Left-Handed Metamaterial Lens Applicator with Build-in Cooling Feature for Superficial Tumor Hyperthermia

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Abstract ─In all hyperthermia schemes with left-handed metamaterial (LHM) lens applicator, water bolus are used to prevent skin from being overheated during the hyperthermia treatment. Owing to water's high refraction index, high reflection usually occurs at the interface between low-index LHM lens and water bolus, and between water and skin, which will lead to the low efficiency of hyperthermia. In this paper, we propose a new LHM lens applicator with build-in cooling feature for superficial tumor hyperthermia. Both simulation and experiment demonstrated that microwave hyperthermia with the proposed applicator may concentrate more microwave energy into deeper tissue if compared to hyperthermia with normal LHM lens.

Index Terms ─Hyperthermia, metamaterial lens, microwave, tumor, water bolus.

I. INTRODUCTION

Left-handed metamaterials (LHM) lens provide new prospects for hyperthermia treatment of superficial tumors. Superficial tumors generally occur at depth no more than several centimeters beneath the skin [1], which is within the near-field focusing depth of LHM lens.

Although losses of LHM will destroy Pendry's perfect lens [2], applicators with LHM lens are still very attractive to superficial tumor hyperthermia for two reasons. First, super-resolved focus of LHM lens characterized by half-power beam-width has been demonstrated in several experiments [3-6] with low-loss LHM slabs. It is the microwave power within half-power beam-width, not within the beam-width charactering the LHM lens resolution defined in [2], which makes dominant contribution to hyperthermia of tumor. Second, a focusing spot of moderate size in tissue is preferred for heating a large or diffusive superficial tumor. Tiny focal spots of LHM applicator, if acquired, will find application in tumor ablation or hyperthermia of early small size tumors.

Potentials of LHM lens applicator for tumor hyperthermia have been demonstrated both numerically and experimentally [7-9]. Furthermore, potential of conformal hyperthermia with LHM applicator was also demonstrated [10]. Due to flexibility of focal point adjustment in both lateral and depth directions of a flat LHM lens, it is reasonable that a relatively large heating zone in tissue can be readily generated if we deploy several microwave sources (antennas) behind a flat LHM lens applicator, and a tilted heating zone in tissue, viz., a heating zone in tissue with different depth of penetration across the array, can be obtained by properly adjusting the distance between the lens and sources. In [11], it is further demonstrated that conformal hyperthermia with low-loss LHM lens applicator can be realized by generating a tilted heating zone in tissue. In addition to adjusting the source-to-lens distance, we find that adjusting the phase of microwave sources may also control the inclination of heating zone.

All these hyperthermia with low-loss LHM lens applicators use water bolus to prevent skin from being overheated during the hyperthermia treatment. As is well-known, water has a refraction index higher than skin, and it is generally hard to build LHM lens with high effective refraction index. Therefore, high reflection usually occurs at the interface between low-index LHM lens and water bolus, and between water and skin, which will lead to the low efficiency of hyperthermia (i.e. to heat a certain tumor, the more time and higher source power are needed).

In this paper, we propose a new LHM lens applicator with build-in cooling feature, i.e. cooling water is filled into partial structures of LHM lens, for superficial tumor hyperthermia. In section II, hyperthermia with proposed applicator is demonstrated. In section III, the design of LHM lens applicator with build-in cooling feature is illustrated. In section Ⅳ, the performance of proposed lens is confirmed by experimental researches.

II. HYPERTHERMIA WITH LHM LENS APPLICATOR WITH BUILD-IN COOLING FEATURE

Fig. 1 shows the scheme of conformal hyperthermia with LHM lens applicator proposed in [11]. In this scheme, several microwave sources ($S_1, S_2, \cdots S_n$, *representing antenna phase centers in practice*) may be set behind a flat LHM lens applicator. The LHM lens will focus microwave emitted from source S_i $(i = 1, 2, ..., n)$ at a corresponding focal point F_i $(i = 1, 2, ..., n)$ in tissue. Therefore, different heating zones enclosing focal point F_i $(i = 1, 2, ..., n)$ can be generated. According to LHM lens' focusing theory, the focusing depth $\mathrm{d}F_\mathrm{i}$, lens thickness D=4cm, source-lens distance $\mathrm{d}S_\mathrm{i}$ and water bolus thickness h=0.5cm satisfy the equation

$$\mathrm{d}F_\mathrm{i} = (D - \mathrm{d}S_\mathrm{i})/K - h \,, \tag{1}$$

where K is usually greater than 1, which indicates the influence of the random inhomogeneity of biological tissue and microwave attenuation on focusing position. Obviously, as the water bolus between tissue and lens is applied, not only the high reflection is generated, but also the focus depth is directly decreased.

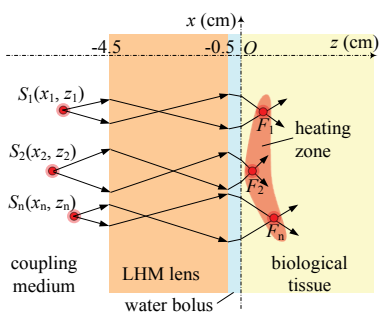


Fig. 1.Conformal hyperthermia scheme with LHM lens applicator proposed in [11].

So we consider a new conformal hyperthermia scheme with LHM lens applicator with build-in cooling feature as shown in Fig.2. It is observed that in this scheme cooling water with height of h is filled into partial structures of LHM lens. The equation (1) should be modified to

$$\mathrm{d}F_\mathrm{i} = (D - \mathrm{d}S_\mathrm{i} - k_w h)/K \,, \tag{2}$$

where k_w is generally less than 1, which indicates the influence of cooling water filled in lens structures on focus depth. Obviously, by applying this new applicator the focus depth can be increased, as the high reflections are prevented. By integral optimization of the water bolus and lens structures, the hyperthermia efficiency should be improved.

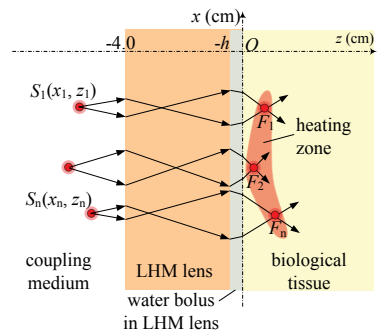


Fig. 2. Conformal hyperthermia scheme with LHM lens applicator with build-in cooling feature.

III. DESIGN OF LHM LENS APPLICATOR WITH BUILD-IN COOLING FEATURE

To facilitate filling water in LHM lens structures, we consider designing the lens based on a volumetric negative refractive-index transmission-line (NRI-TL) metamaterial structure, which is capable of building three-dimensional LHM lens by stacking planar NRI-TL metamaterials in a multilayer manner[12]. Fig. 3 depicts the three-dimensional sketch of conformal hyperthermia scheme as NRI-TL metamaterial lens with build-in cooling feature is applied. And the electromagnetic simulation software HFSS is used to design the proposed lens.

In simulation, in order to reduce computational costs, the model of partial device including antennas and lens is simplified as shown in fig. 4. Fig.5 illustrates the model of practical hyperthermia scheme as the proposed LHM lens is applied. It is observed that, to emulate infinite periodicity in the y direction, a single NRI-TL metamaterial lens composed of a pair of PCB layers is deployed between two metal plates (simulated by perfect E walls in HFSS model), spaced 1.3cm apart. And the side walls except the one meets the tissue are set as absorbing boundary (simulated by perfect H walls) to avoid leak of radiation. A coaxial connector with inner/outer diameter of 1.27mm/4.1mm located at 2cm away from lens is used as the antenna.

The LHM lens is four 4 thick (z direction) and 15 cells width(x direction). And the initial cell is designed based on the structure presented in [12] and has refractive index of $n_\mathrm{eff} = -3.68 + 0.61i$ at 2.45 GHz without build-in cooling water, which means the lens has a size of 4×15cm. The water with a thick of 0.5cm, which is the same as the water bolus applied in hyperthermia scheme proposed in [11], is filled in the cell close to tissue.

And then the parameters of lens cell can be optimized by using the automatic optimization function of HFSS. And the electric field distribution can be calculated by using the field calculator of HFSS. Fig.6 (a) shows the electric field

distribution in tissue obtained by the hyperthermia scheme with optimized LHM lens. Owing to cavity effects, a hot zone is obtained adjacent to skin. And the maximum electric field amplitude in this zone is measured to be 71.2V/m. Meanwhile, it is observed that another hot spot is located at the position of 1cm below skin. And the maximum electric field amplitude in this spot is 41.2V/m measured at (z=0.96cm, x=0).

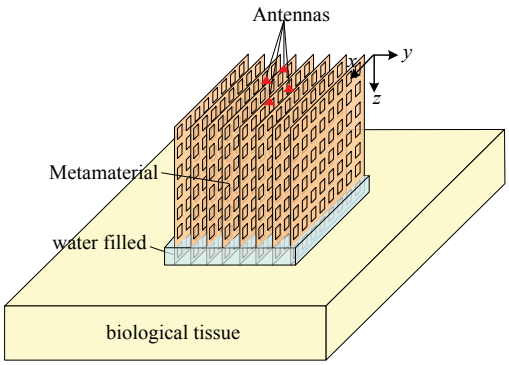


Fig. 3. Three-dimensional sketch of conformal hyperthermia scheme as NRI-TL metamaterial lens with build-in cooling feature is applied.

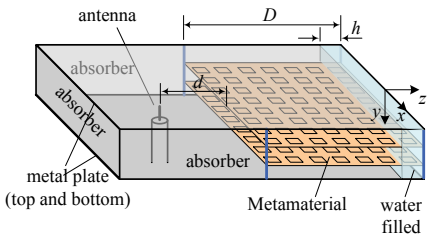


Fig. 4. Simplified model of partial device including antenna and lens.

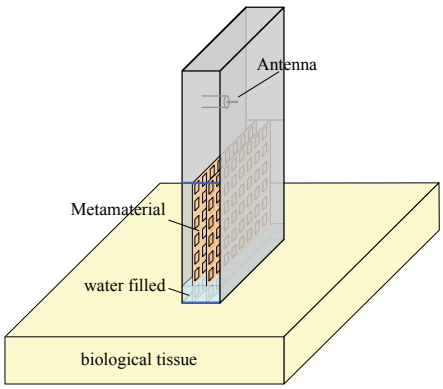


Fig. 5. The simulation model of practical hyperthermia scheme as the LHM lens applicator with build-in cooling feature is applied.

In order to evaluate the performance of the proposed lens applicator, the electric field distribution obtained in the scheme with conventional LHM lens is also presented in Fig.6 (b). A light spot is observed at the location of 0.5cm below skin. The maximum electric field amplitude of 39.7 V/m is measured at (z=0.56cm, x=0.05cm). And the field amplitude measured at (z=0.96cm, x=0) is 11.6 V/m, which is just 28.2% of that measured at the same position as the proposed LHM lens is applied.

In summary, for the same hyperthermia scheme, while the proposed LHM lens applicator is applied, the focusing depth is increased and more microwave energy is concentrated in tissue.

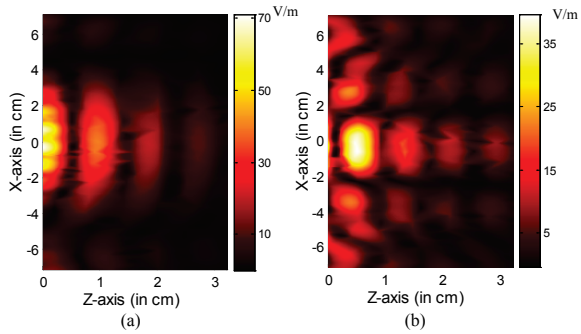


Fig. 6. Electric field distribution in tissue acquired with hyperthermia scheme with (a) LHM lens applicator with build-in cooling feature, (b) traditional LHM lens.

To explore whether the proposed lens is suitable for conformal hyperthermia, the performance of this lens is compared with ideal LHM lens applied in [11], as depicted in table1 1.

In previous works, it is found that the temperature distribution depends on specific absorption rate (SAR) distribution (or power distribution), and SAR over 10% (power over -10dB) have contribution to heat tumor. In [11], it is indicated that 50% SAR zone (-3dB power zone) of single source should not be too small to realize conformal hyperthermia. It is found that the -3dB width obtained with the proposed lens is more than twice of that acquired by ideal lens. Meanwhile, it is also observed the -3dB depth decreases greatly owing to cavity effects. But considering the heat generated in skin will be dissipated quickly by circulated cooling water, and the -5dB depth is close to that acquired by ideal lens, it is concluded the -3dB depth decreasing could not cause too much deterioration to heat depth. In conclusion, the proposed lens is suitable for conformal hyperthermia.

Table 1: Comparison on the performance of the proposed LHM lens applicator with the ideal LHM lens used in[11].

	Maximum -3dB width	**-3dB depth**	**-5dB depth**	**-10dB depth**
Proposed LHM lens	1.81cm	0.32cm	1.1cm	1.32cm
Ideal LHM lens	0.72cm	1.05cm	1.23cm	2.01cm

IV. EXPERIMENT WITH LHM LENS APPLICATOR OF BUILD-IN COOLING FEATURE

Experimental setup for testing the performance of LHM lens applicator with build-in cooling feature is depicted in Fig. 7. Coaxial connectors are used as probe and antenna to provide the fixed-point excitations inside the metal plate. And in all experiments, the distance between antenna and lens is fixed to 2cm. As pictured in Fig. 8, coaxial connectors are connected with two ports of vector network analyzer (VNA) respectively. It is observed that the metal plate with antenna is fixed on a vertical graduated holder, as the other plate with probe is fixed on electric displacement platform (EDP). So just by operating the holder and electric displacement platform, the probe can be moved in the whole focusing zone to measure the transmission coefficient S_{21} between antenna (port 1) and probe (port 2). And then the normalized focusing field can be calculated.

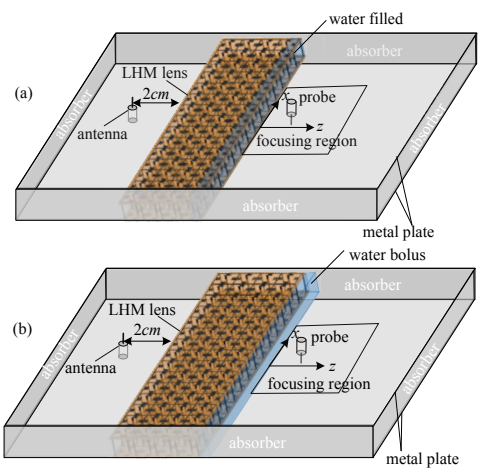


Fig. 7. Diagram of experimental setup including antenna and lens: (a) LHM lens with build-in cooling feature, (b) common LHM lens.

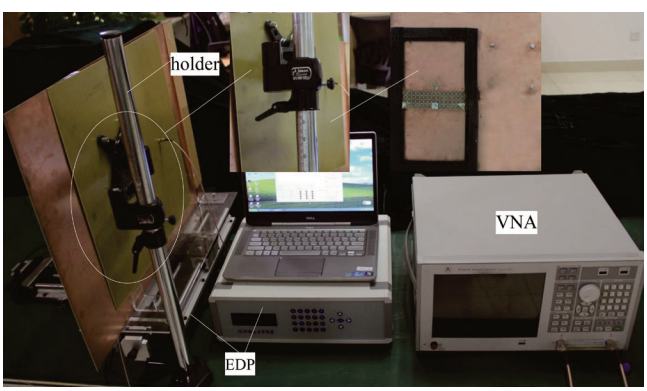
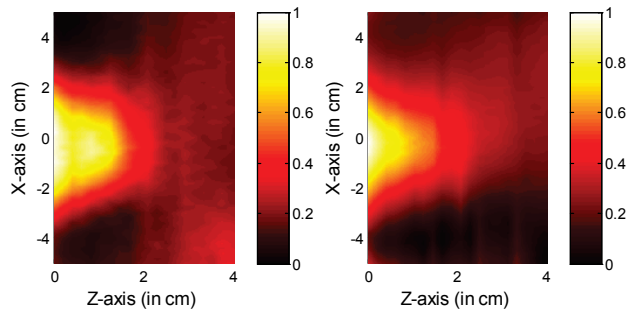


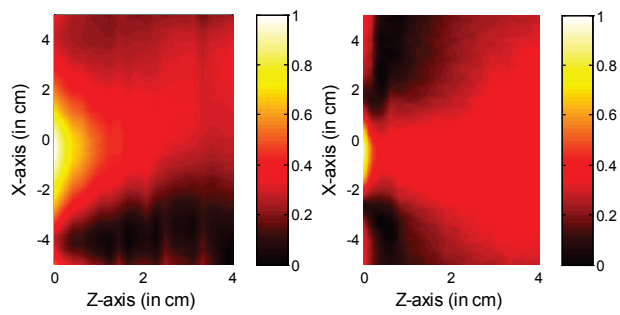
Fig. 8. Picture of the experimental setup.

Fig.9 shows the focusing field distribution obtained by LHM lens applicator with 0.3cm and 0.5cm build-in cooling feature. Obviously, the thinner the water filled in lens, the more and the deeper the microwave energy can be concentrated in focusing region. Analogously, as depicted in Fig.10, the thicker the water deployed behind the common LHM lens, the less and the shallower the microwave energy can be focused. And it is found that, at the same thickness of water, the new LHM lens with build-in water acquire higher focusing depth and concentrate more energy in focus region, which mean the focusing performance is improved.



(a) (b)

Fig. 9. Electric field distribution in focusing region acquired by applying proposed lens with (a) 0.3cm water filled, (b) 0.5 cm water filled.



(a) (b)

Fig. 10. Electric field distribution in focusing region acquired by applying traditional lens with (a) 0.3cm water bolus, (b) 0.5 cm water bolus behind.

V. CONCLUSION

To avoid the high reflection introduced by cooling water bolus used for preventing skin being overheated during the hyperthermia treatment, we present a new LHM lens applicator with build-in cooling feature. The simulation results indicate that as the normal LHM lens and water bolus are replaced by this new applicator, more microwave energy can be concentrated in tissue and the focus depth is increased, which is supported by further experimental studies.

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