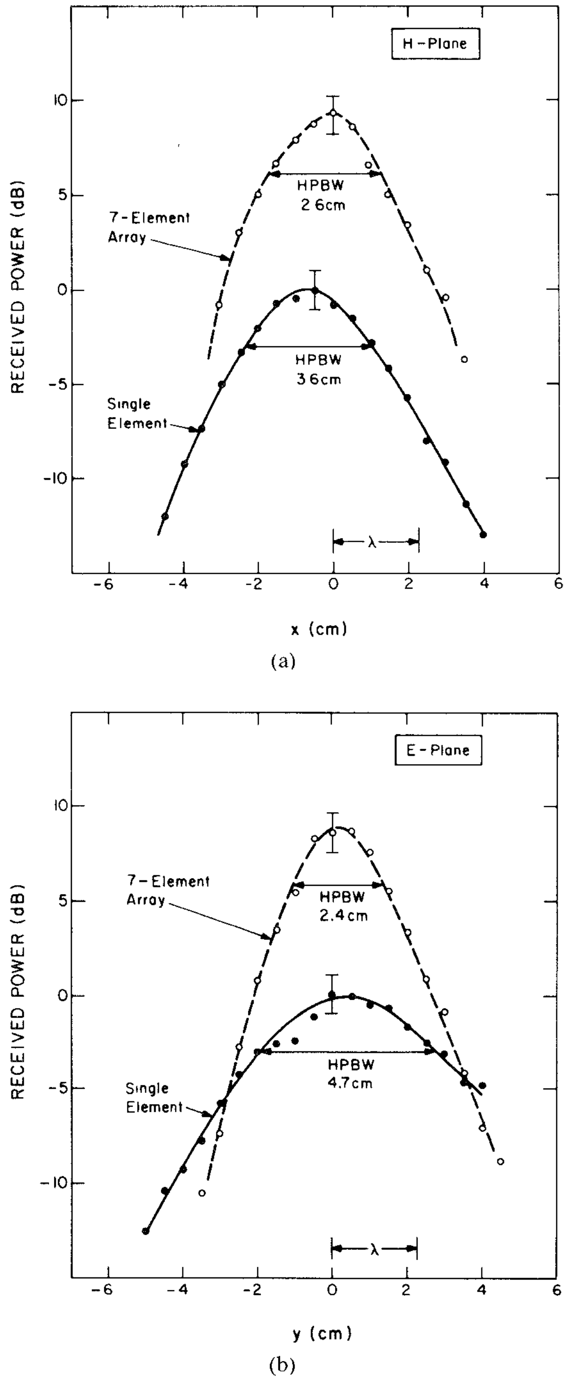


Fig. 4 Comparison of 7-element array and single (center) element patterns. (a) H-plane. (b) E-plane.

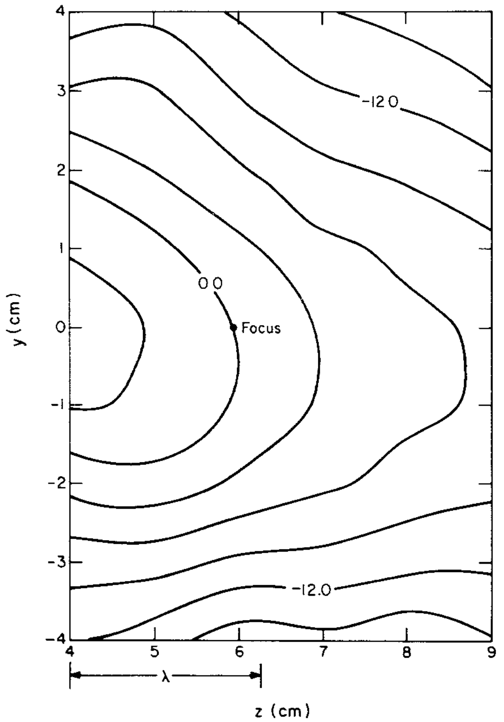


Fig. 5. Contour plot of E-plane pattern.

niques were avoided. All s_{11} loci fell within a 2.5 VSWR circle, implying less than or equal to about 0.9 return loss. As mentioned before, this turned out to be an adequate match for the power dividers. Upon probing the radiated fields 6 cm in front of the individual elements, a variation of about ±1.5 dB was observed over the ensemble for the same incident power. Surely the electrical lengths of the elements varied as well, but neither of these facts caused any concern because of the method used to set the phases. We emphasize that the point of these experiments is to demonstrate the feasibility of phased-array operation in an *arbitrary medium.*

C. Array in a Homogeneous Medium

Patterns of the center single element were taken in the H-plane (xz-plane) and the E-plane (yz-plane) with 6 cm of water (2.7 λ) separating the receiver aperture and the plane of the array. The probe was moved parallel to the array surface in the homogeneous medium. The results are plotted in Fig. 4(a) and (b), showing 3-dB "beamwidths" of approximately 3.6 cm and 4.7 cm for the respective planes. Then the receiver was centered 6 cm in front of the array and all seven elements were set to add in phase as described. With the same generator setting, the received power was 9-dB higher than that for a single element, a significant increase despite the element variations and an observed ±1-dB drift in the power meter. The H- and E-plane patterns taken 6 cm from the operating array are also plotted on Fig. 4(a) and (b), showing much narrower beamwidths. Although the power level in the patterns is based on a single received polarization, it can clearly be argued that this constitutes nearly all of the total $|E|^2$ near the array normal axis, due to destructive interference of cross-polarized fields from elements on opposite sides of the H-plane. The graphs show that the H-plane and E-plane beamwidths are now of the same order, namely 2.6 cm and 2.4 cm, respectively, suggesting that the spot size is a function of the array dimensions and essentially independent of the broader element pattern (as in far-field array theory). Raster data from parallel E-plane cuts taken every 0.5 cm between 4 cm and 9 cm from the array are sum-

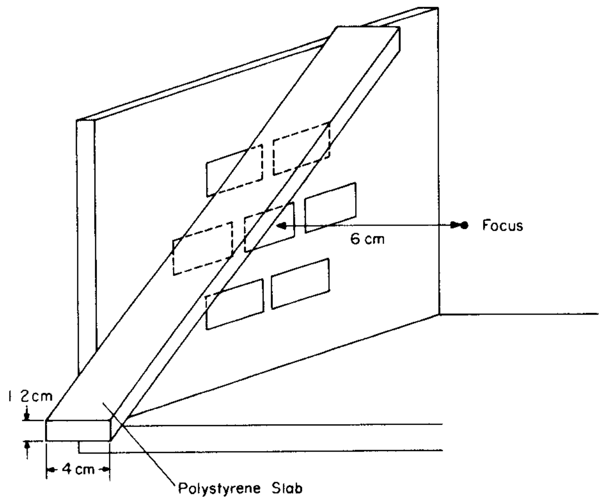


Fig. 6. Dielectric scatterer configuration.

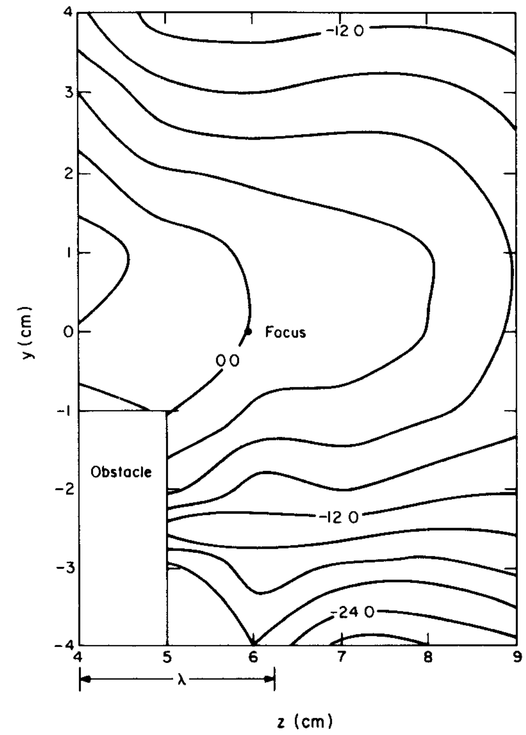


Fig. 7. Contour plot of E-plane pattern with scatterer present.

marized in the contour plot of Fig. 5(a), where the isophotes are 3-dB apart. One can infer that the 3-dB spot size grows larger with increasing distance from the array. The behavior is much like a beam, but the focusing effect does little to overcome the loss. The amplitude gradient always points toward the array; this is the best that one may expect in such a lossy medium.

D. Array in the Presence of Obstacle

In the next part of the experiment, a dielectric scatterer was placed across the array face in order to simulate the effects of irregular inhomogeneities and to bring about randomly phased fields at the focus. The scatterer was a slab of polystyrene ($\epsilon_r \cong 2.5$) arbitrarily situated, as shown in Fig. 6. Upon its introduction, the power level dropped -9 dB at the focal point 6 cm from the array. After the phase-setting procedure was performed again, the received power was 4-dB higher, i.e., -5 dB relative to the reading just before the scatterer.

A contour plot of the E-plane power level with the scatterer present is shown in Fig. 7, obtained in the same fashion as the previous raster. The concentration of power due to focusing is again evident. We conclude that, in general, this focusing method will be effective in arbitrary biological media.

III. CONCLUSIONS

The experimental results presented for the focusing array are encouraging in that they deomonstrate a practical method of focusing a phased array in real-world applications such as microwave hyperthermia. Using our method, a significant power increase at the desired focus over conventional divergent-beam techniques was achieved. The ability to concentrate power at the focus implies less input power required and, thus, less power absorption in unwanted places, including regions near the surface. The underlying principle is general and may also be applied to ultrasound arrays.

REFERENCES

[1] W. Gee, S. W. Lee, N. K. Bong, C. A. Cain, R. Mittra, and R. L. Magin, "Focused array hyperthermia applicator: Theory and experiment," *IEEE Trans. Biomed. Eng.*, vol. BME-31, pp. 38–46, Jan. 1984.

[2] B. E. Lyons, R. H. Britt, and J. W. Strohbehn, "Localized hyperthermia in the treatment of malignant brain tumors using an interstitial microwave antenna array," *IEEE Trans. Biomed. Eng.*, vol. BME-31, pp. 53–62, Jan. 1984.

[3] P. F. Turner, "Regional hyperthermia with an annular phased array," *IEEE Trans. Biomed. Eng.*, vol. BME-31, pp. 106–114, Jan. 1984.

[4] F. A. Gibbs, Jr., M. D. Sapozink, K. S. Gates, and J. R. Stewart, "Regional hyperthermia with an annular phased array in the experimental treatment of cancer: Report of work in progress with a technical emphasis," *IEEE Trans. Biomed. Eng.*, vol. BME-31, pp. 115–119, Jan. 1984.

[5] P Fessenden, E. R. Lee, T. L. Anderson, J W Strohbehn, J. Meyer, T. V. Samulski, and J. B. Marmor, "Experience with a multitransducer ultrasound system for localized hyperthermia of deep tissues," *IEEE Trans. Biomed. Eng.*, vol. BME-31, pp. 126–135, Jan. 1984.

[6] R. Knoechel, "Capabilities of multiapplicator systems for focused hyperthermia," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 70–73, Jan. 1983.

[7] H. Ling and S. W. Lee, "Design optimization of focused microwave hyperthermia applicators," Univ. Illinois, Urbana, Electromagnetics Lab. Rep. 84-2, 1984. Also to appear in *Innov. et Tech. en Biologie et Medicine*, 1986.

[8] J. B. Andersen, "Theoretical limitations on radiation into muscle tissue," *Int. J. Hyperthermia*, vol. 1, pp. 45–56, Jan. 1985.

[9] T. C. Guo, W. W. Guo, and L. E. Larsen, "A local field study of a water-immersed microwave antenna array for medical imagery and therapy," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 844–854, Aug 1984.

[10] M. I. Skolnik and D. D. King, "Self-phasing array antennas," *IEEE Trans. Antennas Propagat.*, vol. AP-12, pp. 142–149, Mar. 1964.

[11] B. A. Sichelstiel, W. M. Waters, and T. A. Wild, "Self-focusing array research model," *IEEE Trans. Antennas Propagat.*, vol. AP-12, pp. 150–154, Mar. 1964.

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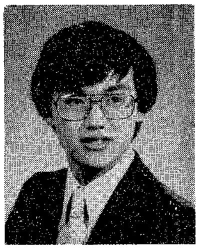

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B. F. Wang, photograph and biography unavailable at the time of publication.

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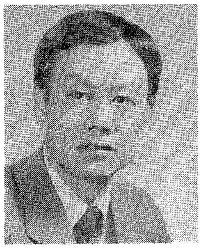

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