Chapter 2. Analysis of Patch Antennas for Hyperthermia Applications

The utilization of microstrip antennas in hyperthermia treatment has garnered considerable attention in recent years, reflecting a convergence of advancements in both medical and electromagnetic technologies. Microstrip antennas, with their compact size, ease of integration, and tunable characteristics, present a compelling solution for delivering controlled and focused electromagnetic energy to specific tissue regions. This literature review aims to explore the current state of research, innovations, and challenges in the application of microstrip antennas for hyperthermia treatment, shedding light on the pivotal role of these antennas in advancing the efficacy and precision of this evolving medical technique. Through an in-depth analysis of relevant studies and developments, this review seeks to provide a comprehensive understanding of the key considerations, emerging trends, and future directions in the intersection of microstrip antennas and hyperthermia treatment.

2.1.Literature Review

The objective of the present thesis is to design antennas for hyperthermia applications at the MICS and ISM bands. In order to outline the scope of the thesis, the literature on MICS and ISM band antennas will now be reviewed in the following sub-sections.

2.1.1. Review of Antennas for the MICS Band of 434 MHz

In **1985**, Trembly explored the application of a linear, insulated antenna embedded in an electrically dense medium for microwave antennas employed in hyperthermia cancer therapy. The research focuses on antennas driven at frequencies exceeding 600 MHz and investigates their power deposition patterns within the array. The findings highlight a nonuniform distribution of power, contributing valuable insights for the optimization and enhancement of hyperthermia cancer therapy using microwave antennas. This research provides a significant contribution to the understanding of antenna behaviour in the context of cancer treatment applications [40].

In **1987**, Uzunoglu et al. explored the development of a water-loaded, indirectly cooled waveguide antenna designed for local hyperthermia applications, specifically targeting superficial tumors. The antenna features a small aperture size of 2×5.5 cm^2 and operates at a frequency of 432 MHz. The goal is to achieve highly directive power deposition into tissues by directly applying the antenna to the tumor surface. The study emphasizes the potential for selective heating of small-sized tumors (< 2 cm in diameter) using this UHF local hyperthermia applicator [41].

In **2004**, Siauve, Nicolas, et al. discussed an optimization process tailored for local and regional hyperthermia in the context of cancer treatment. The approach focuses on achieving a specific absorption rate in the patient using a combination of a genetic algorithm and finite element formulation. The primary objective is to realize localized hyperthermia in human tumor tissues through electromagnetic energy at radiofrequency (RF) or microwave frequency. The research introduces a formulation that integrates finite element methods with genetic algorithm optimization techniques to attain the targeted increase in heat within the tumor region [42]. Kim and Rahmat-Samii investigate the application of implanted antennas within the human body for biomedical purposes. Through a combination of numerical simulations and experimental setups, the study focuses on the design and performance of spiral-type microstrip and Planar Inverted-F Antennas (PIFAs) operating at 402–405 MHz. The chosen frequency range ensures good matching with surrounding biological tissues. A comparative analysis highlights the advantages of PIFAs, emphasizing their smaller dimensions and higher radiation efficiency compared to microstrip antennas. The study also determines the maximum delivered power for both antennas, ensuring that Specific Absorption Rate (SAR) values comply with American National Standards Institute (ANSI) limitations, thus contributing valuable insights for potential applications in biomedical implantable devices [43].

In **2007**, Paulides, Bakker, et al. explored the feasibility of utilizing a circular array of dipole antennas operating at 433 MHz to centrally deposit RF energy in the neck, particularly relevant for hyperthermia cancer therapy. The research concludes that identifying a universally optimal array setup for all patients is challenging. However, based on the obtained results and practical constraints, a configuration consisting of two rings, each comprising six antennas with a radius of 20 cm and an array spacing of 6 cm, is considered a favourable choice. This setup is deemed capable of effectively heating a majority of patients, offering a practical and viable solution for hyperthermia cancer therapy [44]. And further concludes with a specific interest in exploring the application of the probe-fed patch antenna design in the context of a phased-array head and neck (H&N) hyperthermia applicator. The key findings are 80% of co-polarization in broadside direction, the temperature dependence of resonance frequency allows for flexibility in choosing water-bolus temperatures within the range of 15°C to 35°C, proximity of a patient at a distance as close as 4 cm from the ground plane causes a maximum resonance frequency shift of 1 MHz., cross-coupling with neighbouring antennas, explored in various realistic setups, is predicted to be lower than 27 dB [45]. Drizdal, Togni et al. discuss the design and application of a shorted circular microstrip antenna operating at 434 MHz for local hyperthermia in cancer treatment. The study includes the simulation of the three-dimensional Specific Absorption Rate (SAR) distribution in an agar phantom. The findings indicate that these designed applicators exhibit an effective potential for treating tumors with a diameter of around 4 cm. This research contributes valuable insights to the field of hyperthermia therapy using microstrip antennas [46]. The study conducted by Ito and his team focuses on the coaxial-slot antenna operating at 2.45 GHz, a thin microwave internal antenna employed in hyperthermia applications. Specifically, the paper outlines the utilization of this antenna for interstitial and intracavitary microwave hyperthermia. The parameters investigated include a net input power of 5.0 W and a heating time of 600 s. This research contributes valuable insights into the practical applications of the coaxial-slot antenna for hyperthermia treatment [47].

In **2009**, Kok, de Greef et al. focused on the contact flexible microstrip applicators (CFMA) operating at 434 MHz, specifically in sizes 3H (28.7 × 20.7 cm) and 5H (19.7 × 28.5 cm). The study explores the electromagnetic field behaviour of these applicators in both flat and curved configurations. Additionally, the research delves into the implications of such configurations on critical performance parameters, including penetration depth (PD) and effective heating depth (EHD). This investigation contributes valuable insights into the understanding of CFMA behaviour, which is essential for optimizing their performance in applications such as hyperthermia cancer therapy [48]. Curto, McEvoy, et al. explore the application of a smaller novel patch antenna operating at 434 MHz for hyperthermia cancer therapy. The antenna, positioned close to a phantom tissue model, demonstrates an improved specific absorption rate

(SAR) pattern without significant frequency detuning or impedance mismatch. The study employs simplified planar tri-layered tissue models interfaced with a water bolus to analyze the permittivity loading on the antennas and the resulting SAR. The antenna's slotted features contribute to a 69% area reduction compared to conventional square patch designs, preventing load suppression of the resonant mode. This design achieves a SAR penetration depth of 63 mm, surpassing the performance of other waveguides, horn, and microstrip designs [19]. Kok, de Greef et al. discuss the application of single-element near-field antenna applicators for superficial hyperthermia treatment in the context of anatomical modelling. The focus is on designing a 434 MHz compact patch that resonates stably close to various tissue types and shapes. The study evaluates coupling performance on a full-body model, highlighting three specific areas with successful coupling. The research establishes an inverse relationship between the input power needed to attain a target temperature of 43°C and the peak Specific Absorption Rate (SAR). The analysis, however, is constrained by the static thermal parameters of the model. Notably, when perfusion rates in tissues are doubled, the required input power for clinical treatment scenarios increases at specific positions: from 75 to 81 W for the head, 92 to 99 W for the inter-scapular region, and 78 to 81 W for the epigastrium. This quantification of power levels provides valuable insights into optimizing hyperthermia treatment strategies [48].

In **2012**, Trefn’a, Imtiaz, et al. explored the application of three Ultra-Wideband (UWB) antennas for hyperthermia cancer therapy targeting tumors in the head and neck region. The study assesses the suitability of these antennas as the basis for an applicator used in tumor treatment. The investigation includes three frequencies (434 MHz, 800 MHz, and 1000 MHz) and evaluates Specific Absorption Rate (SAR) distributions in a muscle phantom. Among the antennas considered, the triangular patch antenna exhibits limitations in frequency coverage and necessitates a change in matching liquid within the water bolus for effective treatment. The stacked π-slot patch antenna emerges as a potential solution to address bandwidth requirements. Despite lower efficiency, the Vivaldi antenna is identified as the most suitable design for the specified application [49]. In this paper, the design and application of a circularly shaped spiral microstrip antenna and a conventional patch antenna embedded within a distilled water bolus for hyperthermia applications are discussed by Korkmaz, Nassor, et al. The unique radiation pattern of the spiral antenna is highlighted as a distinctive feature suitable for hyperthermia treatments. The study focuses on the integration of these antennas into a water-based medium, emphasizing their potential in the context of hyperthermia therapy [50]. Isik, Korkmaz, et al. explore the suitability of a circularly shaped spiral microstrip antenna and a conventional patch antenna for applicator design. The study involves simulating a head model using both types of antennas to analyze their respective field distributions. The findings indicate that the novel spiral antenna demonstrates superior adequacy as a hyperthermia applicator compared to the conventional patch antenna [51].

In **2013**, Korkmaz, Isik, et al. presented the design and analysis of a circular microstrip spiral antenna intended for hyperthermia cancer therapy at the 434MHz ISM band. The antenna is compact and features a narrower radiation pattern, making it suitable for integration into a multi-antenna applicator. The proposed design is considered appropriate for semi-deep or deep hyperthermia applications. The ability to operate at multiple frequencies provides flexibility for addressing penetration depth and focusing requirements in cancer treatment. This work contributes to the development of effective and versatile hyperthermia applicators for clinical use [52].

In **2014**, Koo, Kazemi, et al. explored the application of a unique antenna design in the context of hyperthermia cancer therapy. Specifically, a linear, insulated antenna embedded in an electrically dense medium is investigated for use in microwave antennas. The study reveals that antennas operated at frequencies above 600 MHz exhibit nonuniform power deposition within the array. This finding suggests the potential effectiveness of such antennas in the context of hyperthermia cancer therapy, opening avenues for further research and development in this field [36].

In **2015**, He, Geyi et al. discussed the optimal design of focused antenna arrays for microwave-induced hyperthermia in the context of cancer therapy. The study focuses on determining the phases and amplitudes of driving signals for array elements to optimize power transmission efficiency. This optimization is carried out within a system comprising a transmitting antenna array, a receiving antenna in the target area, and a phantom representing human tissues. The proposed technique is applied to design a 4 × 2 focused patch array operating at 433 MHz on a fat-mimicking phantom, showcasing the practical application of the research methodology [53]. Lim, Choi, et al. explore the novel design of hexagonal focused arrays operating at 433 MHz for microwave hyperthermia, aiming to enhance power transmission efficiency. The study optimizes the system by incorporating a transmitting hexagonal array, a receiving antenna within the target area, and an equivalent phantom mimicking the human body. Both simulated and experimental outcomes exhibit strong agreement, demonstrating that the microwave energy can be efficiently confined to the target area without causing undesired heat spots in adjacent regions. This research contributes valuable insights into the effective application of microwave hyperthermia for therapeutic purposes [27].

In **2016**, The research outlined in this paper focuses on identifying an optimal microwave antenna array for hyperthermia cancer treatment. Vrba, Rodrigues, et al. propose a novel 434 MHz applicator design based on a metamaterial zeroth-order mode resonator. This design facilitates the construction of larger array configurations. The applicators demonstrate effective heating at depths of 3-4 cm, utilizing a water bolus temperature of 30°C and accommodating moderate to high levels of blood perfusion. The evaluation of applicator performance includes three metrics: the well-established Effective Field Size (EFS), along newly introduced metrics, namely the Therapeutic Thermal Area (TTA) and Therapeutic Thermal Volume (TTV). These new metrics are demonstrated to be suitable for a more comprehensive characterization of hyperthermia applicators [54].

In **2017**, In this study, a high-frequency (433 MHz ISM band) printed circuit board antenna was designed and validated with a focus on minimizing its magnetic resonance (MR)-footprint by Paulides, Mestrom, et al. The antenna demonstrates a measured impedance bandwidth of 7.2%, deemed sufficient for its intended application. Simulations reveal that the dominant E-field component aligns with the desired direction along the patient axis. Temperature effects on the antenna indicate detuning only occurs at temperatures exceeding 35 °C, rendering it unsuitable for use in the applicator under such conditions. Additionally, the measured mutual coupling level at the worst-case scenario is found to be −23 dB at 433.92 MHz, well below the specified threshold [55]. Younesiraad, Bemani, et al. explore the application of a simple dual-band compact slotted square ring patch antenna for hyperthermia cancer therapy, specifically targeting cancerous human cells at superficial depths within the body. The antenna operates at two frequencies (434 MHz and 915 MHz), providing a dual-band capability. The study investigates the impact of different gaps between the antenna and biological tissues at the specified frequencies. Furthermore, the research delves into the distribution of Specific Absorption Rate (SAR) at a depth of 1 cm inside muscle tissue, utilizing a simulated muscle phantom for liquid return loss and measuring SAR [56].

In **2018**, Muntoni, Fanti, et al. presented a preliminary multi-physics analysis within the context of local hyperthermia for cancer treatment. The study incorporates a simple patch antenna operating at 434 MHz as a heat source, a water bolus, a bi-layered body phantom, and a specific tumor (rhabdomyosarcoma) placed within the phantom. Notably, the research introduces a space-dependent blood perfusion model tailored to the characteristics of rhabdomyosarcoma. The findings suggest that this proposed multi-physic analysis, particularly the utilization of the blood perfusion model, offers an efficient approach to gaining a comprehensive understanding of hyperthermia treatment. This insight contributes to the effective sizing of the system and the planning of therapy in clinical practice [57].

2.1.2. Review of Antennas for the ISM Band of 915 MHz

In **1983**, Sugimachi, INOKUCHI, et al. explored two types of antennas, specifically the Intraluminal Microwave (MW) antenna and the Intraluminal Radio Frequency (RF) electrode, designed for hyperthermia cancer treatment. Through experiments involving both MW and RF, the authors achieved the targeted hyperthermia treatment temperature range. Notably, effective results were obtained even at a distance of 6mm from the mucosal surface. This suggests promising applications of these antennas in hyperthermia cancer therapy [58].

In **1989**, Kobayashi, Nikawa, et al. presented a novel applicator featuring a coupled microstrip antenna designed for hyperthermia applications. The antenna's purpose is to assess temperature changes within the human body by measuring the scattering parameter. The experiments, conducted using a simulated human model with 0.4% NaCl solution, reveal that the transmission coefficient of the electric field demonstrates a change of 0.73 dB/°C in the temperature range of 35°C to 50°C. The applicator utilizes one antenna as a transmitter and another as a receiver, allowing for versatile functionality. Additionally, both antennas can be employed as transmitters, transforming the applicator into a heating device. These findings highlight the potential of the proposed applicator for effective hyperthermia cancer therapy [59].

In **1991**, Ryan focused on interstitial techniques involving catheter insertion into tumors for therapeutic irradiation and hyperthermia applications. Various miniature microwave antenna designs, such as multi-section, hot-tip, 2- and 3-node, dipole, and helical antennas, are extensively utilized in these treatments and are commercially available. The diversity in antenna designs is highlighted, emphasizing their significant impact on power deposition patterns, both as standalone antennas and when employed in arrays [60].

In **1992**, Underwood, Peterson, et al. explored the near-zone radiation characteristics of a rectangular microstrip antenna radiator submerged in water. The investigation involves comparing calculations based on a cavity model theory with actual electric field measurements. To capture the field data, a miniature non-perturbing diode dipole E-field probe with a 3 mm tip is employed, and its positioning is automated using a three-axis scanning system. This study provides insights into the antenna's performance within a water medium, contributing valuable information for potential applications, especially in the context of its near-field radiation behaviour [61]. In this paper, the Finite-Difference Time-Domain (FDTD) method is employed to assess electromagnetic (EM) power deposition patterns within inhomogeneous tissue models representing tumors by Cherry and Iskander. The study focuses on utilizing radiated near-field patterns generated by a collection of uniformly and step-insulated interstitial antennas. These patterns serve as incident fields on excitation planes to derive scattered fields and overall Specific Absorption Rate (SAR) patterns within tumors. This approach contributes to understanding the distribution of EM power in tissue models relevant to the context of cancer therapy [62].

In **1996**, Schaller, Erb, et al. explored the electromagnetic field characteristics of dipole antennas for interstitial microwave hyperthermia in the context of cancer therapy. The investigation employs a finite integration algorithm program to analyze both conventional applicators commonly used in clinical settings and advanced applicators, such as those utilizing triaxial techniques. The numerical method employed in this study serves not only to understand the electromagnetic field of existing applicators but also to enhance and optimize the performance of sophisticated designs, contributing to the advancement of microwave hyperthermia technology in cancer treatment [63].

In **1999**, Sabariego, Landesa, et al. discussed the design of a hyperthermia applicator for heating biological tissues, featuring an array antenna within a perfect electrically conducting reflector. To mitigate heat hazards on superficial tissues, a dielectric protecting layer is introduced. The synthesis methodology integrates the Method of Moments (MoM) with an optimization technique, offering a closed formulation. This approach enhances the efficiency and precision of hyperthermia cancer therapy, addressing both antenna configuration and safety concerns related to tissue exposure. The paper contributes valuable insights to the field, offering a comprehensive and optimized solution for hyperthermia applicator design [64].

In **2000**, T Sabariego, Landesa, et al. presented a synthesis of an array antenna designed for hyperthermia treatment at a frequency of 915 MHz. The chosen antenna configuration involves an array surrounded by a semicircular reflector, which has demonstrated enhanced penetration and focalization in malignant biological tissues. The primary objective of the research is to achieve localized hyperthermia in malignant human tissues through electromagnetic energy at microwave frequencies. The proposed solution involves the synthesis of an antenna array with a semicircular Perfect Electric Conductor (PEC) reflector. To achieve the desired targeted heat, and increase in the tumor region, the paper introduces a closed formulation that combines the Method of Moments (MoM) with optimization techniques. The integration of these methods aims to optimize the antenna design for effective hyperthermia treatment [65].

In **2004**, Maccarini, Rolfsnes, et al. discussed the application of dual concentric conductor antennas (DCCs) in microwave hyperthermia for cancer therapy at a frequency of 915 MHz. The choice of DCCs is motivated by their simple construction using flexible printed circuit board (PCB) material. The study identifies three key properties of DCCs crucial for their effectiveness in this application: the specific absorption rate (SAR) pattern in the target plane, radiation efficiency in converting feedline energy into radiated power, and the ability to accept generator power with minimal reflection (matching). These properties are essential considerations for optimizing the performance of DCCs in the context of hyperthermia cancer therapy [66].

In **2005**, Maccarini, Rolfsnes et al. explored the application of flexible printed circuit board (PCB) arrays containing trans-receiving elements composed of a dual concentric conductor antenna and a spiral antenna. These arrays are designed for hyperthermia cancer therapy, enabling precise and conformal non-invasive control of power deposition and temperature monitoring in large target regions. The use of such arrays offers the potential for effective and uniform treatment, showcasing advancements in the field of microwave antennas for therapeutic purposes [67].

In **2006**, Johnson, Neuman, et al. investigated a novel planar array applicator designed for microwave hyperthermia treatment, focusing on evaluating its uniformity and adjustability in SAR (Specific Absorption Rate) patterns within muscle tissue. The applicator's characteristics are extensively studied through E-field and return-loss measurements in a muscle tissue-equivalent phantom. Additionally, 'treatment-planning' simulations are conducted to compare various array SAR patterns with those obtained from non-coherently driven spiral array antennae. The findings indicate the applicator's favourable attributes, including low return loss across a broad bandwidth and the capability to generate highly uniform heating patterns. Moreover, the applicator demonstrates the ability to spatially adjust SAR contours to accommodate specific shapes, highlighting its potential for customized and effective hyperthermia cancer therapy [68].

In **2010**, Du, Xi et al. focused on introducing a novel four-arm spiral antenna designed for microwave hyperthermia in the context of cancer therapy. The study involves simulation results that demonstrate the ability of the antenna to influence the heating region based on the frequency of input excitation. Notably, at frequencies of 915 MHz and 2.45 GHz, the heating region exhibits a complementary pattern. The research findings indicate that, when operating at these frequencies, the therapeutic area is predominantly concentrated in the centre of the antenna, extending to a distance of 1 cm from the centre. This insight into the antenna's behaviour contributes valuable information to the field of microwave hyperthermia for potential applications in cancer treatment [69].

In **2012**, Yacoob and Hassan presented the utilization of the Finite Difference Time Domain (FDTD) method for the development and simulation of an affordable, non-invasive hyperthermia applicator system designed to heat both deep-seated and superficial brain tumors. The study emphasizes the importance of accurately modelling the head geometry with a realistic 3D head model to correctly predict Specific Absorption Rate (SAR) patterns. The careful design and selection of the antenna, along with the implementation of a partial half-ellipsoidal chamber, were found to be effective in raising temperatures to therapeutic levels in the targeted brain tumor. The study suggests that the results obtained could serve as the foundation for a clinical prototype. Notably, the proposed hyperthermia system simplifies operation, requiring the placement of the brain tumor centre at a pre-specified location (one of the foci) and the excitation of the antenna at a single frequency of 915 MHz [70].

In **2014**, Merunka, Fiser, et al. explored the use of an ultra-wideband (UWB) balanced antipodal Vivaldi antenna for hyperthermia treatment in head and neck cancer. The study focuses on analyzing the shape of the iso-surface, where the specific absorption rate (SAR) decreases to 25% of its maximal value for one antenna. The experiments are conducted on a simple rectangular phantom at a frequency of 915 MHz, considering three different distances between the antenna and the phantom. The findings provide valuable insights into the potential effectiveness of UWB antennas for targeted hyperthermia cancer treatment in the head and neck region [71].

In **2015**, Curto, Ramasamy, et al. explored the application of a coupled electromagnetic-bioheat transfer solver in the context of designing and optimizing a 915 MHz patch antenna for hyperthermia cancer therapy. The study focuses on key optimization objectives such as device miniaturization, operating bandwidth, improved energy deposition patterns in target tissues, and reduced electromagnetic field (E-field) back radiation. The research involves the use of a hemispheric heterogeneous numerical breast phantom to evaluate antenna performance. Two ground-plane configurations, namely conformal and rectangular, are considered in the assessment of antenna functionality. Simulated results demonstrate a stable -10 dB return loss bandwidth of 88 MHz for both ground-plane configurations. The conformal ground-plane exhibits specific advantages, including a 26% power reduction compared to the antenna with a rectangular ground-plane. Additionally, the conformal ground-plane minimizes E-field radiation away from the targeted tissue, potentially mitigating interference with other equipment. Overall, this literature review provides valuable insights into the optimization of microwave antennas for hyperthermia cancer therapy, emphasizing the importance of specific design parameters for achieving enhanced performance [72]. Curto and Prakash discuss a proposed patch antenna featuring a flared ground plane, designed for integration into a wearable applicator for hyperthermia treatment of intact breast targets. The antenna aims to enhance efficiency, improve patient comfort, and potentially contribute to better clinical outcomes in hyperthermia therapy [73].

In **2023**, Lyu, Li et al. explore the design and application of a three-ring phased array featuring ultra-wideband (UWB) microstrip antennas for breast cancer therapy. Operating at frequencies of 0.915 GHz and 2.45 GHz, the proposed antenna exhibits an ultra-wideband spanning from 0.7 GHz to 5.5 GHz, with resonant frequencies at 0.915 GHz and 2.45 GHz. The antenna's dimensions are specified as $15 \times 43.5 \times 1.575$ mm^3. The choice of 12 rings for each array is informed by considerations such as SAR distribution and performance indicators, particularly focusing on tumor off-centre results. Simulation outcomes demonstrate the efficacy of the designed applicator at 0.915 GHz and 2.45 GHz, specifically for tumors of 1 cm^3 and 2 cm^3 at various locations. The findings suggest that the proposed applicator, tailored to treat tumors at the appropriate resonant frequencies, proves effective in analyzing tumor volume. This research contributes valuable insights to the field of breast cancer therapy through innovative antenna design and frequency optimization [74].

2.1.3. Review of Antennas for the ISM Band of 2.4-2.5 GHz

In **1980**, Bahl, Stuchly, et al. discussed the application of a ring-type microstrip antenna as a potential microwave power radiator for biomedical purposes, particularly in the context of hyperthermia applications. The paper provides design formulae and experimental results for a 2.45 GHz ring-type microstrip radiator. The study explores the heating patterns in muscle using a thermographic technique and highlights similarities to the aperture-type contact applicator. Overall, the research suggests the viability of the proposed ring-type microstrip antenna for microwave power radiation in biomedical scenarios, specifically for hyperthermia treatments [75].

In **1987**, Lin and Wang discuss a novel microwave antenna designed to improve heating at the tip for interstitial hyperthermia applications. The antenna, featuring a balun-fed folded dipole design, is analyzed for its temperature distribution patterns in a saline phantom under both transient and steady-state conditions. The focus is on enhancing heating efficiency for interstitial hyperthermia treatments, and experimental results are presented to support the antenna's effectiveness in generating desired temperature distributions [76].

In **1988**, Satoh, Seilhan, et al. discussed the utilization of a 2.45 GHz helical coil microwave antenna for inducing interstitial hyperthermia in the normal dog brain. The experimental setup involved stereo tactically implanting a single antenna along with two or three temperature probes. The study aimed to measure and compare temperature distributions surrounding the antenna with those induced by a dipole antenna [77].

In **2000**, Lin, Hirai, et al. explored the specific-absorption-rate (SAR) distributions generated by arrays of sleeved-slot interstitial antennas in brain-equivalent tissues. The study considers three, six, and seven-element arrays, conducting computer simulations and experimental measurements at 2.45 GHz using a brain-equivalent gel phantom. The findings reveal that the region of elevated SAR corresponds to the width of the antenna arrays and extends 35 mm, encompassing the distal antenna-tip region. The hexagonal array configuration with either six or seven sleeved-slot interstitial antennas is identified as potentially providing elevated SARs in brain tissues [78].

In **2003**, Pisa, Cavagnaro, et al. discussed the application of a graded-mesh finite-difference time-domain (FDTD) code and an alternate-direction-implicit finite difference (ADI-FD) solution of the bioheat equation to analyze arrays of sleeved-slot antennas within a brain-equivalent phantom. The study demonstrates the efficacy of these antennas in selectively heating deep-seated tumors while minimizing damage to superficial tissues. The results indicate that equilateral triangular arrays with specific spacing (10, 15, and 20 mm) can effectively treat deep-seated tumors ranging from 10 to 40 mm in diameter. The study considers input powers in the range of 2 to 32 W for the treatment process [79].

In **2004**, Saito, Yoshimura, et al. focused on the study of coaxial-slot antennas for minimally invasive microwave thermal therapies, particularly interstitial microwave hyperthermia. The authors conducted two clinical trials to assess the heating characteristics of a coaxial-slot antenna with two slots. The investigation involved studying the dependency on insertion depth and revealed that the antenna generates a localized heating region under various depths. The paper also provides details on two clinical trials where the authors successfully applied the antennas to effectively heat targeted tumors in patients with shallow tumors [80]. Ito, Saito, et al. discuss the application of interstitial microwave hyperthermia for cancer treatment using a specialized array applicator. The applicator is comprised of four coaxial-slot antennas, and the study likely presents design considerations, experimental results, and insights into the effectiveness of this approach for cancer therapy [81]. Sherar, Trachtenberg, et al. discuss the potential use of a ring-type microstrip antenna as a microwave power radiator for biomedical applications, specifically focusing on hyperthermia applications.

It presents design formulae and experimental results for a 2.45 GHz ring-type microstrip radiator. The study explores the heating patterns in muscle using a thermographic technique, noting similarities to aperture-type contact applicators. The findings suggest the potential applicability of this antenna design in biomedical scenarios, particularly for hyperthermia treatment. Additionally, the paper highlights the effectiveness of interstitial microwave thermal therapy as an alternative to surgery for treating solid tumors. The use of arrays of helical antenna is emphasized, which can generate complex heating patterns. The combination of these patterns with the active cooling of normal tissue structures is proposed as a means to achieve conformal heating for the thermal coagulation of tumors. This indicates a promising approach for the non-invasive treatment of certain solid tumors using microwave thermal therapy [82].

In **2005**, Brace, Laeseke, et al. discussed the application of a novel triaxial antenna for microwave ablation procedures on an ex vivo bovine liver. The antenna comprises a coaxial monopole inserted through a biopsy needle, positioned strategically for optimal performance. Compared to a traditional coaxial design, the triaxial configuration enhances return losses by up to 11.2 dB, demonstrating improved efficiency in the context of microwave ablation [83].

In **2006**, Saito, Kikuchi, et al. discussed the development of a coaxial-slot antenna designed for microwave hyperthermia at a frequency of 2.45 GHz. The focus is on exploring the applications of this antenna for both interstitial and intracavitary microwave hyperthermia. The coaxial-slot antenna is intended for biomedical purposes, specifically in the context of raising tissue temperature using microwave radiation. The paper presents design details, experimental results, and insights into the potential applications of the proposed antenna in the field of hyperthermia [84]. Yong-Xing, Xiao-Li et al. investigate an Archimedes planar spiral hyperthermia antenna operating at

2.45 GHz. The study reveals that expanding the separation between adjacent spiral circles or increasing the number of spiral circles decreases the minimum frequency (f_{min}). Additionally, enlarging the diameter of the spiral wire reduces the specific absorption rate (SAR) parameter without altering f_{min}. Consequently, the antenna achieves a radiation depth of 12-13 mm when SAR is set to 100 W/kg, demonstrating its stable performance under these conditions [85].

In **2007**, Ito, Saito, et al. explored antennas for hyperthermia, a thermal cancer therapy. The authors focus on a coaxial-slot antenna designed for both interstitial and intracavitary microwave hyperthermia, presenting two variations tailored for treating brain tumors and bile duct carcinoma. The study highlights the significance of these antennas in the context of cancer treatment through hyperthermia [86]. Park, Seo, et al. discuss the use of a ring-type microstrip antenna for microwave power radiation in biomedical applications, particularly for potential hyperthermia therapy. The design formulae and experimental results of a 2.45 GHz ring-type microstrip radiator are presented. The study explores heating patterns in muscle using a thermographic technique, noting similarities to an aperture-type contact applicator. Additionally, the paper highlights the application of impedance-matching techniques to optimize resonance characteristics in a coaxial slot configuration within a phantom at 2.45 GHz. The specific focus is on calculating the Specific Absorption Rate (SAR) distribution in the liver using a temperature-controlled ring slot antenna, showcasing its localized heating performance in the phantom for hyperthermia therapy [87].

In **2009**, Xia, Saito, et al. introduced a cavity slot antenna with an H-shaped slot for use as an implanted antenna, with a target gain of over 26.5 dBi based on the link budget. Numerical simulations demonstrate resonance at 2.45 GHz with a peak gain of 22.3 dBi. The study also evaluates Specific Absorption Rate (SAR) values around the antenna, finding a maximum 1-gram average SAR of 1.65×10^{-2} W/kg [88]. Du, Qin, et al. discuss the application of the finite element method to simulate the electromagnetic field distributions and specific absorption rate (SAR) of a microstrip spiral antenna operating at 2.45 GHz in phantom muscle tissues. The analysis includes studying the S_{11} parameter for antennas with varying structural parameters. The findings indicate that increasing the spacing between adjacent spiral circles or the number of spiral circles in the antenna design can lead to a decrease in the minimum frequency (f_{min}) [89].

In **2010**, Dobšíček Trefn'a, Vrba, et al. discussed the design and experimentation of a ring-type microstrip antenna for potential use as a microwave power radiator in biomedical applications, particularly in hyperthermia treatments. The focus is on a 2.45 GHz ring-type microstrip radiator, and the paper presents both design formulas and experimental results. The obtained heating patterns in muscle analyzed through thermographic techniques show similarities to aperture-type contact applicators. The potential application of this antenna in hyperthermia treatments is highlighted [90].

In **2012**, IP Soares, MM Ferreira, et al. discussed the use of a ring-type microstrip antenna as a potential microwave power radiator for biomedical applications, specifically in the context of hyperthermia treatment. The design formulae and experimental results of a 2.45 GHz ring-type microstrip radiator for potential hyperthermia applications are presented. The study utilizes a thermographic technique to analyze heating patterns in muscle, revealing similarities to aperture-type contact applicators. The focus is on exploring the antenna's effectiveness in biomedical applications, particularly in hyperthermia treatment [91].

In **2014**, Tofigh, Nourinia, et al. discussed a ring-type microstrip antenna designed for potential microwave power radiation in biomedical applications, specifically focusing on hyperthermia applications at 2.45 GHz. The paper presents design formulas and experimental results for the antenna, highlighting its suitability for generating heating patterns in muscle similar to aperture-type contact applicators. The focus is on exploring the antenna's potential use in biomedical scenarios, particularly for hyperthermia treatment [92]. Ito and Saito introduce microwave techniques for medical treatment, specifically focusing on the thermal effects of electromagnetic waves. Two applications are discussed: hyperthermia for cancer treatment and surgical devices utilizing high-power microwave energy. The paper provides an overview of these microwave-based treatments and their potential applications in the medical field [93].

In **2016**, Singh, Sahu, et al. discussed a novel microstrip antenna design for potential use in biomedical applications, specifically in hyperthermia treatment. The proposed design involves a ring-type microstrip antenna operating at 2.45 GHz, intended for microwave power radiation. The study presents both the design formulas and experimental results for this antenna, highlighting its potential for hyperthermia applications. The heating patterns observed in muscle, as determined by thermographic techniques, are found to be similar to those produced by aperture-type contact applicators. Additionally, the paper introduces an applicator with an artificial magnetic conductor (AMC) composed of modified ring patches on a grounded dielectric substrate. This applicator, positioned at an optimized distance from the microstrip slot antenna, aims to enhance overall performance. The modified slot and feed arrangement in the applicator contribute to improved heating depth in a phantom muscle medium. The proposed microstrip slot antenna with AMC as a reflector is noted for offering various desirable features for hyperthermia applications, including enhanced power deposition, insensitivity to variations in the dielectric properties of muscle medium, good impedance match for different bio-models, and a conformal design [94].

In **2018**, Kumar, Raj, et al. focused on the design of a patch antenna for implantable biomedical applications operating at 2.45 GHz within the ISM band. The study aims to optimize antenna parameters, such as return loss, impedance matching, and gain. The use of Teflon as the substrate material is highlighted for its favorable dielectric constant, resulting in improved performance and miniaturization of the antenna. The achieved results suggest that the proposed antenna design holds promise for applications in the biomedical field [95].

In **2019**, Elsaadi, Aid, et al. discussed the potential application of a slotted circular patch antenna operating at 2.45 GHz for hyperthermia treatment of breast tumors. The investigation involves the fabrication and measurement of the antenna to validate simulated results. The ultimate objective is to achieve an efficient and high-gain slotted circular antenna array for improved breast tumor hyperthermia treatment [96]. Ghasemlouy and Rajebi discuss the design of a 2.24 GHz frequency antenna for biomedical applications, specifically focusing on mitigating skin burns caused by water bolus usage. The antenna utilizes silicone tissue instead of water bolus to minimize skin burn percentages. The key improvement is the efficient transfer of heat to the upper layers of skin and fat, with evaluations conducted for different configurations: water bolus, water bolus with silicone, silicone with water bolus, and silicone alone. The results indicate that only when silicone is used, the energy successfully penetrates the muscular tissue without causing damage to other body tissues, highlighting the potential for enhanced safety and effectiveness in hyperthermia applications [97].

In **2022**, Eltigani, Ahmed discusses the design, modeling, and simulation of a microwave sleeve antenna intended for hepatic (liver) hyperthermia in biomedical applications. The antenna operates at 2.45 GHz with 0.5 W input power. The study involves testing the antenna in six different 3D liver models, resulting in elevated tumor temperatures (43-45 °C) while maintaining surrounding tissue temperatures below 41 °C. Specific Absorption Rate (SAR) values ranged between 29 and 30 W/kg in tumors and below 24 W/kg in surrounding tissues. The return loss of the antenna varied from −45 to −25 dB for the different models, demonstrating the antenna's ability to heat hepatic tumors of varying sizes and locations [98]. Sharma, Kaur, et al. discuss a lens applicator for microwave medical applications, comprising a double spiral antenna (DSA) and a frequency selective surface (FSS) as a superstrate. The antenna structure is designed with a double spiral on the upper substrate, a slotted ground plane between the upper and lower substrates, and a microstrip feed line on the bottom of the lower substrate. The overall size is 32 × 32 × 3.27 mm^3. Additionally, a 64 × 64 mm^2 FSS structure acts as a lens, converting the bidirectional field pattern of the DSA into a unidirectional pattern, enhancing focusing on the phantom. Thermal simulations indicate that the proposed applicator, resonating at 2.45 GHz with 2.5 W input power, achieves effective temperature distribution for treating superficial and deep tumors [99].

2.2. Description of Measurement Setup

2.2.1. Dielectric Properties and Measurement Setup

The electrical characteristics of the human body are explained through permittivity and conductivity. The attributes of biological tissue are predominantly influenced by the water content within the tissue. Biological tissue can be categorized into those with low water content and those with high water content [100]. Tissues with low water content exhibit lower permittivity and conductivity, resulting in decreased attenuation when exposed to an electromagnetic wave [101]. Dielectric loading alters the resonant frequency of the antenna by enhancing the capacitance of the dielectric material. This change in capacitance, a result of dielectric loading, contributes to a shift in the antenna's resonant frequency, showcasing the significant impact of dielectric properties on antenna performance and tuning [102]. Low water content tissues include fat or breast tissue, bone, and inflated lungs. On the other hand, high-water-content tissues encompass skin and muscle. When an electromagnetic wave propagates between different mediums, it can undergo reflection, transmission, or absorption. These outcomes are contingent upon factors such as tissue conductivity, permittivity, and the frequency of the source. Reflection at the interface of tissue layers can lead to the formation of standing waves and increased energy absorption in specific layers, influenced by their permittivity and conductivity. The absorbed energy is subsequently converted into heat. Tissues with a higher water content exhibit greater energy absorption compared to tissues with lower water content. The open-ended dielectric measurement approach and the measured dielectric properties graph, illustrated in Fig.2.1 and Fig.2.2 respectively, Fig.2.1 involves connecting one end of the open-ended cable to the R&S(ZNB8) vector network analyzer (VNA) and emerging the other end into the TEL phantom. Data related to this measurement is collected by a computer connected to the VNA.

Table 2.1 presents the permittivity and conductivity of some of the body tissues at 434 MHz, 2.45 GHz, and 2.48 GHz **[103-105]**.

Table 2.1 Dielectric Properties of the Tissue Equivalent Liquid (TEL)

Tissue Type	434 MHz		2.45 GHz		2.48 GHz	
	ε_r	σ (S/m)	ε_r	σ (S/m)	ε_r	σ (S/m)
TEL	64.28	0.253	60.36	1.8343	60	1.8347

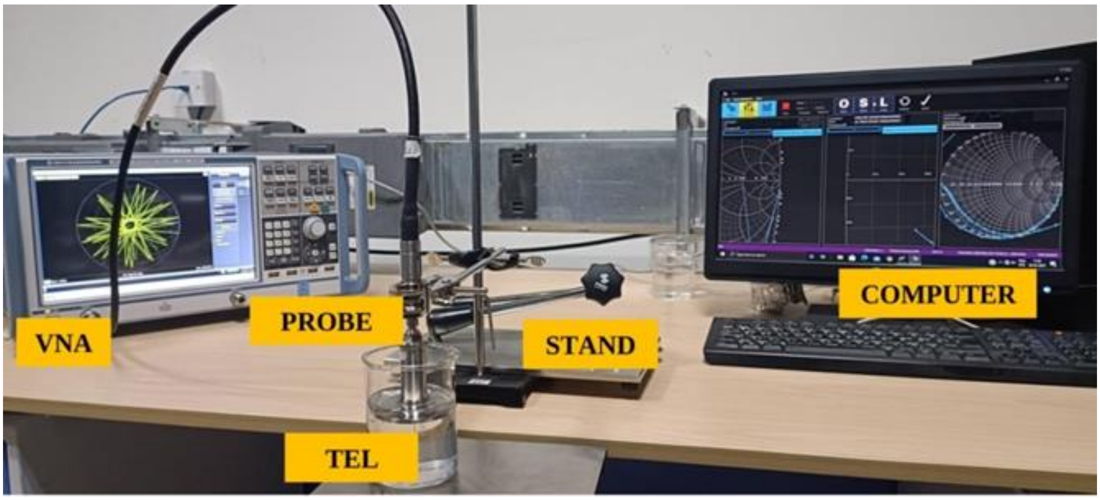

Figure 2.1 Dielectric measurement setup.

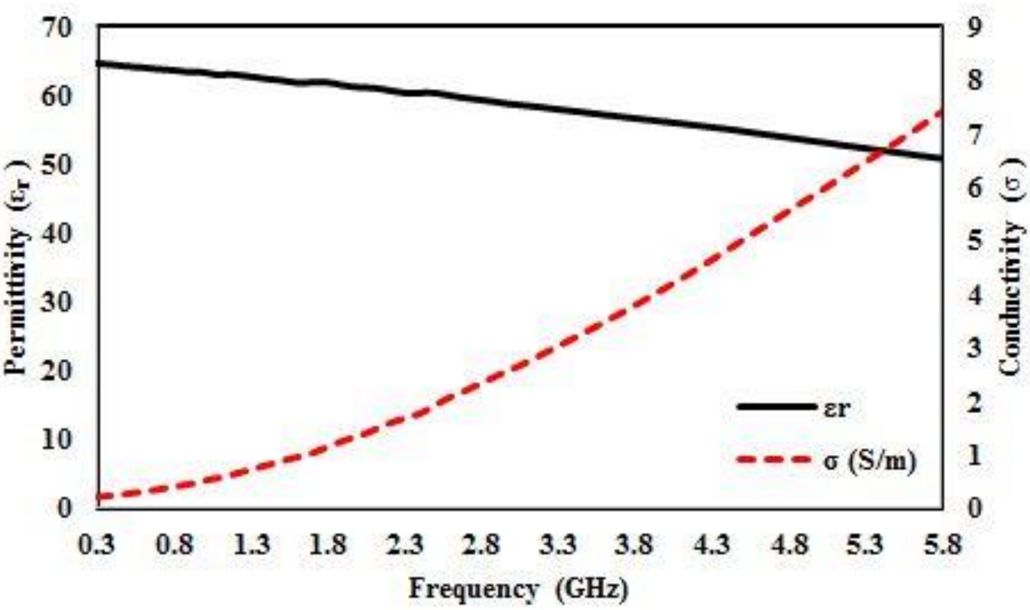

Figure 2.2 Permittivity and conductivity plots for TEL phantom.

2.2.2. SAR Measurement Setup

Figure 2.3 illustrates the block diagram employed for Electric Field measurement in SAR calculation. In this configuration, the Power level of the SMR-40 (R&S SMR SMB 100A 10 MHz-40GHz) is set to 0 dBm (1 mW). The operating frequency is specified and adjusted accordingly on both the SMR-40 and the spectrum analyzer. Subsequently, the Electric Probe [106] is connected to the spectrum analyzer. The Probe is then inserted into the Phantom tissue at various positions along the y-axis penetration depth and x-axis penetration depth. The calculation of SAR is determined by equation number (1.1), involving the Electric field, conductivity, and density of the tissue.

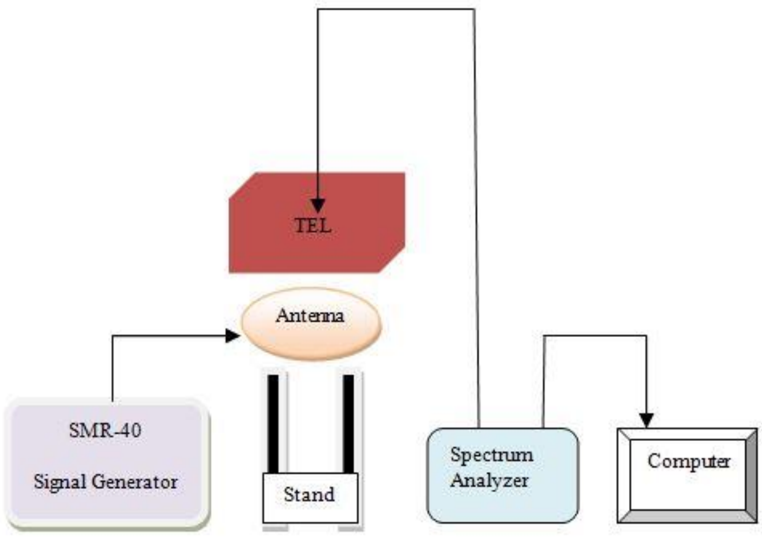

Figure 2.3 Measurement setup of E-field for SAR calculation

This chapter conducts a thorough review of current literature on Medical Implant Communication Service (MICS) and ISM band patch antennas. It covers pivotal studies, methodologies, and advancements in these areas. The subsequent chapter will concentrate on designing an antenna tailored for hyperthermia applications in the MICS band. **Chapter 3** will meticulously examine the conceptualization and development of this antenna, aiming to enhance hyperthermia treatments.