Comparison Study of Microwave Patch Antennas At 434 MHz for Intra Cavitary Hyperthermia Applicator Design

Tharrini Rajendran
Department of Engineering Design,
Indian Institute of Technology Madras,
Chennai, Tamilnadu 600036, India.
Email: ed13s018@smail.iitm.ac.in

Dr. Kavitha Arunachalam
Department of Engineering Design,
Indian Institute of Technology Madras,
Chennai, Tamilnadu 600036, India.
Email: akavitha@iitm.ac.in

***Abstract*—Targeted heating with minimal dose to neighboring tissues is possible with intra cavitary microwave applicators as they can treat tumors within/or nearby body cavities. Here we present an intra cavitary applicator for hyperthermia treatment of gynecological cancers at 434 MHz. A 3D numerical model of the applicator with conformal patch antenna in muscle tissue is studied for rectangular patch, variations of bow tie and spiral antennas. Antenna performance is evaluated in terms of size, return loss, bandwidth, specific absorption rate (SAR) and effective field surface (EFS). Fish tailed bow tie and spiral patches exhibited $\leq$-25 dB return loss and $\geq$25 MHz bandwidth compared to other shapes. EFS of spiral antenna is larger than fish tail. However, ratio of EFS to patch area indicates larger volumetric power deposition for fish tailed bow tie. From simulation results, it can be concluded that an array of fish tailed bow tie and/or spiral patch antennas would provide adjustable heating profile with high power deposition.**

***Index Terms*—microwave; hyperthermia; intra cavitary; patch antenna.**

I. INTRODUCTION

Hyperthermia is a thermal therapy that selectively raises the temperature of a localized region in the body affected by cancer cells. Cancer treatment modalities such as chemo and radiation therapies have shown improvement in clinical response when administered with heat than alone [1]. Temperature elevation in tissue is achieved by placing applicators on the skin surface(external) or through natural openings of the body(intra cavitary) or piercing to the deep seated tumors directly (interstitial) [2] [3]. Most of the engineering efforts on hyperthermia devices are on interstitial and external heating applicators. Highly localized and targeted heating of deep seated tumor is possible by intra luminal or intra cavitary applicators as they can be placed in the vicinity of affected area [4]. Hence, there is a huge scope for research and development of microwave intra cavitary applicators for volumetric power deposition with minimal discomfort [5]. Amongst the family of antennas, patch antennas are well suited for microwave tissue heating due to their low profile and ease of construction. The purpose of this study is to design and evaluate patch antennas resonating at 434 MHz industrial scientific and medical (ISM) band and select a suitable design for intra cavitary applicator design. The paper is organized as follows: Numerical model and design guidelines are presented in Section II. Performance of the individual antennas are discussed in Section III and Section IV concludes this study.

II. DESIGN APPROACH

A. 3D model:

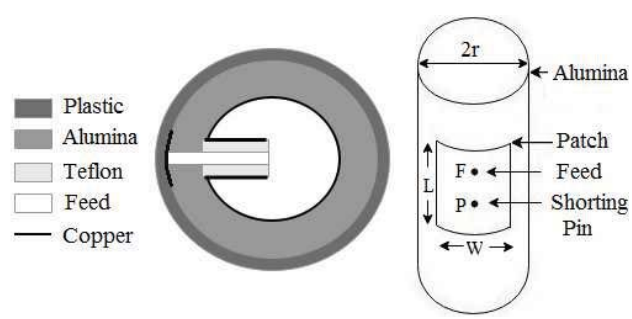

Fig. 1. Top and side views of the proposed intra cavitary applicator.

Figure 1 illustrates the top and side views of the proposed intra cavitary applicator model. The applicator consists of a hollow cylindrical alumina tube with 2 mm thick plastic cover of permittivity, $\epsilon_r = 2.25$, loss tangent,$\tan\delta = 0.001$ on the outer surface and 1 mm thick metal coating on the inner surface. Alumina is chosen as the substrate due to its high dielectric permittivity and low loss tangent. The high dielectric constant, $\epsilon_r = 9$ aids in antenna size reduction which is essential for array design. The antenna dimensions are further minimized with reactive loading using a shorting pin. The outer plastic covering provides mechanical rigidity and electrical safety during treatment. The patch is probe fed using a 50 Ω coaxial connector. The radiating met al patch, inner and outer conductors of coaxial feed and ground plane of the alumina substrate are assigned material property of copper. The applicator is centrally placed in a 11 cm wide block of muscle tissue terminated by perfectly matched layer (PML) boundary condition. A Debye model is employed in the swept frequency simulations to describe muscle dielectric property [6]. 3D numerical simulations were carried out using HFSS 15.0 [7]. HFSS solves the vector wave equation inside the computational domain using finite element method (FEM).

B. Design constraints:

There is an economical and clinical advantage in utilizing existing devices for developing new devices with enhanced performance. Thus, various intra cavitary brachytherapy applicators available in the market for gynecological and colorectal cancers were surveyed in determining the maximum acceptable size for our intra cavitary microwave applicator. Based on this survey, the size of our applicator is constrained to 46 mm diameter and 60 mm height. The surface of the cylindrical applicator was partitioned into three sectors and size of the radiating patch was constrained to only one sector to facilitate array design in future.

C. Proposed antenna shapes:

Figure 2 shows the patch antennas namely (a) rectangular patch, (b) bow tie, (c) truncated bow tie,(d) fish tail,(e) bow tie with parasitic patch, and (f) spiral studied in this work. Initially, a simple rectangular patch of length (L) and width (W) with coaxial feed at the origin (F) and a shorting pin offset from the origin (P) was studied. The patch dimensions were optimized for resonance at 434 MHz. Subsequently, bow tie patch with variations was studied. Due to the shorting pin, only one arm of the probe fed bow tie of Figure 2 (b) radiated effectively. Thus, a truncated bow tie shown in Figure 2 (c) with single arm was studied. To minimize reflections from edges, truncated bow tie was converted to a fish tail as in Figure 2 (d). To study the effects of parasitic capacitance, regular bow tie of Figure 2 (b) was studied using triangular patches located at a distance d_x from the radiating patch as in Figure 2 (e). By Monte Carlo method, a rectangular spiral of 2 turns, length, L and width, W with feed located mid way of the last segment and a shorting pin offset at a distance, P from the end of the last segment was designed.These designs were drawn on the surface of the cylindrical substrate defined at $r = 21$ mm as in Figure 1.

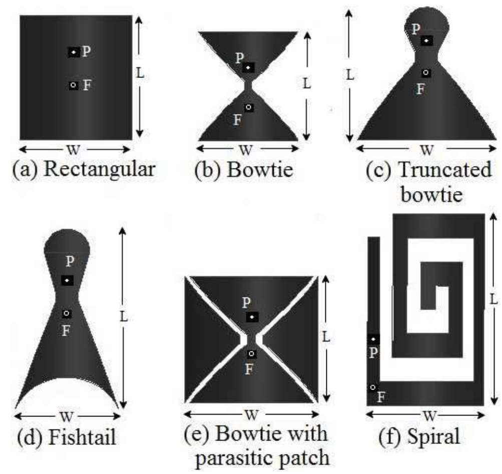

Fig. 2. Patch antennas studied for intra cavitary applicator design.

D. Optimization steps and deduction:

Swept frequency simulations were performed from 350 MHz till 500 MHz for 1 Watt input power. Parametric sweeps were carried out to determine the optimized design parameters for each shape for resonance at 434 MHz. The steps involved in optimization for all the patch is as follows: Initially position of the feed is offset from origin (F) by 5 mm. Then, patch maximal dimension, length (L) is swept followed by width (W) and shorting post distance from the origin (P).

TABLE I
Antenna design parameters.

Shape	L (mm)	W (mm)	F (mm)	P (mm)
Rectangular	26.5	30	5	8.5
Bow Tie	32	35	5	8.5
Truncated Bow Tie	30	31	5	8.5
Fish Tail Bow Tie	41.8	22	5	8.5
Parasitic Bow Tie ($d_x = 2mm$)	28	33	5	8.5
Spiral (N=2)	48	22.6	0	-10.4

III. Simulation results and inference

Antenna simulation results for dispersive tissue model is presented here for continuous wave excitation of the various patch antennas mentioned in Section II C.The final optimized design parameters in the simulations for each patch shape is tabulated in Table I.

A. Parametric sweep:

Patch maximal dimension (L) influenced the resonance significantly unlike other design parameters. Increase in arm length lowered the resonant frequency. An average 25 MHz shift in resonance was observed for 5 mm variation in patch length (L). Patch width affected resonant frequency and magnitude of return loss, S_{11}. Increase in width decreased the resonant frequency. The return loss, S_{11} reduced almost 1 dB for every 5 mm increase in patch width (W). Shift in the location of the shorting post improved bandwidth at resonance and shifted resonance by 7.5 MHz for every 2 mm shift. Presence of parasitic patch did not provide bandwidth improvement at 434 MHz.

B. Power reflection coefficient and bandwidth:

Figure 3 shows applicator power reflection coefficient, $10\ \log_{10}|S_{11}|^2$ over 350 MHz - 500 MHz with a vertical reference line at 434 MHz. It can be inferred from Figure 3 that power coupled to the tissue is relatively more for fish tail and spiral patch antennas.In terms of bandwidth, traditional bow tie and spiral shows superior performance. Due to probe feed and shorting pin, simulated bandwidth of the bow tie and spiral patch antennas is smaller than usual.

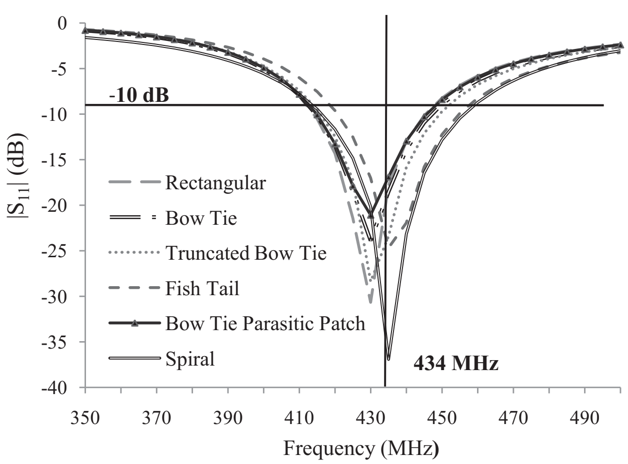

Fig. 3. S_{11} of various patch shapes.

C. Size and polarization:

From the values in Table I, surface area of the patch is calculated. In terms of patch surface area, fish tail patch ranks the least followed by truncated bow tie with single arm, regular bow tie, rectangular patch, spiral and bow tie with parasitic patch. The patch feed and shorting pin were selected such that the radiated electric field, $\overrightarrow{E}$ is oriented parallel to the patch surface. This co-polarized electric field ensures tangential continuity across tissue interfaces and minimizes unwanted hot spots during treatment.

D. SAR distribution and EFS:

EM energy deposited by the radiating patch antenna in the lossy tissue is converted into heat. Power deposited by the incident EM field is quantified using specific absorption rate SAR.

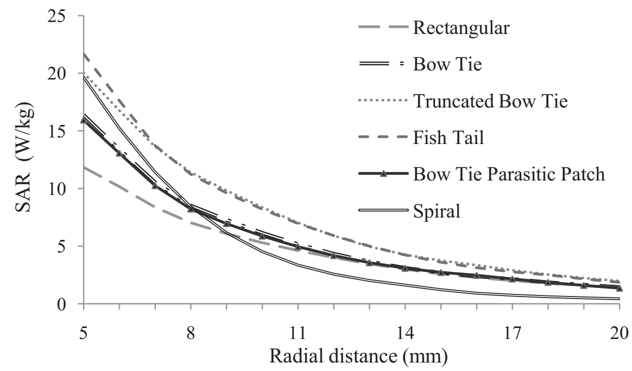

Fig. 4. Variation of SAR at 5 mm along muscle depth.

SAR was calculated in sectoral planes cut at varying radial distance from patch surface to assess volumetric heating of individual patch antennas. The steep change in material conductivity at the interface between the loss less plastic shell of the applicator and the lossy muscle tissue results in sudden unphysical increase in SAR at the interface. Hence, SAR is measured at a distance 5 mm from the applicator surface. Figure 4 shows a comparison of antenna SAR profiles inside muscle tissue starting at 5 mm depth from the surface of the intra cavitary applicator. It can be observed that the penetration depth of the incident EM field for a given excitation power (1 W) inside the tissue varies for the different patch shapes. Fish tail patch antenna has the largest SAR and deepest penetration followed by truncated bow tie.

Figure 5 shows the normalized local SAR in ϕZ plane at 5 mm radial distance from applicator surface. The patch shape is projected on SAR distribution to indicate antenna location. It can be observed that the heating pattern in the reference plane is localized and resembles the radiating part of the patch. SAR distribution of the regular bow tie antenna clearly indicates that only one arm of the antenna is radiating effectively. SAR pattern of the bow tie with parasitic patches is broader than regular bow tie antenna due to parasitic coupling. For the spiral patch antenna with corner feed, peak SAR is observed near the feed. Antennas designed for thermal therapy applications are often characterized in terms of effective field size (EFS) defined as the surface area with SAR value $\geq$50 % of the maximum SAR

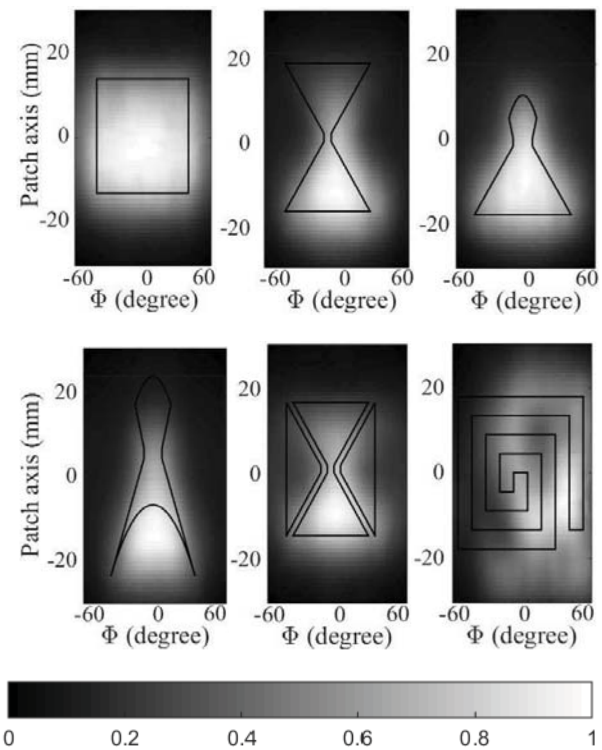

Fig. 5. Normalized SAR distribution in ϕZ plane at r = 28 mm for various patch shapes.

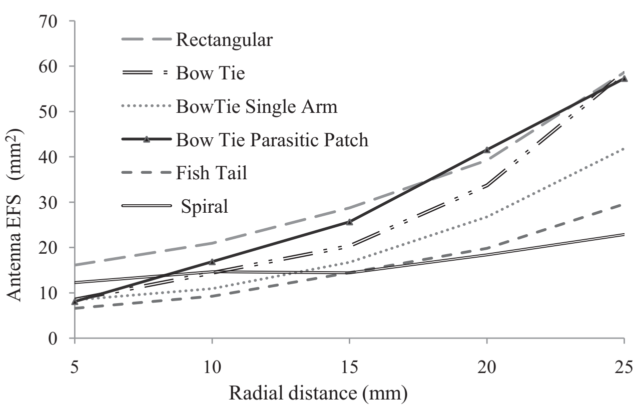

Fig. 6. Antenna EFS along muscle depth.

in a given plane adjacent to the applicator. It can be observed that applicator EFS increases along the depth inside muscle tissue for all patch shapes. This is because the field radiated by a single patch element diverges and decays faster than exponentially in the antenna reactive near field. But absolute heating area by the patch antennas are related to its radiating aperture. Figure 6 shows EFS of all patch shapes calculated in ϕZ plane for varying radial distance from the applicator surface. Amongst the different patch shapes, rectangular and spiral antennas has larger effective field size due to larger surface area ($L \times W$) of the radiating patch. Despite the highest penetration depth, fish tail patch antenna has lowest EFS value due to its compact size. However the ratio of EFS to patch surface area, called as effective field coverage (EFC) value of fish tail patch antenna ($\approxeq 2$) calculated at reference plane (5mm) shows volumetric heating of fish tailed bow tie patch antenna is superior to rectangular and spiral antennas. Patch antenna with larger penetration depth in tissue and smaller size is important for array design to provide full and/or selective coverage in ϕ plane. The detailed simulation study indicate that fish tail antenna and/or spiral antenna could be used for designing an intra cavitary microwave array applicator at 434 MHz for hyperthermia treatment of gynecological cancers.

IV. Conclusion:

A comprehensive 3D simulation study of an intra cavitary microwave heating antenna is presented for hyperthermia treatment of cancer. Antenna dimensions and substrate choice were constrained based on the physical dimensions of commercially available intra cavitary brachytherapy applicators. High permittivity substrate and shorting pin were used for patch size reduction to support applicator array design in future. Basic and modified patch shapes were studied for resonance at 434 MHz ISM band. Antenna performance was quantitatively assessed using patch size, simulated return loss, band width, SAR and EFS at 434 MHz. Amongst the patch shapes, spiral and fish tail patches exhibited superior performance for localized tissue heating at 434 MHz. Based on the simulation study, conformal applicator design consisting of an of array fish tail and/or spiral patch antennas is being investigated.

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