Recent Advances in Designing Balun-Free Interstitial Antennas for Minimally-Invasive Microwave Ablation

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***Abstract*—We discuss recent advances in the design of balun-free interstitial antennas for minimally-invasive microwave ablation (MWA). Specifically, two different classes of balun-free MWA antennas are discussed in this paper. The first class of antennas consists of monopole-type radiators fed at their bases using coaxial cables and operated at the second resonant frequency. Under these conditions, a compact specific absorption rate (SAR) pattern is achieved without the need to use a coaxial balun encompassing the outer periphery of the feeding coaxial cable as is done in conventional coax-fed MWA antennas. The second class of antennas consists of balanced dipole or loop antennas fed with inherently balanced, shielded transmission lines. In such a structure, the current flowing on one conductor of the feeding line (and the antenna arm) is balanced by the current flowing on the other conductor (the other antenna arm). Therefore, no RF current flows on the outer surface of the floating shield and the antenna achieves a compact SAR pattern and localized heating zone. Design considerations, principles of operation, and measurement results including the results of *ex vivo* ablation experiments for representative prototypes of both classes of antennas are presented and discussed in the paper.**

Keywords—Microwave ablation; Hyperthermia; Biomedical applications of electromagnetic radiation; Interstitial antennas.

I. INTRODUCTION

Microwave ablation (MWA), a promising technology for the treatment of cancers as well as several non-oncological diseases, makes use of an interstitial antenna to deliver a microwave-induced cytotoxic dose of heat to the tumor. Most interstitial antennas designed for MWA are implemented using coaxial cables, which require baluns to suppress the electric currents excited on the outer conductors of the coaxial feed and achieve localized heating [1]. A coaxial balun is typically implemented by encompassing the feeding coaxial cable with a hollow circular conductor which may be either electrically connected to the outer conductor of the coaxial cable [2]-[3] or electrically isolated from it [4]-[5]. The use of a balun increases the overall diameter of the antenna and therefore its invasiveness. Thus, new antenna designs which provide localized heating patterns and good impedance match without the use of balun are highly desirable for minimally invasive MWA.

There are several existing solutions for reducing the invasiveness of coax-fed antennas. In [6], a double-slot antenna that does not use a balun was evaluated for MWA. By introducing an additional slot, this antenna provides a better localized SAR pattern compared to the single-slot coaxial antenna and its performance is independent of insertion depth. In [7]-[8], biopsy needles used to introduce coax-fed antennas to tissue served as adjustable chokes for the antennas. This practical implementation offers a less invasive solution than conventional choked antenna designs for improving impedance matching and SAR localization.

In this paper, we discuss two new classes of interstitial MWA antennas that we have recently developed. The first class of antennas comprises a monopole-type radiator fed at its base with a coaxial cable [9]. When this antenna is operated at its second resonant frequency, the feed point acts as a natural high-impedance point and chokes the current flow on the outer surface of the feeding coaxial cable. Consequently, the antenna can create compact specific absorption rate (SAR) patterns in the absence of a coaxial balun. The second class of antennas comprises balanced dipole or loop antennas fed with balanced, shielded two-wire transmission lines. In such a structure, the current flowing on one conductor of the feeding line (and one antenna arm) is balanced by the current flowing on the other conductor (and the other antenna arm). Therefore, no RF current flows on the outer surface of the floating shield and the antenna provides a compact SAR pattern and localized heating zone without using any current choking baluns. Compared to conventional interstitial antennas used in MWA today (e.g. [2], [3], [10]), the interstitial antennas discussed in this paper have narrower external diameters for the same underlying coaxial dimensions while providing compact SAR patterns and heating zones.

II. BALUN-FREE HELICAL ANTENNAS

Fig. 1(a) shows the topology of a balun-free coax-fed helical antenna. The antenna consists of a helical monopole fed at its base using a coaxial cable. The specific helical shape shown in Fig. 1(a) is used to reduce the length of the antenna and does not have any significance beyond that. Therefore, all the subsequent discussions about this antenna are equally applicable to other types of monopoles as well (e.g. linear, zig-zag, and curved monopoles). The feed point of the antenna presents a natural, high-impedance point at the second resonant

This material is based upon work supported by the U.S. National Science Foundation under NSF Award No. ECCS-1406090 and by the Wisconsin Alumni Research Foundation.

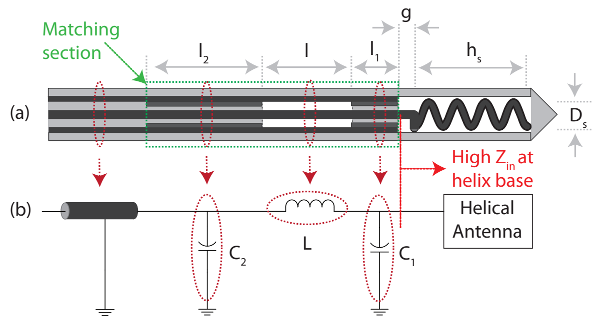

Fig. 1. (a) Topology of the proposed helical antenna and matching section. Dark grey represents copper, light gray represents Teflon, and white represents air. (b) Equivalent circuit model of the matching section.

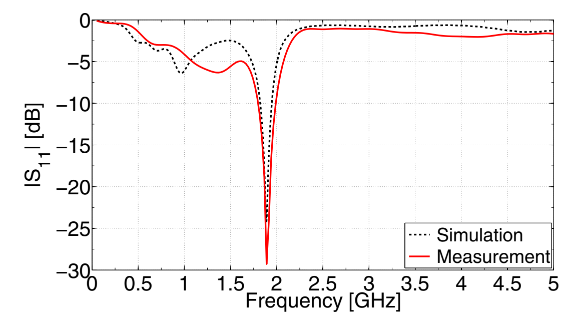

Fig. 2. Simulation and measurement of S_{11} for the helical antenna operating in liver tissue. The antenna design parameters are as follows: n=10 turns, h_s=20 mm, l_1=6 mm, l_2=22 mm, l=18 mm, and g=2 mm.

frequency. Operating the antenna at this second resonance chokes the currents that tend to flow on the outer surface of the outer conductor of the feeding coaxial cable. This choking occurs without the need to use any external coaxial balun on the periphery of the feeding coaxial cable. Therefore, at this resonant frequency, the antenna works as if it has an inherent choke and does not need to use any external coaxial baluns. This results in a very compact SAR pattern and localized heating when this antenna is used for microwave ablation.

The high feed-point impedance of this antenna, however, does not allow it to be fed directly with a 50 Ω coaxial cable. This is due to the large impedance mismatch between the feeding coaxial cable and the antenna. This problemcan be solved by using an impedance matching network within the feeding coaxial cable that matches the high feed-point impedance to the lower impedance of the feeding cable. Fig. 1(b) shows one example of an impedance matching network composed of two parallel capacitors and a series inductor that can perform this task. The parallel capacitors and series inductor are implemented using short sections of a low-impedance and a high-impedance coaxial cable, respectively. Other impedance matching networks, such as a quarter-wavelength transformer, can also be designed to perform this task.

A prototype of the antenna shown in Fig. 1 was designed, fabricated and experimentally characterized recently [9]. This prototype was designed to operate at 1.9 GHz in bovine liver. The antenna was fed using a 50Ω UT-085C-LL semi-rigid coaxial cable with a maximum outer diameter of 2.197 mm. It was placed in a Teflon catheter with an outer diameter of 3.2 mm. The relatively large dimensions were chosen here to ease the fabrication process during the proof-of-concept demonstration phase. The outer diameter of this antenna can be significantly reduced with the proper choice of smaller coaxial cables and a correspondingly thinner catheter.

Fig. 2 shows the comparison between the measured and simulated input reflection coefficients of this antenna. The dimensions of the fabricated prototype are provided in the caption of Fig. 2. Observe that an excellent impedance match is obtained at the desired frequency of operation using the impedance matching network shown in Fig. 1. Moreover, a very good agreement between the measurement and simulation can be seen as well.

This fabricated prototype was used in a number of *ex vivo* ablation experiments in bovine liver. In all experiments, the antenna generated compact ablation zones without heating the region along the insertion path of the antenna. Additionally, in all experiments, the antenna response was found to be independent of its insertion depth into the tissue. These observations experimentally confirm the fact that no RF current flows along the shaft of the antenna on the outer surface of the feeding coaxial cable.

Recently, we performed a series of controlled experiments to compare the *ex vivo* ablation performance of this antenna with those of a triaxial [10] and a choked dipole [11] MWA antenna. These two specific types of antennas were chosen because they are used in commercially-available MWA systems marketed by respectively by NeuWave Medical and Covidien (now Medtronic). In these experiments, 24 *ex vivo* ablations were performed in bovine livers (8 experiments with each antenna type). After each experiment, the ablated tissue was excised and the ablation zone was visually examined and the lesion dimensions were measured. All the experiments were performed at the frequency of 1.9 GHz and for the same duration (5 minutes) and input power (40 W). The balun-free MWA antenna shown in Fig. 1 consistently produced lesions that were more spherical in shape compared to the triaxial [10] and choked dipole [11] antennas. Specifically, the average aspect ratio (ratio of the long to short axis dimensions) of the ablation zones of the balun-free helical antenna was 1.43 whereas those of the choke and the triaxial antennas were 1.57 and 1.95 respectively. These preliminary studies demonstrate that even though the balun-free antenna shown in Fig. 1 does not use a coaxial balun, it provides more confined and spherical heating zones compared to the MWA antennas of the types used in state-of-the-art, commercially-available MWA systems.

III. Balanced Non-Coax-Fed Antennas

Another method for eliminating the use of a balun in MWA antennas is to use balanced antenna types in conjunction with inherently balanced transmission lines. For example, when a dipole or a loop antenna is fed with a two-wire transmission line, there is no need to use a balun. For an interstitial antenna, however, using a conventional two-wire transmission line is not appropriate because the fields of such a line are not shielded

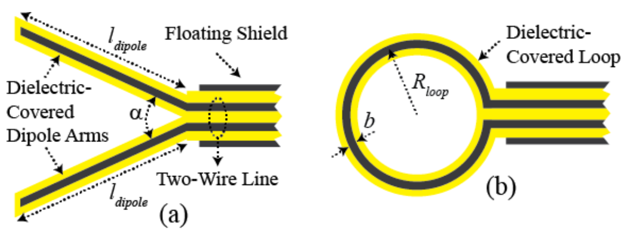

Fig. 3. Topology of a balanced dipole (a) and loop (b) antenna fed with a shielded two-wire line.

from its surrounding environment. This problem can be solved by using a shielded two-wire transmission line. In this case, the balanced two-wire line is placed inside a hollow conductor that acts as a floating shield and does not allow the fields of the line to penetrate into the surrounding region. Fig. 3 shows an example of a dipole and a loop antenna fed using such a line.

We recently use this technique to develope balanced interstitial MWA antennas. Specifically, a dipole antenna fed with a balanced two-wire transmission line was designed. A floating shield was used to enclose the fields of the feeding transmission line and prevent them from penetrating into surrounding tissue. Initial proof-of-concept experiments were conducted at 10 GHz. This choice of frequency was motivated by two reasons. First, high-frequency (e.g. 10 GHz) microwave ablation was recently demonstrated to be as effective as low-frequency (e.g. 1.9 GHz) microwave ablation in producing large ablation volumes [12]. Secondly, at higher frequencies, the smaller wavelength allows for reducing the active length of the antenna without compromising the size of the ablation zones that can be achieved. Therefore, by operating at higher frequencies and using MWA antenna designs that do not need a balun, both the length and the diameter of interstitial antennas used for MWA can be reduced. This is expected to reduce the invasiveness of MWA as therapy for cancer.

The balanced dipole MWA antenna designed in this work has arm lengths of 3.5 mm. The two dipole arms form an angle of 60° (see Fig. 3(a)) and the diameter of the outer shield is 2.5 mm. The fabricated prototype was used to perform a number of *ex vivo* ablation experiments in pork loin. After each experiment, the tissue was excised and the ablation zone was visually examined. In each case, the antenna provided confined ablation zones. Additionally, the response of the fabricated antenna was found to be independent of the insertion into the tissue. Both of these observations experimentally validate the balanced nature of the fabricated prototypes. Details of the design procedure along with simulation and measurement results of this antenna will be presented and discussed at the symposium.

IV. Discussion

To reduce the invasiveness of microwave ablation as a therapy for cancer and other non-oncological diseases, interstitial antennas with smaller diameters and shorter active lengths may prove to be useful. Regardless of the antenna type, reducing the active length of an interstitial antenna is possible by using higher frequencies to perform microwave ablation. We recently demonstrated that by using higher microwave frequencies (e.g. 10 GHz) to perform MWA, it is possible to achieve ablation zones that have comparable dimensions to those achieved using low-frequency (e.g. 1.9 GHz) microwave ablation [12]. MWA at higher frequencies also happens at a faster pace compared to that at lower frequencies [12]. One drawback of using higher frequencies, however, is the increased losses of the feeding cables (which increase with square root of the frequency) that result in increased cable heating.

Reducing the diameter of MWA antennas is possible by eliminating the coaxial balun that is a common feature of most MWA antennas reported to date. In this paper, we examined two techniques for accomplishing this. The first technique relies on using a coax-fed monopole type antenna at its second resonant frequency where the antenna has a high feed point impedance. This approach allows for achieving compact heating zones that are more spherical compared to those of at least two other coax-fed antennas used in commercial MWA systems. The second balun-elimination technique relies on using a balanced antenna in conjunction with an inherently balanced feeding line. Our initial proof-of-concept experiments in this area have shown the feasibility of using this approach in achieving compact ablation zones. Using such balanced antennas also offers the possibility of generating non-symmetric heating zones by using asymmetrical dipole antennas. This is a degree of flexibility that is not available from coax-fed MWA antennas, which provide axisymmetric ablation zones.

More details of the design of both classes of balun-free MWA antennas as well as measurement results and results of various *ex vivo* ablation experiments conducted for each class of antenna will be presented and discussed at the symposium.

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