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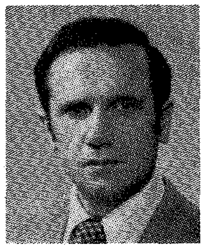

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Microstrip Loop Radiators for Medical Applications

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Abstract—**Three microstrip loop radiators designed to operate at frequencies of 433, 915, and 1300 MHz are described. Empirical design methods and experimental results obtained with phantoms and human tissues are presented. The radiators are relatively well matched when applied to water boluses followed by muscle phantoms or human tissues. When used with the boluses, the radiators have circular surface-temperature distribution while the in-depth heating patterns are similar to those of the aperture-type radiators.**

I. Introduction

VARIOUS microstrip radiators and arrays of radiators for inducing local hyperthermia and for other medical applications of microwaves have been investigated [1]–[7]. For example, an array of printed dipoles was developed to heat a large volume of tissue at 2450 MHz [1]. A coplanar-waveguide coupler was designed to minimize stray coupling in transmission measurements at 915 MHz [2]. Various microstrip-ring radiators were also constructed for inducing local hyperthermia at 915 and 2450 MHz [3], [5]. These radiators are matched when spaced a few millimeters from muscle or muscle phantom or when muscle is covered by a layer of fat. However, in these configurations, the heating pattern of the small fundamental-mode radiators is highly nonuniform because of the near-field effects. To improve the uniformity of the heating pattern, higher order mode, large-diameter radiators would be required. A microstrip slot radiator was also developed for inducing local hyperthermia as well as for medical diagnostics at 2450 MHz [4]. This radiator has relatively low leakage, is matched to human tissue, and has a heating pattern comparable to aperture-type radiators [8]. A microstrip rectangular patch antenna was found to be an efficient radiator when the width of the patch was one wavelength (or less) in the tissue [6].

Three microstrip loop radiators for medical applications

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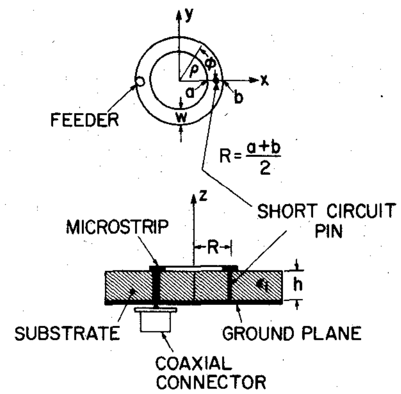

Fig. 1. The geometry of the microstrip loop radiator.

are described in this paper. Two of them were designed for inducing local hyperthermia at 433 and 915 MHz, while the third one was constructed for detection of breast cancer using microwave radiometry at 1300 MHz.

II. Design Principles

The geometry of the loop radiator is shown in Fig. 1. The radiating element is a ring conductor on one side of a dielectric substrate with a ground plane on the other side. The ring is fed at $\phi = \pi$ and connected to the ground plane at $\phi = 0$ by a pin. The radiator is fed from a coaxial line by a probe protruding the substrate.

The resonant frequency of the loop radiator radiating into free space can be calculated by considering a transmission-line equivalent circuit. At resonance, the mean radius of the ring conductor is given by

$$R = \frac{\lambda_0}{2\pi^2\sqrt{\epsilon_e}} \tan^{-1}\left(\frac{3X_L Z_0}{2X_L^2 - Z_0^2}\right) \tag{1}$$

where ϵ_e is the effective relative dielectric constant, Z_0 is the characteristic impedance of the loop-forming line, X_L is the reactance of the feed probe and the shorting pin, and λ_0 is the free-space wavelength.

When the loop radiator is coupled to a semi-infinite lossy medium (viz., muscle), the transmission-line equivalent circuit can no longer be used to calculate the resonant frequencies. Therefore, an empirical design method was used in this research.

Several radiators of various widths and mean radii of the ring conductor were fabricated using a 0.318-cm duroid substrate ($\epsilon_r = 2.32$) and a Custom High-K substrate ($\epsilon_r = 10.0$). Resonant frequencies of these radiators coupled to a muscle phantom and to human tissue (skin-fat) were measured. From these measurements, two empirical relationships between the resonant frequency and the dimensions of the ring were developed. For a thick lossy medium with the relative permittivity $\hat{\epsilon}_r$ the mean radius of the ring on the duroid substrate ($\epsilon_r = 2.32$) can be calculated from

$$R \simeq \frac{6}{f\sqrt{|\hat{\epsilon}_r|}} \tag{2}$$

where f is the resonant frequency in gigahertz. However, when the thickness of the lossy medium in contact with the ring conductor is less than the thickness of the dielectric substrate, (2) becomes

$$R \simeq \frac{3}{f\sqrt{|\hat{\epsilon}_e|}} \tag{3}$$

where $\hat{\epsilon}_e$ is the effective relative permittivity of the radiator structure [5][1]. The width of the loop-forming conductor is selected to match the radiator to the 50-Ω input line. The dimensions of the loop radiators designed to operate at frequencies of 433 MHz, 915 MHz, and 1.3 GHz under various loading conditions are given in Table I.

TABLE I
Dimensions of the Loop Radiators Fabricated Using 0.318-cm-Thick Substrates

Operating frequency (MHz)	ϵ_r	R (cm)	W (cm)	Typical loading condition
433	2.32	2.0	0.5	Direct contact with muscle
433	2.32	1.6	0.5	Contact with a water bolus followed by a muscle phantom
915	2.32	0.9	0.3	Direct contact with muscle or through a water bolus
1300	2.32	1.9	0.4	Direct contact with human female breast
1300	10.0	1.4	0.6	(Direct contact with human female breast)

III. Experimental Results

The radiators were placed in contact with the human female breast, a muscle phantom, and a distilled water bolus followed by a muscle phantom and the return loss was measured using a network analyzer. The experimental results are shown in Figs. 2, 3, and 4. The radiators were found to be well matched, especially to human tissues, in a relatively broad range of frequencies.

The heating patterns of the 433 MHz and 915 MHz radiators were investigated using a thermographic method as well as by liquid crystal films. Initial measurements indicated that the heating patterns of these radiators placed in direct contact with the muscle phantom [9] were asymmetrical with respect to the axis of the radiator. The region near the feed point was heated more than the region near the shorting pin. This was attributed to the near-field effect created by the higher order modes. In order to obtain symmetrical heating patterns, the energy of the higher order modes should be dissipated before reaching the tissue. To accomplish this, distilled-water boluses of various thicknesses were used. Implantable miniature thermocouples as well as liquid crystal films were used to measure the temperature distribution in the phantom after irradiation for a few seconds.

Fig. 5 depicts the temperature distribution in the phantom along the main axis, after irradiation by a 100-W, 30-s pulse at frequencies of 433 and 915 MHz. For comparison,

[1] The effective relative permittivity $\hat{\epsilon}_e$ includes the effect of the substrate as well as the multilayer medium in contact with the radiator.

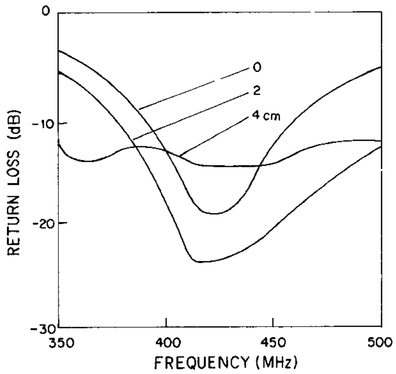

Fig. 2. The return loss versus frequency for the 433-MHz loop radiator in contact with a distilled-water bolus followed by a muscle phantom for three different thicknesses of the bolus.

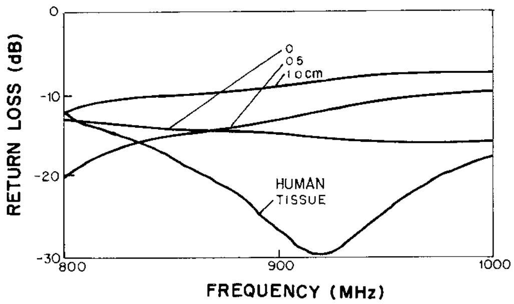

Fig. 3. The return loss versus frequency for the 915-MHz loop radiator in contact with a water bolus followed by a muscle phantom for three different thicknesses of the bolus, as compared with the return loss of the same radiator in direct contact with the human body—upper abdomen with 0.2 cm of skin, 2 cm of fat followed by muscle, (estimated).

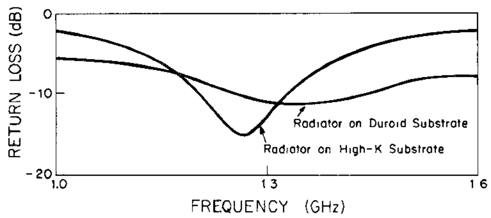

Fig 4. The return loss versus frequency for the 1.3-GHz experimental radiators in direct contact with the human female breast.

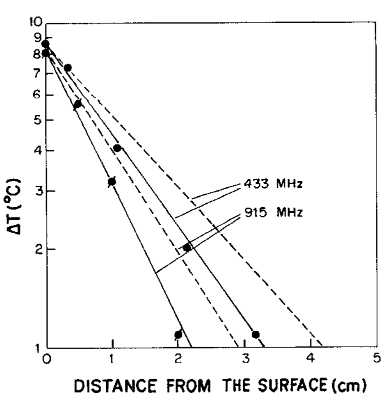

Fig. 5. Temperature rise along the main axis in the muscle phantom irradiated by experimental radiators versus distance from the surface of the phantom. Experimental points for ● 433-MHz radiator, ● 915-MHz radiator, respectively, and — — — theoretical (plane-wave approximation).

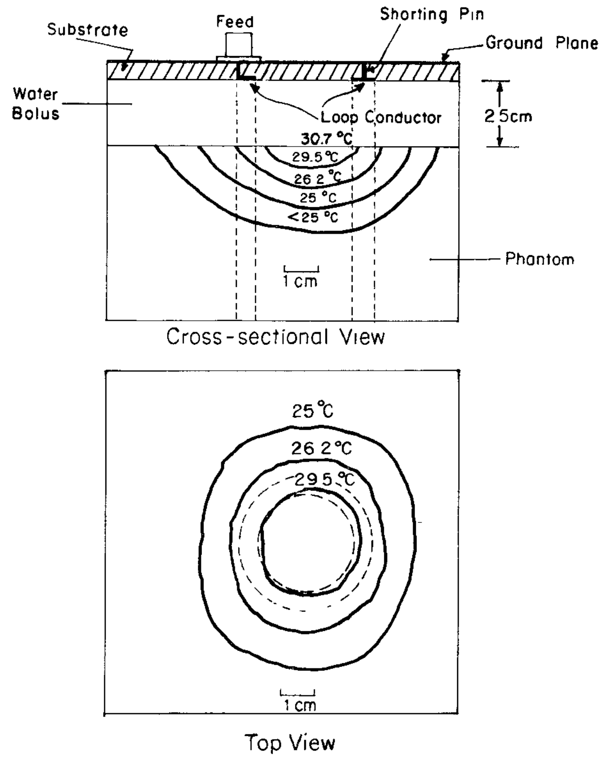

Fig. 6. Temperature distribution in the muscle phantom irradiated through a water bolus by the 433-MHz radiator.

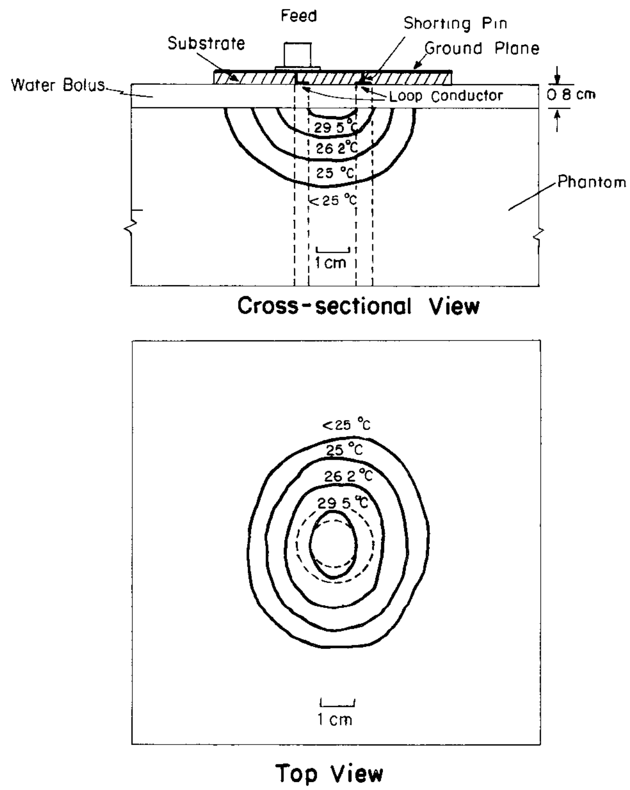

Fig. 7. Temperature distribution in the muscle phantom irradiated through a water bolus by the 915-MHz radiator

theoretical results corresponding to plane-wave irradiation are also shown. For the plane-wave case the temperature distribution was calculated from

$$\Delta T = \Delta T_m e^{-2\alpha z} \tag{4}$$

where ΔT_m is the maximum increase in temperature at $z=0$ and α is the attenuation constant in the phantom. The measured values of the attenuation constant for phantoms are 2.3 dB/cm at 433 MHz and 3.1 dB/cm at 915 MHz. As expected the temperature decreases exponentially with the distance from the surface.

To determine and analyze the surface and in-depth heating patterns, liquid crystal films were used. The initial phantom temperature was kept between 24 and 25°C and the temperature range of liquid crystal film (Edmund Scientific Co. No. 72374) was 25–30°C. Immediately following irradiation, the liquid crystal film was placed in contact with the phantom and heating patterns were photographed using a Polaroid camera. Different colors of the liquid crystal, from red to blue, indicate different temperatures. These heating profiles were later mapped and are shown in Figs. 6 and 7 for 433-MHz and 915-MHz radiators, respectively. The heating pattern in the plane of the radiator with the distilled-water bolus is symmetrical in respect to the axis. The penetration depth of heating defined as $1/e\,\Delta T_m$, for the 433 MHz, 3.2-cm diameter radiator is 1.6 cm, while for the 915 MHz, 1.8-cm diameter radiator is 1.1 cm. The corresponding values for the plane wave are 2.1 cm and 1.4 cm, respectively.

IV. Conclusions

Three microstrip loop radiators matched to the human tissue or to a distilled water bolus followed by a muscle phantom and operating at 433, 915, and 1300 MHz were designed using empirical formulas. With the water bolus, the heating pattern of the radiators is symmetrical in respect to the axis. The penetration depth of the heating depends upon the frequency of operation and the size of the radiator and was found to be equal to 1.6 cm for the 433-MHz radiator and 1.1 cm for the 915-MHz radiator.

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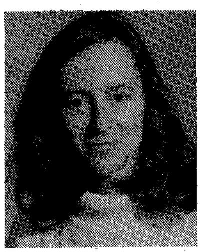
J. J. W. Lagendijk, photograph and biography not available at the time of publication.



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