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Reactive-Loaded Interstitial Antenna

리엑턴스가 장하된 인체에 사용되는 삽입형 안테나

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안희란 · 명노훈 · 김범만*

Abstract

A reactive-loaded interstitial antenna(RLIA) is proposed for 2.45 GHz. It basically consists of a coaxial cable and a reactive load(RL). The RL is tipped at the end of the antenna and contributes to almost perfect matching and desirable heating area. For the almost perfect matching, a matching technique based on transmission line theory is suggested and the RLIA immersed in muscle phantom is designed, fabricated, measured and compared. The measured return loss of the RLIA is −28.377 dB, which may be considered the best among those reported. Due to the excellent matching performance, the RLIA can also be applied for the treatment of deep-seated tumor or cancer with only one RLIA.

요약

인체에 사용되는 삽입형 안테나가 새롭게 제안되었다. 이 안테나의 동작 주파수는 2.45 GHz이며, coaxial cable과 리엑턴스 성분으로 구성되어 있다. 이 리엑턴스 성분은 안테나 끝에 존재하며 거의 완전한 정합과 가열되는 영역을 넓히는데 기여한다. 완전한 안테나 정합을 위하여 전송선로 이론에 기초한 정합방법을 제시하였고 그 정합 방법을 이용하여 이 안테나가 근육에 삽입되었을 때 완전한 정합이 이루어지도록 안테나를 제작, 실험하였다. 측정된 반사계수는 -28.377 dB로써, 지금까지 문헌에 보고된 가장 좋은 결과이다. 그렇기 때문에, 하나의 안테나로도 간, 뇌, 심장과 같이 인체 깊숙이 존재하는 종양이나, 암 세포를 제거하는데 사용될 수 있음을 보여주고 있다.

Key words : Microwave Antennas, Interstitial Antennas, Hyperthermia, Antenna Matching Technique and *SAR* Distributions

Ⅰ. Introduction

Since stable temperature gradient from the experimental results may be expected, the microwave antennas are especially suitable for inducing hyperthermia of deep-seated tumors(e.g. certain brain tumors). They are inserted into medical plastic catheters embedded in target heating area to prevent direct electrical contact with tissue, and the plastic catheters used in interstitial combination therapy(radiotherapy/ hyperthermia) can be used for accommodation both, e.g. radioactive iodine seeds and microwave antennas. Due to less expense, easy operation and short recover time, the use of the interstitial antennas has recently been on a dramatic increase and many studies on them have been published [1]~[7]. However, none of the resulting design is directly

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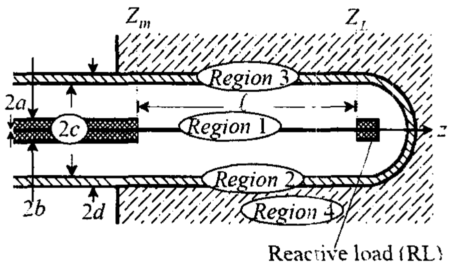
applicable to catheter ablation of the large target(e.g. brain or liver tumors) because of not so desirable energy concentration in the target volume and small effective area for the treatment. Also, since some of conventional ones were designed with optimization[3] or not exact design method[5], antenna matching is poor[7].

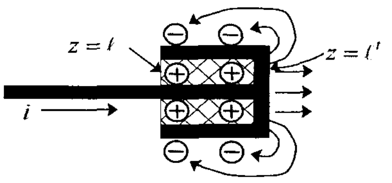
In this paper, a RLIA(reactive-loaded interstitial antenna) is proposed, so that high energy concentration and almost perfect matching can be produced for as little damage as possible to the healthy surrounding tissue. To prove the excellent performance, the RLIA is compared with a conventional one[3], and the compared results show much better performances for *SAR*(specific absorption rate) distribution and smaller size. While all the other conventional ones have sinusoidal current distribution with null at the end points[1]~[7], the RLIA has no current null at the end point and its input impedance may arbitrarily be changed. Due to these distinctive characteristics, good matches together with smaller size may be achieved for the RLIA. To verify the excellent performances, it has been designed, fabricated and measured for muscle phantom. The measured return loss is −28.377 dB at 2.45 GHz and the measured region greater than 43°C is a ruby ball(major axis 4.5 *cm* and minor axis 2.45 *cm*). The value of −28.377 dB can be considered the best among those reported and the measured *SAR* distribution confirms that the RLIA can be applied for the removal of a deep-seated tumor or cancer.

II. Analyses

Fig. 1 shows the RLIA in Fig. 1(a) and its RL in Fig. 1(b). It basically consists of coaxial cable, and its inner conductor is extended to approximately $\lambda_{eff}/4$(*Region* 1) and tipped with the RL shown in Fig. 1(b). It is insulated by a dielectric layer(inner and outer radii, c and d, respectively, and a dielectric constant ε_3), forming *Region* 3, and *Region* 2 is filled with air, all of which are immersed in an infinite ambient medium (*Region* 4) as shown in Fig. 1(a). The RL in Fig. 1(b) is composed of a certain length of the coaxial cable and its inner conductor at the end($z=l'$) is connected with the outer conductor which is open-circuited at $z=l$.

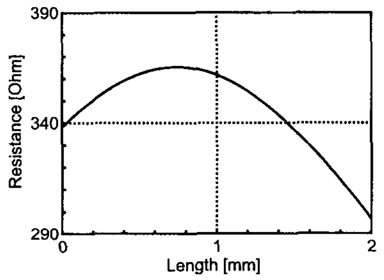


(a) RLIA

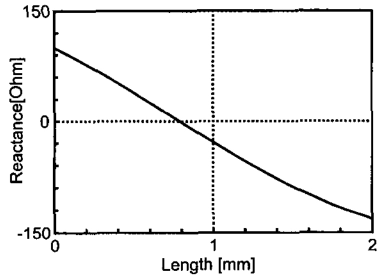


(b) RL

Fig. 1. A RLIA.



(a) Resistance



(b) Reactance

Fig. 2. Calculated impedances of the RL.

Therefore, when the power is fed to the RLIA, the current will flow along its inner conductor and the opposite charges are induced at the same time on the outer conductor. Due to wider surface than cross section of the inner conductor at $z=l'$, the current on the inner conductor at $z=l'$ spreads faster on the top plate. Fig. 1 (b) shows the case that positive current is excited and the approximate electric-field is produced as indicated with arrows. The opposite charges on the outer conductor help the current on the top plate at $z=l'$ flow faster toward the end at $z=l$ in $-z$ direction. Thus, the electric field can be concentrated around the RL but not too strong at the end, which is very important to protect healthy surrounding tissue.

Fig. 2 shows the calculated input impedances of the RL depending on the length l_s where $l_s = l_t - l$ in Fig. 1(b). The inner and outer radii of the coaxial cable are 0.145 *mm*, 0.595 *mm*, respectively and its relative dielectric constant $\varepsilon_d = 2.1$. Those of the crystal glass tube are 1.15 *mm*, 2.1 *mm*, respectively and $\varepsilon_3 = 5.1$. All of them are immersed in infinite muscle phantom (complex relative dielectric constant $\tilde{\varepsilon}_4 = 52.7 + j13.3$). The calculations have been carried out with a program working on Matlab 6.1. Their resistance is plotted in Fig. 2(a), whereas the reactance in Fig. 2(b), where the positive values means inductance and the negative ones capacitance. The results in Fig. 2 indicate that the RL has capacitance and inductance depending on its length.

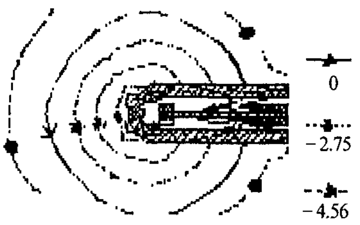
The relation between *SAR* and temperature distribution, *T*[1] is derived as

$$SAR = \frac{\sigma}{2\rho} = |E|^2 = kc\frac{\Delta T}{\Delta t}, \tag{1}$$

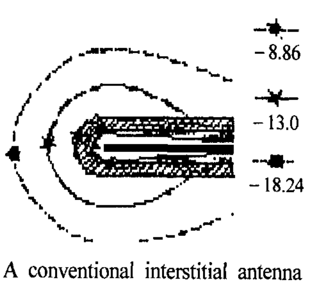
where ρ is a density of an ambient medium, σ an electric conductivity of the ambient medium, k=4186 *J / kcal*, *c* the specific heat of the medium(c=0.84 *k*cal / for muscle phantom tissue K_g℃), *T* a medium temperature, and *t* time(second). Since *SAR* is proportional to electric energy density as shown in (1), it has been simulated and the RLIA is compared with the conventional one[3]. For the simulations, a semi rigid coaxial cable with inner and outer radii 0.29 *mm* and 1.4 *mm*, respectively, and $\varepsilon_d = 2.1$ is utilized. A crystal glass tube $\varepsilon_3 = 5.1$ with inner and outer radii, 2.3 *mm* and 4.2 *mm* is used as a microwave catheter. The two antennas are designed for good matching and the length of the RL shown in Fig. 1(b) is 2 *mm*. The two are immersed in air, the air is also filled in *Region* 2, and the excited powers are the same in both cases. The simulations have been carried out with the *Region* 4 filled in air but the comparison will be the same effect in the case of lossy medium because of the same behavior of electric energy density. The simulated results are plotted in Fig. 3 where the RLIA in Fig. 3(a) and the conventional one in Fig. 3(b). The numbers are normalized values to the maximum one. The simulated results indicate the electric energy density around the RLIA is more concentrated.

When these interstitial antennas like that in Fig. 1 are placed in dissipative media, they may be treated as sections of lossy transmission lines with generalized propagation constants that reflect the losses due to radiation from the antennas to the ambient medium. Since the dielectrics actually used in the *Region* 2 and 3 are highly non-conducting and that of the ambient medium in the *Region* 4 conducting, ε_2 and ε_3 are assumed to be real and $\tilde{\varepsilon}_4$ complex.

Fig. 4 shows a transmission line equivalent circuit of the RLIA. The input impedance of the RL, Z_L in Fig.



(a) A RLIA



(b) A conventional interstitial antenna

Fig. 3. Simulated electric energy densigy.

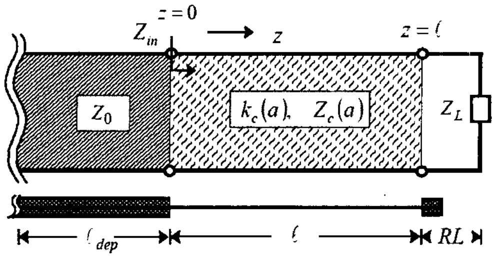


Fig. 4. Transmission line equivalent circuit of the RLIA.

1(a), may be calculated based on the transmission line model as shown in Fig. 2 and the input impedance of the RLIA, Z_{in} is derived as

$$Z_{in} = Z_c(a)\frac{Z_L + jZ_c(a)\tan[k_c(a)\,l]}{Z_c(a) + jZ_L\tan[k_c(a)\,l]} \tag{2}$$

where

$$k_c(a) = k_{2e}(a)\left[\frac{\ln(d/a) + F}{\ln(c/a) + n_{24}^2F}\right]^{1/2},$$

$$k_{2e}(a) = \omega\sqrt{\mu_0\varepsilon_0\varepsilon_2}\left[\frac{\ln(d/a)}{\ln(c/a) + n_{24}^2\ln(d/c)}\right]^{1/2},$$

$$Z_c(a) = \left(\omega\mu_0 k_c(a)/2\pi k_{2e}^2\right)\left[\ln(d/a) + n_{23}^2\ln(d/c) + n_{24}^2F\right],$$

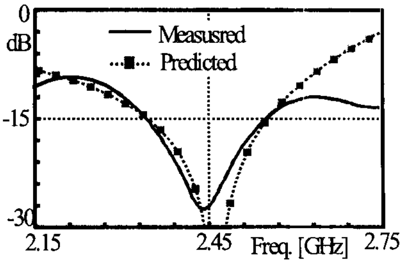
$$k_4 = \omega\sqrt{\mu_0\varepsilon_0\widetilde{\varepsilon}_4},\quad \widetilde{\varepsilon}_4 = \varepsilon_4 + j\sigma_4/\omega,$$

$$n_{23}^2 = \varepsilon_2/\varepsilon_3,\quad n_{24}^2 = \varepsilon_2/\widetilde{\varepsilon}_4,\ \text{and}$$

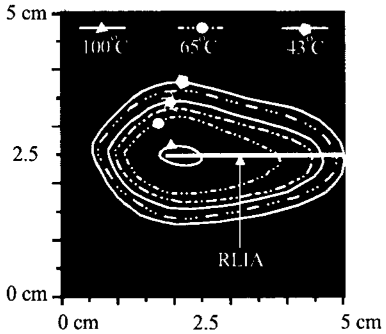
$$\text{F} = H_0^{(1)}(k_4d)/\left(k_4dH_1^1(k_4d)\right)$$

with H : Hankel function.

Since the two values of Z_{in} and l are still unknown in (2), an optimization method is needed for the minimum reflection coefficient at $z=0$ in Fig. 4, and $l=18.64$ *mm* may be determined as the solution of (2) in the case of $2a=0.29$ *mm*, $2b=1.19$ *mm*, $2c=2.3$ *mm*, $2d=4.2$ *mm*, $\varepsilon_d=2.1$, $\varepsilon_2=1$, $\varepsilon_3=5.1$ and $\widetilde{\varepsilon}_4 = 52.7 + j13.3$(muscle) and $l_s = 2$ *mm*. The RLIA has been tested, immersed in a 10 *cm*×10 *cm*×10 *cm* muscle phantom. Measured and predicted return losses are compared in Fig. 5(a). The predictions have been carried out by a program working on a mathematical software and the measured return loss is −28.377 dB at 2.45 GHz. The value of −28.377 dB can be considered the best among those reported[6],[7]. Fig. 5(b) shows the measured *SAR* distribution pictured by IRCON(Inspect IR 500 PS) digital camera, serial number SS-7. For the measurement, a 5 *cm*×5 *cm*×5 *cm* muscle phantom is used and it is displayed that the measured region greater than 43°C is a ruby ball(major axis 4.5 *cm* and minor axis 2.45 *cm*) in Fig. 5(b).



(a) Measured and predicted return losses



(b) Measured *SAR* distributions

Fig. 5. Measured results of RLIA.

Ⅲ. Conclusion

In this paper, a RLIA is proposed for the almost perfect matching. It basically consists of coaxial cable and a RL. The RL is needed for a good matching, smaller size and energy concentration around the RLIA. Based on an transmission line equivalent circuit of the RLIA, a matching technique is suggested for the exact design of the RLIA. The measured reflection coefficients of the RLIA is −28.377 dB which may be regarded as the best one among those reported. If a different type of reactive load is located in the middle of the RLIA, more desirable *SAR* distribution pattern may be expected. From the measured *SAR* distribution of the RLIA, the region greater than 43 ℃ forms a rugby ball shape(major axis 4.5 *cm* and minor axis 2.45 *cm*), by which a deep seated and large-sized tumor can be treated with only one antenna. Using the matching technique suggested and the input impedance of the RL, any size of the interstitial antennas can be designed for a good matching property and desirable *SAR* distribution.

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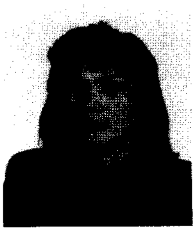

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Noh-Hoon Myung was born in Seoul, Korea, in 1953. He received the B. S. degree in electrical engineering from the Seoul National University, Korea, in 1976, and the M. S. and Ph.D. degrees from the Ohio State University, Columbus, in 1982 and 1986, respectively. He was a Research Member at the ElectroScience Laboratory, Ohio State University, for six years, working in the area of electromagnetic wave scattering and propagation before joining the EECS Dept., Korea Advanced Institute of Science and Technology(KAIST). He was also a member of the research staff of the National Highway Traffic and Safety Administration(NHTSA), Ohio, where he constructed a ground-based optical vehicle tracking system. His current research areas include wave scattering and propagation analysis, RCS(radar cross section) analysis, antenna and radar system design, mobile and satellite communications, and electromagnetic interference and electromagnetic compatibility(EMI/EMC).

Bumman Kim

Bumman Kim received the Ph. D. degree in electrical engineering from Carnegie-Mellon University, Pittsburgh, PA, in 1979. From 1978 to 1981, he was engaged in fiber-optic network component research at GTE Laboratories Inc. In 1981, he joined the Central Research Laboratories, Texas Instruments Incorporated, where he was involved in development of GaAs power FET's and MMIC's. He has developed a large-signal model of a power FET, dual-gate FET's for gain control, and high-power distributed amplifiers, and various millimeter-wave MMIC's. In 1989, he joined the Pohang University of Science and Technology(POSTECH), Pohang, Korea, where he is a Professor in the Electronic and Electrical Engineering Department, and Director of the Microwave Application Research Center, where he works on device and circuit technology for RFIC's. His main interest is in power amplifiers for base station and hand-set. He has published over 150 technical papers in this area. He is an associate editor of IEEE Transaction on MTT. Dr. Kim is a member of the Korean Academy of Science and Technology and a member of Academy of Engineering of Korea.