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Entitled

DESIGN OF A MICROSTRIP TRANSMISSION LINE RESONATOR FOR MAGNETIC RESONANCE IMAGING SYSTEM

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Abstract

Magnetic Resonance Imaging (MRI) is a medical imaging technique that uses powerful magnetic fields and radio waves to obtain detailed images of the inside of the human body. It allows visualization of tissues, organs, and anatomical structures using the magnetic properties of atoms present in the body. MRI is non-invasive, safe, and widely used in various medical fields for diagnosing and monitoring medical conditions.

This thesis presents a study on the design of microstrip antennas for Magnetic Resonance Imaging (MRI) applications. The main objective of this end-of-study project is to propose microstrip antenna structures as an alternative to conventional resonators, such as birdcage resonators, used in MRI systems. These new structures function as resonators capable of generating magnetic fields acting as uniform B1 fields within an MRI system.

As part of this study, a Yagi microstrip antenna design is proposed and analyzed for its suitability in MRI environments. The designed microstrip antennas are modeled and simulated using the HFSS (High-Frequency Structure Simulator) software . The simulations allow the evaluation of the performances of the microstrip antennas, such as the Larmor resonance frequency suitable for the considered MRI system, radiation patterns and the magnetic field distribution around the antenna.

Keywords: MRI systems, Microstrip antennas, Larmor resonant frequency, HFSS soft ware

ملخص

التصوير بالرنين المغناطيسي هو تقنية تصوير طبية تستخدم مجالات مغناطيسية قوية وموجات راديو للحصول على صور مفصلة لداخل جسم الإنسان. يجعل من الممكن تصور الأنسجة والأعضاء والتركيبات التشريحية باستخدام الخصائص المغناطيسية للذرات الموجودة في الجسم. التصوير بالرنين المغناطيسي غير جراحي وآمن ويستخدم على نطاق واسع في مختلف المجالات الطبية لتشخيص ومراقبة الحالات الطبية .

تقدم هذه الرسالة دراسة حول تصميم هوائيات الشريط الصغير المصممة لتطبيقات التصوير بالرنين المغناطيسي. الهدف الرئيسي لمشروع نهاية الدراسة هذا هو اقتراح هياكل هوائيات الشريط الصغير كبديل للرنانات التقليدية، المستخدم في أنظمة التصوير بالرنين المغناطيسي. تعمل هذه الهياكل الجديدة كرنانات قادرة على توليد مجالات مغناطيسية تعمل كحقول ب 1 موحدة في نظام التصوير بالرنين المغناطيسي .

كجزء من هذه الدراسة، تم اقتراح وتصميم هوائي ميكرو شريطي من نوع ياغي وتحليله من حيث ملاءمته لبيئات التصوير بالرنين المغناطيسي, تم نمذجة الهوائيات الميكروشريطية المصممة ومحاكاتها باستخدام برنامج HFSS (محاكي الترددات العالية). تتيح هذه المحاكاة تقييم أداء الهوائيات، مثل تردد رنين لامور المناسب لنظام التصوير بالرنين المغناطيسي المدروس، وأنماط الإشعاع، وتوزيع المجال المغناطيسي حول الهوائي.

الكلمات المفتاحية: نظام التصوير بالرنين المغناطيسي، هوائيات الشريط الصغير، تردد لارمور الرنيني,HFSS Soft ware

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Résumé

L’Imagerie par Résonance Magnétique IRM, est une technique d'imagerie médicale qui utilise des champs magnétiques puissants et des ondes radio pour obtenir des images détaillées de l'intérieur du corps humain. Elle permet de visualiser les tissus, les organes et les structures anatomiques en utilisant les propriétés magnétiques des atomes présents dans le corps. L'IRM est non invasive, sûre et largement utilisée dans divers domaines médicaux pour diagnostiquer et surveiller les conditions médicales.

Ce mémoire présente une étude sur la conception d'antennes microrubans destinées aux applications d'Imagerie par Résonance Magnétique (IRM). L'objectif principal de ce projet de fin d'étude est de proposer des structures d'antennes microrubans comme une alternative aux résonateurs conventionnels, tels que la cage d'oiseau. Ces nouvelles structures fonctionnent comme des résonateurs capables de générer des champs magnétiques agissant comme des champs B1 uniformes dans un système IRM.

Dans le cadre de cette étude, une antenne micro-ruban de type Yagi est proposée et analysée pour son adéquation aux environnements d’IRM. Les antennes micro-ruban conçues sont modélisées et simulées à l’aide du logiciel HFSS (High-Frequency Structure Simulator). Les simulations permettent d'évaluer les performances des antennes microrubans, notamment la fréquence de résonance appelée fréquence de Larmor, adaptée au système IRM considéré, les diagrammes de rayonnement et la répartition du champ magnétique autour de l’antenne.

Mots clés: Systèmes d’imagerie IRM, Antennes Microrubans, fréquence de Larmor, HFSS Software

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List of Abbreviations

MRI	**Magnetic Resonance Imaging**
CT	**Computed Tomography**
PET	**Positron Emission Tomography**
3D	**3 Dimension**
RF	**Radio frequency**
SNR	**Signal to noise ratio**
EM	**Electromagnetic**
MHZ	**Megahertz**
GHz	**Gigahertz**
HFSS	**High-Frequency Structure Simulator**
T	**Tesla**
SAR	**Signal to noise ratio**
UHF	**Ultra High Field**
MTL	**Microstrip Transmission line**
PCB	**Printed Circuit Board**
iMTL	**inverted microstrip transmission line**

List of Symbols

d	**Substrate thickness**
εr	**Relative permittivity**
W	**Width of the conductor strip**
H	**Magnetic field distribution**
E	**Electric field distribution**
B_0	**Static magnetic field**
B_1	**radiofrequency electromagnetic field**

General Introduction

General Introduction

Magnetic Resonance Imaging (MRI) is a non-invasive medical imaging technique widely used for producing high-resolution images of the internal structures of the human body. Unlike traditional imaging modalities such as X-rays or CT scans, MRI operates without ionizing radiation, relying instead on strong magnetic fields and radiofrequency (RF) signals to excite and detect the response of hydrogen nuclei within tissues. The quality and resolution of MRI images significantly depend on the efficiency and performance of the RF components, particularly the resonators, which are responsible for transmitting and receiving the RF signals. One critical element in the RF chain of an MRI system is the transmission line resonator. Traditional resonators, while effective, often face limitations in terms of size, efficiency, and frequency selectivity—particularly at higher field strengths where miniaturization and performance become increasingly important. To address these challenges, microstrip transmission line resonators have emerged as a promising alternative due to their compact size, ease of fabrication, and compatibility with high-frequency applications.

Microstrip resonators, which are a type of planar transmission line structure, are particularly well-suited for integration in modern MRI systems. They offer significant advantages in terms of tunability, geometric flexibility, and electromagnetic field distribution control. Their planar nature allows for enhanced compatibility with multi-channel and phased-array coil systems, which are increasingly used in advanced MRI techniques.

The principal goal of our work focuses on designing special transmission lines called Microstrip Transmission Lines (MTLs) that are used in MRI (Magnetic Resonance Imaging) systems.

This master thesis consists of four chapters organized as follows:

- **Chapter 1** presents an introduction about the MRI system and its main components.
- **Chapter 2** concerns the microstrip line theory with highlight on the design equations.
- **Chapter 3.** Throughout this chapter, we will proceed with the design and simulation of microstrip transmission line antennas structures dedicated for 7Tesla MRI systems based on previously published work.
- **Chapter 4.** A general conclusion, in which the main obtained results are highlighted together with foresight for future study.

This thesis focuses on the design, simulation, and analysis of a microstrip transmission line resonator specifically tailored for use in MRI systems. The objective is to optimize the resonator design to achieve efficient RF performance and compact form factor suitable for integration in MRI coils. The work aims to contribute to the ongoing development of advanced MRI technology by improving the fundamental components involved in RF signal transmission and reception.

Chapter 1

Magnetic Resonance Imaging System

1.1 Introduction

Magnetic resonance imaging (MRI) is a medical imaging technique used In radiology to generate pictures of the anatomy and the physiological processes inside the body [1].

MRI scanners use strong magnetic fields, magnetic field gradients, and radio waves to form images of the organs in the body. [2].

MRI does not involve X-rays or the use of ionizing radiation, which distinguishes it From computed tomography (CT) and positron emission tomography (PET) scans [3]. It is powerful and safe way diagnose health problems without surgery or harmful radiation [3].

1.2 Principles of the MRI System

Magnetic Resonance Imaging (MRI) is a powerful medical diagnostic technique that provides high-precision anatomical 3D or cross-sectional images (axial, sagittal, and coronal) [4].

Magnetic resonance imaging is a noninvasive medical imaging test that produces detailed images of almost every internal structure in the human body, including the organs, bones, muscles and blood vessels.

MRI is based on fundamental principles of nuclear magnetism and magnetic resonance, combined with the use of rotating radiofrequency (RF) fields to disturb the equilibrium state of atomic nuclei in the body.

The patient is placed inside a small tunnel with a magnetic field, as shown in **Figure 1.1.** The emission of a radio wave causes the hydrogen nuclei in the patient's body to enter a special state called resonance. When these hydrogen nuclei return to their equilibrium state, a signal is generated and picked up by a receiving antenna. Finally, the analysis of this signal by a computer makes it possible to obtain images of the different parts of the human body [4] [5]

Figure 1.1 : Magnetic Resonance Imaging (MRI)

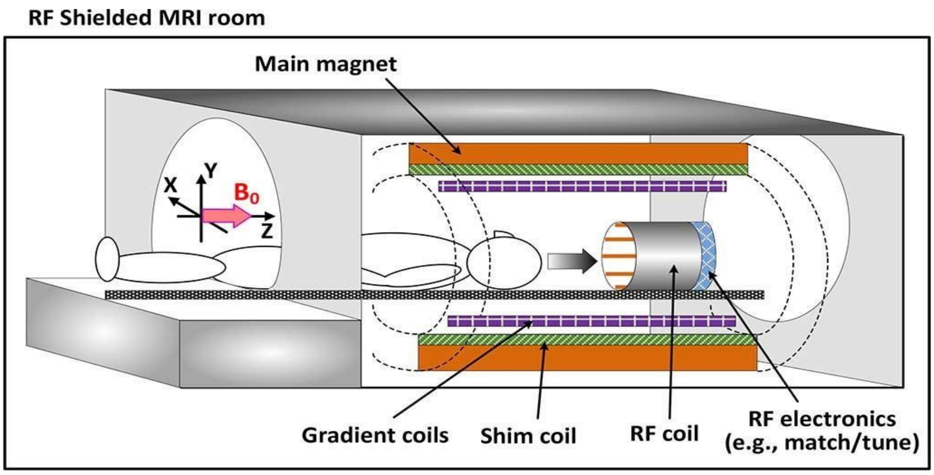

Figure 1.2: Structure illustration of a general MRI scanner.

1.3 Advantages and Disadvantages of MRI System

The main advantages of magnetic resonance imaging scans are [6]:

- High spatial resolution.
- Non-ionizing system (no radiation exposure).
- Provides detailed information about body anatomy.
- MRI is useful for diagnosing diseases and injuries in many medical fields, such as neurology, oncology, cardiology, and radiology [7].

However, this technology also has some disadvantages [8] [3], such as:

- High cost.
- Can be uncomfortable for the patient.

- Slow examination process (more than 25 minutes).
- The loud noises that are made by the magnets during the scan
- Limited effectiveness in examining the skeletal system.
- The patient may feel afraid of being in a small space (claustrophobia).
- Patients must stay still during the scan, which can be hard for some people, especially those with movement disorders.
- A contrast agent may need to be injected for certain types of tests.

1.4 Components of MRI System

The MRI system consists of four major components as follows:

1. **Magnetic Field**: Generated by a powerful magnet, made of superconducting materials, which creates a large, stable magnetic field that aligns the hydrogen atoms in the body in a specific direction.
2. **Radio Waves**: A radiofrequency pulse is then sent into the body, temporarily disrupting the alignment of these hydrogen atoms. When the radio wave pulse is turned off, the hydrogen atoms return to their original alignment, releasing energy in the process.
3. **Signal Detection**: This released energy is detected by sensors in the MRI machine, which then use it to create a detailed image of the body part being scanned.
4. **Image Creation**: The data from these signals is processed by a computer to construct highly detailed cross-sectional images of the body. Radiologists can then use these images to diagnose and monitor various medical conditions.

1.5 How does MRI System work ?

Magnetic Resonance Imaging (MRI) works by using a strong magnetic field and radio waves to create detailed images of the inside of the body. It is based on the physical phenomenon of nuclear magnetic resonance (NMR) [11]. The strong magnetic field created by the MRI scanner causes the atoms in your body to align in the same direction. A radiofrequency pulse is then applied to disturb this alignment. As the atoms return to their original state, they emit signals that are detected by the scanner. These signals are received by a computer and converted into an image of the part of the body being examined. This image appears on a viewing monitor [11]. Figure 1.2 illustrates the sequence of processes in the Magnetic Resonance Imaging (MRI) system.

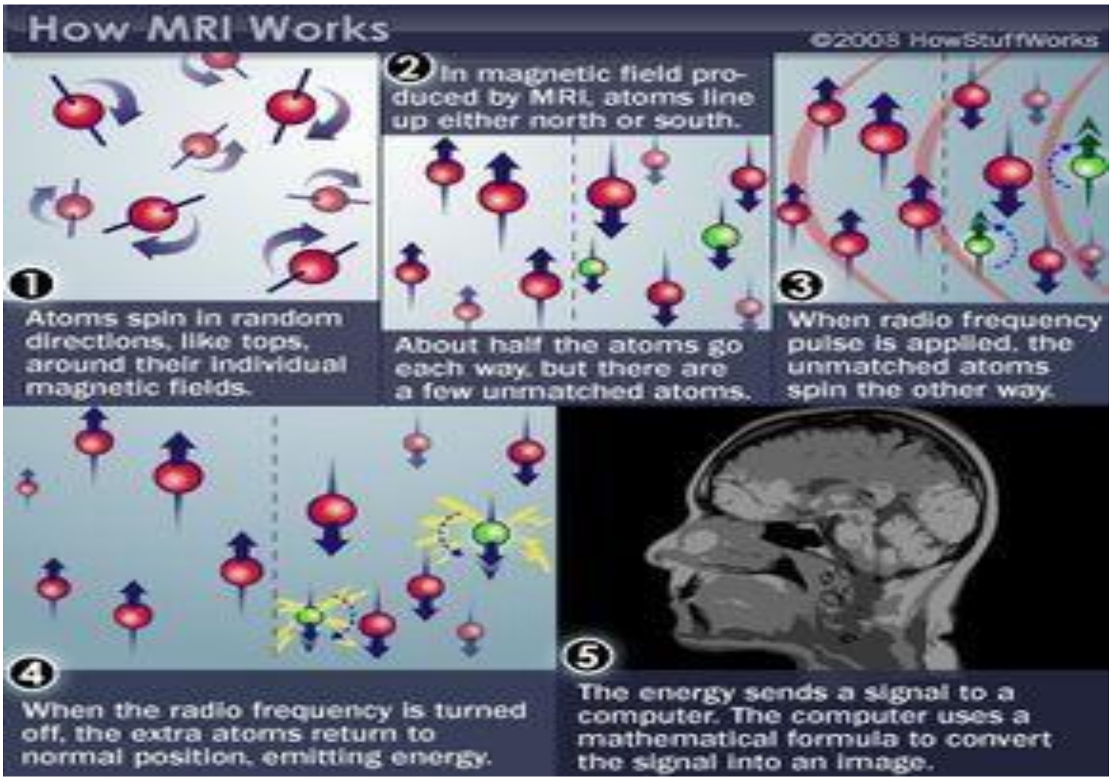

Figure 1.3: MRI Imaging Process

1.6 Phenomenon of Magnetic Resonance

The phenomenon of magnetic resonance is a physical process that occurs when an atomic nucleus with a magnetic moment is placed in an external magnetic field. In this situation, the atomic nucleus can absorb energy from the magnetic field and move to a higher energy state. When the nucleus returns to its original state, it emits energy in the form of a radiofrequency signal, which can be detected and used to produce a detailed image of the internal structure of a material, such as the human body [13].

Nuclear Magnetic Resonance (NMR) is a technique that allows the study of changes in the magnetic orientation of nuclei in a substance when exposed to two magnetic fields [13]:

B_0→: Static magnet field, fixed and strong.

B_1 →: Rotating electromagnetic field (electromagnetic wave or radiofrequency — RF)

1.7 MRI Field Strength – Measured in Teslas:

The strength of an MRI magnet is measured in Teslas (T), which determines the quality of the images produced. Higher Tesla values mean stronger magnets and clearer images. The most common MRI machines operate at 1.5T and 3T, each suitable for different diagnostic purposes.

While some scanners have lower strengths like 0.2T, 0.3T, or 0.4T, and others can go as high as 7T, the quality of the images also depends on the machine's software and age [12].

1.7.1 Low-field MRI Machines:

Low-field MRI scanners (0.2T–0.4T) are more affordable and cost-effective than high-field systems. They are often open-bore designs, making them ideal for claustrophobic patients. While 0.2T scanners are mostly used for extremities, 0.3T and 0.4T models can also support full-body imaging [12].

1.7.2 High-field MRI Machines:

High-field MRI machines (1.0T, 1.2T, 1.5T, 3T, and 7T+) offer stronger magnetic fields for higher image quality and faster scan times [12]:

- 1.5T MRIs are the clinical standard—fast, cost-effective, and suitable for most routine scans.
- 3T MRIs provide higher resolution—ideal for detailed imaging. They are faster but more expensive and less suitable for patients with implants.
- 7T and above ultra-high-field MRIs offer exceptional image detail, especially for research and advanced diagnostics, but are limited in clinical use due to high cost, accessibility, and safety considerations.

In MRI, higher field strengths provide higher signal-to-noise ratios (SNR) to enable improved imaging performance compared with lower fields. Optimal performance in ultra-high field (UHF) MRI is highly dependent on radiofrequency (RF) coils tailored for specific anatomical regions and imaging applications [12]. As a result, studies on the use of MR scanners, such as 7T, are increasing.

1.8 Conclusion:

MRI is a valuable medical imaging technique used for diagnosing and monitoring many diseases and functional disorders. It offers important advantages in terms of safety and image quality. The key element in an MRI system is the antenna, as it is responsible for receiving and transmitting electromagnetic signals. The following chapter will be dedicated to presenting a specific type of antenna - microstrip antennas -

Chapter 2:

Microstrip Antenna Technology for Magnetic Resonance Imaging System

2.1 Introduction

Magnetic Resonance Imaging (MRI) is a medical tool used to create clear and detailed images of the inside of the body, such as organs, tissues, and bones. MRI machines work by sending and receiving special radio signals, which help create these images. As MRI technology improves becoming stronger and more compact there are a growing need for small, efficient, and low-energy parts to handle these radio signals [14].

One technology that is helping meet these needs is called microstrip technology. As MRI machines are built with higher power and better image quality, the parts that handle the radio signals must also improve. Microstrip technology is one of the most promising solutions for making these parts smaller, faster, and more effective [15].

2.2 Fundamentals of Microstrip Technology:

Microstrip technology is a cornerstone of modern RF and microwave engineering, providing a compact, planar platform for the integration of passive and active components. It involves the use of a conductive strip (usually copper) separated from a ground plane by a dielectric substrate, forming a transmission line capable of guiding high-frequency signals with relatively low loss [14]. This configuration allows for the creation of microwave components like antennas, filters, and couplers on a printed circuit board (PCB) [16].

2.3 Microstrip Transmission Line Structure and Composition:

At the heart of a microstrip line lies a thin strip of conductor positioned atop a dielectric material, which is in turn placed over a ground plane. The conductor typically comprises copper due to its excellent conductivity and affordability. This metallic strip acts as the signal trace, guiding electrical signals through the circuit. The dielectric material, often made of materials like FR-4, PTFE, or ceramic, determines the speed at which signals travel within the microstrip line. This parameter, known as the dielectric constant (εr), influences the characteristic impedance and overall performance of the line [17].

Adjacent to the dielectric material lies the ground plane, usually a conductive layer beneath the dielectric. This serves as a return path for the electrical signals, maintaining signal integrity and reducing electromagnetic interference [16].

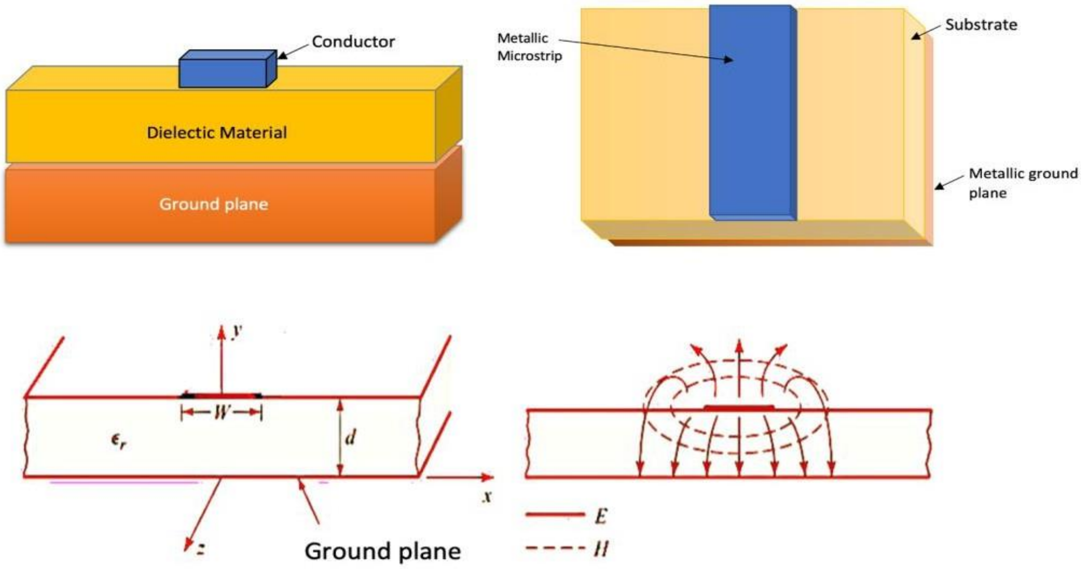

Figure 2.1: Microstrip Transmission Line Structure

Where:

d : Substrate Thickness (or Height)

W: Width of the Conductor Strip

εr: Relative Dielectric Constant (Permittivity)

E : Electric Field Distribution

H: Magnetic Field Distribution

2.4 Relevance of Microstrip Transmission Lines in MRI Systems:

Microstrip transmission lines (MTLs) are used in MRI systems, particularly in high-field MRI, as a component of RF coils for both transmitting and receiving signals. They are employed to generate and manipulate magnetic fields, allowing for more precise and uniform excitation of tissue for imaging [18], [19].

2.5 Role of Radiofrequency (RF)Coils in MRI Systems:

Radiofrequency (RF) coils are an essential MRI hardware component, acting as its "antenna." They directly impact the spatial and temporal resolution, sensitivity, and uniformity in MRI. Advances in RF hardware have resulted in a variety of designs optimized for specific clinical applications. RF coils are the “antennas” of the MRI system and have two functions: first, to excite the magnetization by broadcasting the RF power (Tx-Coil) and second to receive the signal from the excited spins (Rx-Coil) [18],[20]. Transmit RF Coils emit magnetic field pulses (B1) to rotate the net magnetization away from its alignment with the main magnetic field (B0), resulting in a transverse precessing magnetization. Due to the precession around the static main magnetic field, the magnetic flux in the receive RF Coil (B1) changes, which generates a current *I*. This signal is “picked-up” by an antenna and preamplified, usually mixed down to a lower frequency, digitized, and processed by a computer to finally reconstruct an image or a spectrum. Transmit and receive functionality can be combined in one RF Coil (Tx/Rx Coils) [14].

2.6 Microstrip Antenna:

The operation of microstrip antennas is based on a conductive metallic patch placed on a dielectric substrate. This metallic patch is often square, rectangular, or circular in shape, and can be fed with energy at the center or at one of this edges [21]. When the antenna is energized, electromagnetic currents are generated on the metallic patch, thereby creating electromagnetic waves thzt propagate throught the air. The electromagnetic properties of both the metallic patch and the dielectric substrate are crucial for the antenna’s performance. The microstrip antenna structure is designed to control radiation characteristics such as polarization, directivity, and bandwidth. The dimensions of the metallic patch and substrate, the shape of the patch, the feeding position, and the dielectric properties of the substrate are all critical factors influencing antenna performance[21], [22]. Engineers use electromagnetic simulation tools, such as Ansys HFSS to design and optimize microstripantenna performance according to specific application requirements. In summary, microstrip antennas operate by using a conductive metallic patch on a dielectric substrate to generate electromagnetic waves, and their performance depends on several key factors that are optimized to meet the demands of each particular application [22].

2.7 Relevance of Microstrip Antennas in MRI Systems:

Microstrip antennas have gained increasing relevance in Magnetic Resonance Imaging (MRI) systems, particularly for ultra-high field MRI applications (≥7 Tesla), where traditional loop coils face limitations in uniformity and penetration depth. Due to their low profile, conformability, and ability to support various modes of electromagnetic wave propagation, microstrip antennas are used as part of radiofrequency (RF) coil arrays to enhance signal-to-noise ratio (SNR) and achieve better spatial resolution [19][23].

Their planar structure allows easy integration into multi-channel arrays, which are essential for parallel imaging techniques and accelerated acquisition. Moreover, microstrip antennas can be designed to focus the RF field in specific regions, improving imaging of targeted anatomical areas while reducing specific absorption rate (SAR), a critical safety parameter in MRI [23].

2.8 Why Microstrip Antennas for MRI:

Microstrip antennas are becoming popular for use in MRI systems due to their compact size, planar structure, and ease of integration into array configurations. Unlike traditional loop or birdcage coils, microstrip antennas are low-profile and can be fabricated on dielectric substrates, making them ideal for conformal or surface coil applications, particularly in targeted anatomical regions such as the brain, spine, or extremities [18], [21]. Their ability to be tuned and matched at specific MRI frequencies (e.g., 64 MHz for 1.5T or 128 MHz for 3T systems) ensures efficient energy transfer and resonance with the proton precession frequency [6]. Additionally, microstrip designs can be optimized to improve local signal-to-noise ratio (SNR) and reduce mutual coupling in phased arrays [23]. Their flexibility in layout also allows for multichannel and parallel imaging configurations, which are essential in modern MRI systems for faster scan times and improved spatial resolution [22], [23].

2.9 Performance Parameters

The performance of microstrip antennas in MRI applications is evaluated using several key parameters, including return loss, bandwidth, gain, RF field homogeneity (B1 field), and signal-to-noise ratio (SNR).

1) **Return loss** indicates how effectively the antenna is matched to the MRI system impedance, with values below –10 dB generally considered acceptable for minimizing power reflection and maximizing energy delivery to the tissue [16], [17].
2) The **bandwidth** reflects the frequency range over which the antenna maintains efficient operation, which is critical for covering the necessary resonance frequencies in clinical MRI (e.g., 64 MHz for 1.5T, 128 MHz for 3T) and accommodating frequency shifts due to loading effects [22].
3) **Antenna gain** affects the spatial coverage and sensitivity; while MRI antennas typically operate in near-field conditions, effective gain can influence the efficiency of RF excitation and signal reception [22].
4) The **homogeneity of the B1** field, representing the uniformity of the transmitted RF field, is essential for consistent image contrast and uniform excitation across the imaging volume. Poor homogeneity leads to shading and non-uniform signal intensities, especially in high-field systems [23], [24]
5) Lastly, **SNR** is a critical parameter determining image quality; microstrip antennas can be optimized through geometry and substrate selection to enhance local SNR, particularly when used in phased arrays for parallel imaging [19], [23].

2.10 Outline of the MRI systems in the literature:

2.10.1 Summary of the Work by Zhang, Ugurbil, and Chen (2001)

Title: Microstrip RF Surface Coil Design for Extremely High-Field MRI and Spectroscopy

In their research study, Zhang, Ugurbil, and Chen proposed a new type of high-frequency RF surface coil optimized for ultra-high-field MRI at 7 Tesla and beyond. They introduced a **microstrip transmission line structure**, , which uses a distributed-element approach instead of using discrete components such as capacitors as in conventional coils (traditional surface coil). This design consists of a thin metal conductor over a ground plane, separated by a low-loss dielectric material, enabling simpler, smaller, and more efficient coil construction.

The authors explored various coil configurations, including single-turn and two-turn square-shaped coils as in **Figure 2.2, Figure 2.3** and tested different substrate thicknesses to optimize performance.

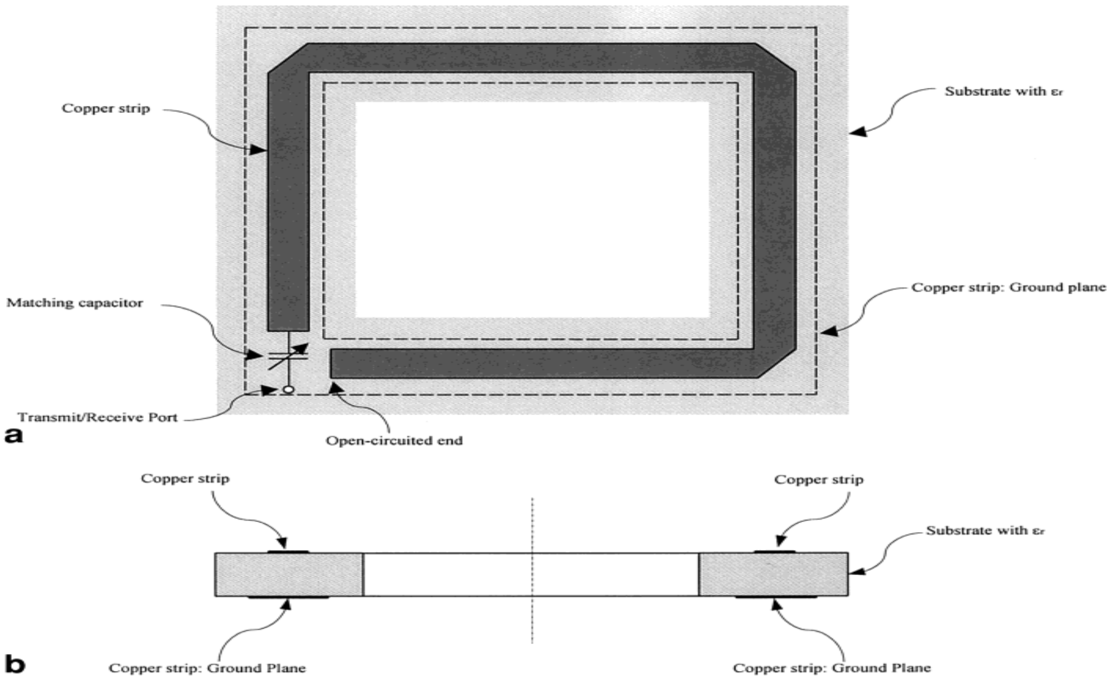

Figure 2.2 Single-turn microstrip surface coil with the square shape **a/b**

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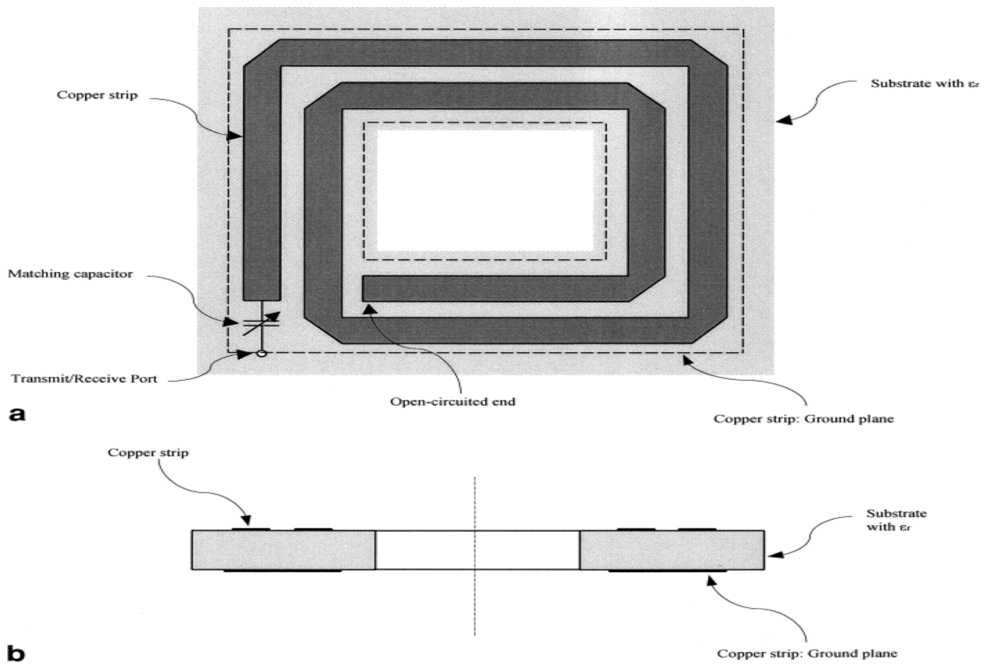

Figure 2.3 Two-turn microstrip surface coil with the square shape
(a) and its cross section (**b**).

Experimental results show that that a dielectric thickness of 5–7 mm offers the best B1 field penetration and uniformity. Notably, two-turn microstrip coils demonstrated superior B1 symmetry compared to single-turn versions.,as in Figure 2. which is essential for obtaining clear images.

The microstrip coil provided a 20% higher Signal-to-Noise Ratio (SNR) than an unshielded conventional coil.

Human head imaging at 7T confirmed its capability to deliver high-resolution, high-contrast images with reduced hardware complexity.

The study concludes that microstrip coils are not only highly effective but also more compact and versatile than traditional RF coils, making them well-suited for advanced imaging at ultra-high fields. This design can be extended to various geometries for both head and body applications, offering a promising path forward for next-generation high-field MRI and MRS technologies.

2.10.2 Summary of the Work by Sohn, DelaBarre, Gopinath, and Vaughan (2014)

Title: RF Head Coil Design With Improved RF Magnetic Near-Fields Uniformity for MRI Systems

In this study, the authors present a new RF head coil design specifically developed for use in 7 Tesla (7T) MRI systems, where achieving uniform RF magnetic (B_1) fields is a significant challenge. Traditional microstrip-based RF coil elements often produce stronger fields at the center and weaker ones at the ends, leading to image inhomogeneity—particularly problematic at high frequencies used in ultra-high-field MRI.

To solve this, the researchers proposed a double trapezoidal-shaped microstrip transmission line (MTL) as a replacement for the conventional uniform-shaped coil elements. This shape introduces a gradual impedance variation along the length of the conductor, which leads to a more uniform current distribution and thus a more consistent and stronger B_1 field across the imaging area.

They designed and constructed two eight-channel RF head coils: one using traditional uniform microstrip elements and another with the proposed trapezoidal-shaped elements.

Simulations using HFSS software and physical phantom experiments at 7T demonstrated that the trapezoidal design significantly outperformed the conventional one. The new coil produced more uniform B_1 fields**,** especially near the coil ends, where field drop-off is usually most pronounced. The trapezoidal coil showed up to 61% improvement in localized signal intensity, with an average gain of around 30%**,** leading to better image quality.

The study concludes that this design enhances MR image quality and is a promising approach for improving RF field uniformity in ultrahigh-field MRI applications.

2.10.3 Summary of the Work: Volume RF Coil Using Inverted Microstrip Transmission Line (iMTL) for 7T Human Head Imaging (2019)

This article presents the design and development of a novel volume RF coil for human head imaging at 7 Tesla (7T) using an inverted microstrip transmission line (iMTL) configuration. The iMTL is a modified form of conventional microstrip transmission line technology, specifically engineered to address challenges associated with high-frequency RF operation in ultra-high-field MRI systems, such as signal losses, inefficient field penetration, and non-uniform field distribution.

The proposed iMTL coil comprises 16 resonant elements arranged symmetrically around the head, forming a volume coil that provides full coverage and improved homogeneity. The construction is based on two concentric acrylic cylinders**:**

The inner tube supports the copper conductor strips on its outer surface, and the outer tube supports the ground plane on its inner surface**.** The space between the two tubes acts as a controlled dielectric medium, while capacitors are placed at both ends of each resonant element to fine-tune resonance and improve the coil's electromagnetic efficiency.

The iMTL architecture offers several technical advantages. Unlike conventional micro strip coils where the ground plane is beneath the conductor, the inverted structure creates a more enclosed and efficient transmission path**,** reducing radiation losses and improving power handling. This leads to better B_1 field efficiency**,** improved signal-to-noise ratio (SNR), and more uniform RF field distribution, which are critical for consistent image quality at 7T.

In conclusion, this innovative iMTL-based volume coil demonstrates strong potential for advancing ultra-high-field MRI. Its efficient and symmetrical design enables high-quality human head imaging, combining the structural benefits of a volume coil with the electromagnetic performance improvements of inverted transmission line technology.

2.11 Conclusion

Microstrip antennas represent a significant advancement in the development of radiofrequency (RF) technology for magnetic resonance imaging (MRI). As MRI continues to evolve as a non-invasive, high-resolution imaging modality, the role of RF coils—particularly microstrip antennas—has become increasingly critical in enabling efficient signal transmission and reception.

Their compact size, low-profile structure, and tunable design make microstrip antennas ideally suited for surface imaging and integration into phased arrays, allowing for improved signal-to-noise ratio (SNR) in targeted anatomical regions. These antennas can be precisely tuned to match MRI system frequencies (such as 64 MHz for 1.5T or 128 MHz for 3T), ensuring optimal performance across various clinical and research applications.

Design considerations, including the use of biocompatible, non-magnetic substrates, tuning/matching networks, and adherence to safety standards such as SAR limits, are essential to ensure both patient safety and system efficiency. Performance metrics such as return loss, bandwidth, gain, B_1 field uniformity, and SNR are used to evaluate and optimize coil function for high-quality imaging.

Microstrip antennas are increasingly utilized in surface coils for regions like the brain, spine, and breast, and in multichannel phased array systems that support parallel imaging and faster scan times. Their versatility and performance make them a promising solution in the future of both conventional and ultra-high-field MRI systems.

Chapter 3:

Numerical results and Discussion

3.1 Introduction

Microstrip antennas play a fundamental role in the image acquisition process of MRI systems. Their design and optimization contribute to improving image quality and providing critical information for medical diagnosis.

The study and analysis of antenna structures are conducted using the electromagnetic (EM) simulation software Ansys HFSS 2024 R2. These investigations aim to design microstrip antenna structures specifically intended for Magnetic Resonance Imaging (MRI) applications. The primary objective of this study is to demonstrate that these structures, operating as resonators, are capable of generating magnetic fields that function as uniform B_1 fields within an MRI system.

The structure we propose to study is a radiofrequency coil array consisting of 8 channels, as proposed in article [25].

In this chapter, a planar Yagi dipole antenna is simulated for applications in a 7 Tesla (7T) MRI system. The designed antenna resonates at 298 MHz, which corresponds to the Larmor frequency of the 7T MRI system.

The radiation characteristics of the antenna are reported and commented. The main parameters are the magnetic field B1 inside the structure and the Specific Absorption Rate (SAR) are calculated.

The study considers both single-channel and 8-channel antenna configurations, in unloaded and loaded conditions.

An actual human head biological tissues is used in the mean of the most realistic practical situations

3.2 Single Channel Microstrip Transmission Line Antenna:

A high-frequency RF coil based on the use of microstrip transmission line (MTL) antenna has been developed for MR applications on the human head at 7T.

3.2.1 Microstrip Transmission Line Antenna Structure:

In order to ensure a highly uniform magnetic field in UHF MRI system, Yagi antenna principle using a driver placed in the center, and two planar dipoles as reflectors elements located on either side is implemented. The driven element is responsible for generating electromagnetic radiation, while the reflectors are used to make the radiation more directional.

These elements are placed on a dielectric substrate of type FR-4, with a thickness h, measuring 654 × 400 × 0.5 mm³, and a relative permittivity of $\varepsilon_r = 4.4$. The bottom side of the substrate is fully covered with a metallic layer that serves as the ground plane, as illustrated in **Figure 3.1.**

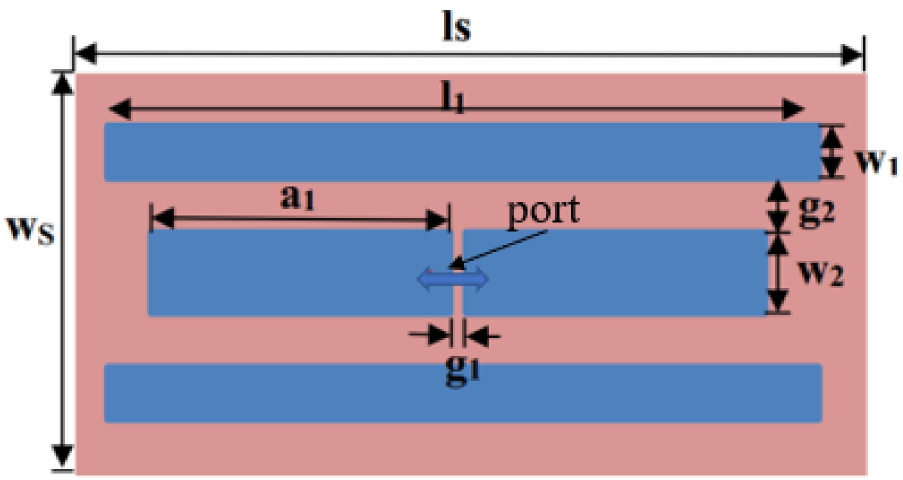

Figure 3.1: Geometrical Structure of the Single Channel Microstrip Transmission Line Antenna [25].

The dimensions of each element are specified in **Table 3.1.** They are determined in such a way to achieve resonance at 298 MHz**,** which corresponds to the Larmor frequency for a 7 Tesla system. [25]

Table 3.1: The parameters of the designed RF coil element **[25]**

Parameters	**Dimensions (mm)**
ls	654
Ws	400
l1	518.4
w1	40
g2	80
w2	55
a1	239.7
g1	17

3.2.2. Simulation Results

The geometrical configuration of the single-channel microstrip transmission line (MTL) was designed and modeled using the **HFSS (High-Frequency Structure Simulator)** software, as shown in **Figure 3.2**

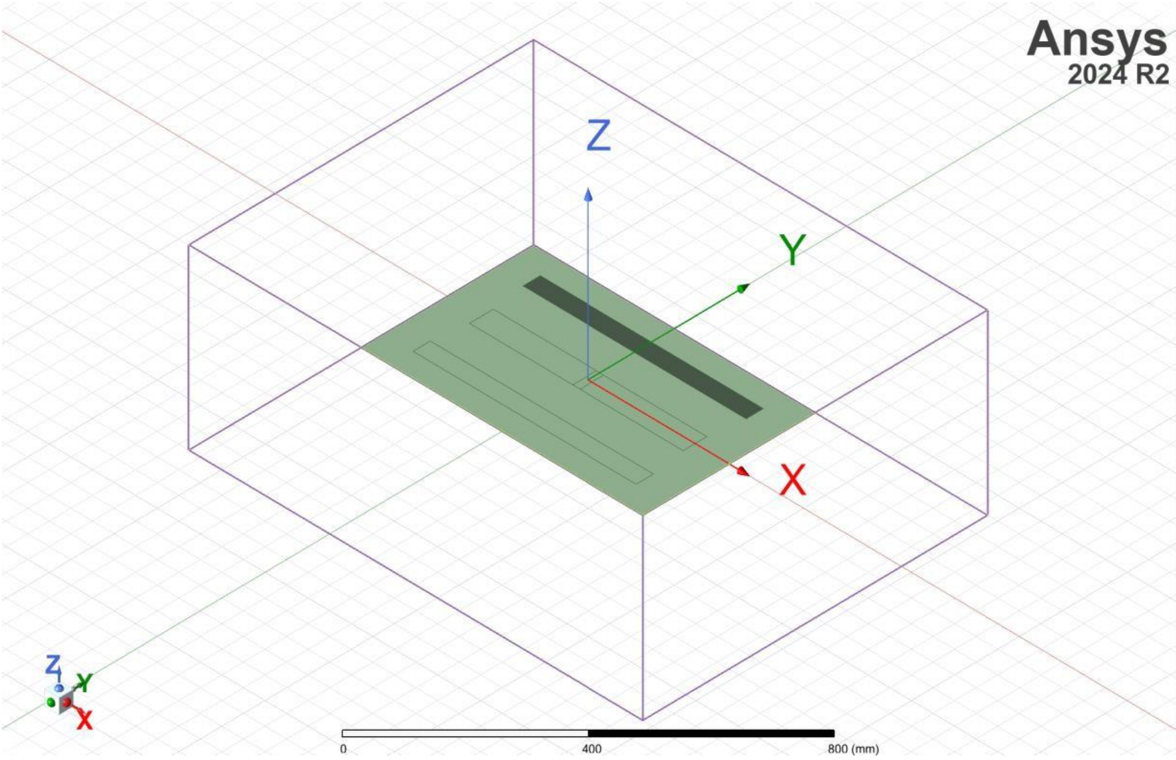

Figure 3.2 : The detailed schematic of the MTL structure

The simulation of this structure was carried out using **HFSS**, which enabled the visualization of the frequency response of the reflection (S11) coefficient across this channel.

Figure 3.3. illustrates the variation of the reflection coefficient at Port as a function of frequency. A clear resonance is observed at 261.5 MHz, with a reflection coefficient (**S11**) level of -1.85 dB**.**

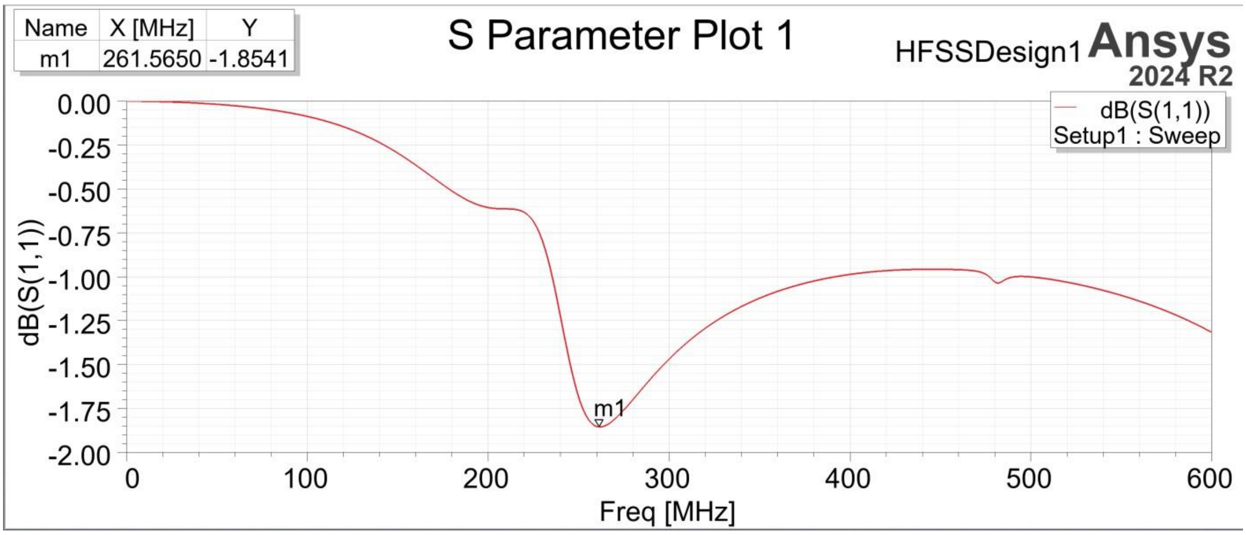

Figure 3.3: The simulated S11 parameters of the single channel antenna

3.2.3 Loaded Microstrip Transmission Line Antenna:

In this section, we consider a single-channel MTL loaded with a human head model; the human head is a complex structure composed of various tissues, each with unique properties. A three-dimensional human head model was taken from the **HFSS 2024 R2** library and used. The human head model used in the simulation is a realistic, anatomically accurate representation composed of multiple biological tissues, including skin, skull, brain (gray and white matter), cerebrospinal fluid (CSF), and other relevant structures. Each tissue is assigned appropriate dielectric properties (permittivity and conductivity) corresponding to the Larmor frequency of 298 MHz (7T MRI); this model enables accurate evaluation of RF field distribution, B_1 field uniformity, and Specific Absorption Rate (SAR) within the head, supporting the optimization of coil performance and safety analysis in ultra-high-field MRI systems. SAR and the absorbed RF energy by the human tissue depend not only on the electromagnetic field parameters but also on the electrical properties of tissues; dielectric properties of the tissues influence electromagnetic absorption, and consequently, the absorbed electromagnetic energy in the tissue layers increases SAR values. The dielectric properties of the tissues used in this study were taken from the literature; the relative permittivity (ε) and conductivities (σ) of human tissues at different frequencies are shown in Table 3.2.

Table 3.2: Dielectric and Physical Properties of Human Head Tissues at MRI Frequencies

Tissue	Relative Permittivity (εr)	Conductivity (σ) [S/m]	Density [kg/m³]
Skin	45–49	0.68–0.88	~1100
Fat	5–6	0.04–0.05	~920
Skull (bone)	12–18	0.1–0.15	~1900
Cerebrospinal Fluid (CSF)	~68–70	~2.0	~1007
Gray Matter	60–65	0.9–1.1	~1040
White Matter	38–42	0.6–0.75	~1030
Blood	58–62	~1.2	~1060
Brain (average)	~50–60	~0.8–1.0	~1040

These values are frequency-dependent and specifically tuned for 298 MHz (the Larmor frequency at 7T).

3.2.4. Simulation Results

The simulation setup was constructed and visualized using **HFSS** to evaluate the electromagnetic interaction between the microstrip transmission line (MTL) and biological tissue.

As illustrated in **Figure 3.4**, the geometrical model comprises a single-channel MTL structure positioned in close proximity to a realistic human head model, which serves as a biological phantom to emulate in vivo imaging conditions.

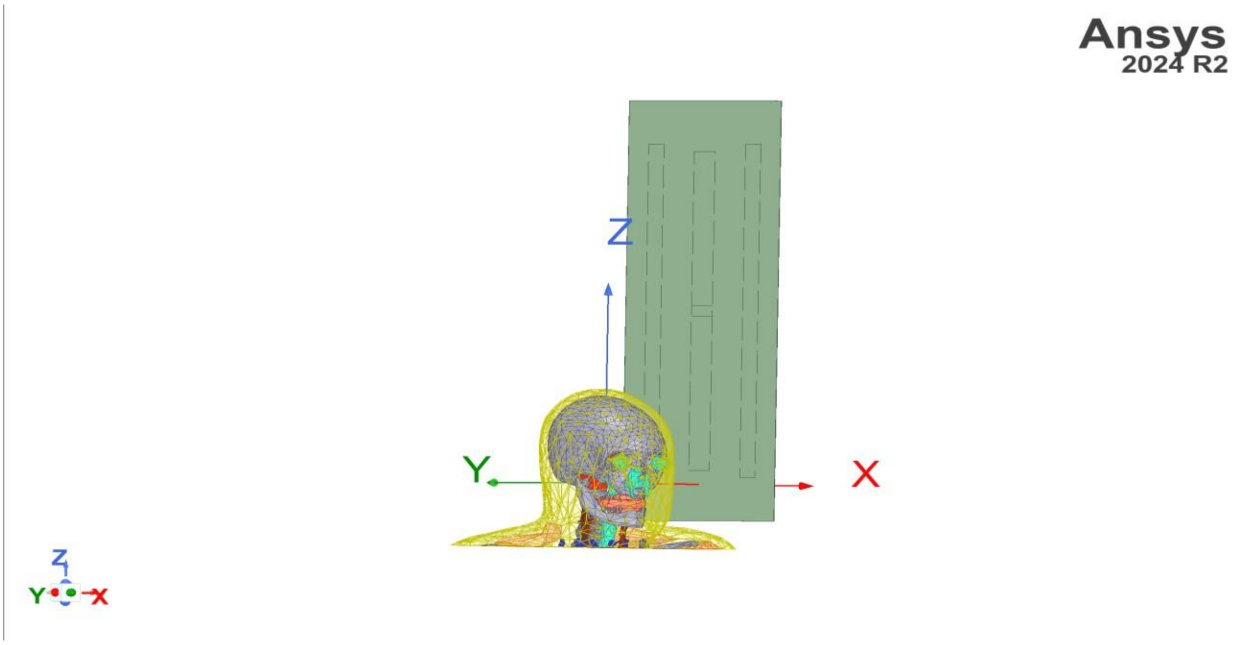

Figure 3.4: Geometrical Model of a Single-Channel Microstrip Transmission Line (MTL) Coupled with a Human Head Phantom

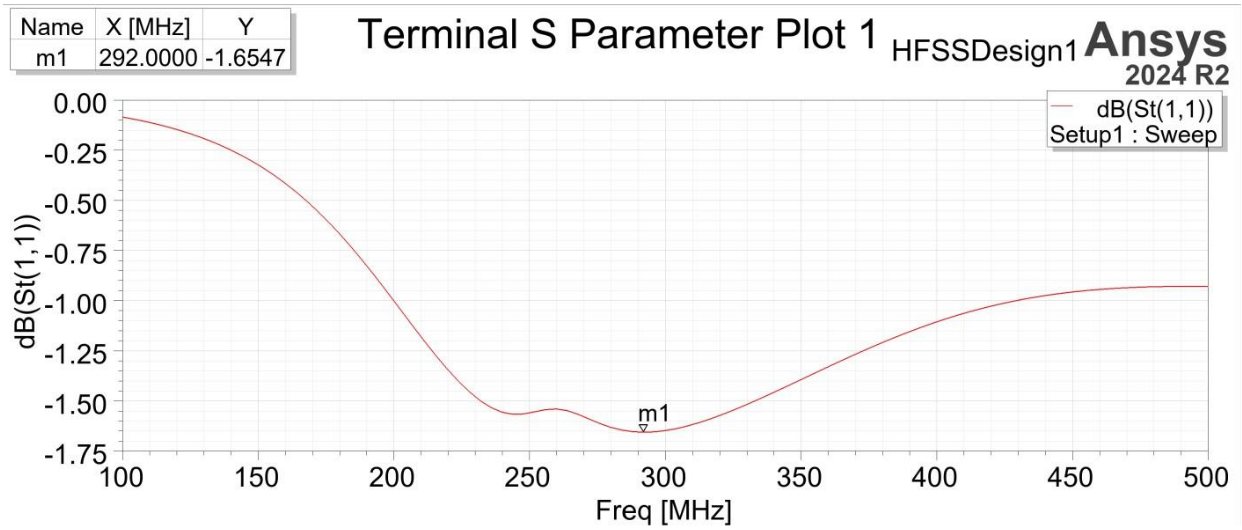

Figure 3.5: The simulated S_{11} parameter of the single channel loaded antenna with human head.

3.3. Multi Channel Microstrip Transmission line Antenna:

Since the human tissue is a complex three-dimensional electromagnetic model, single RF coil element cannot guarantee the same magnetic field strength at different depths of the imaged object, an 8-channel coil array is proposed in paper [25]. It has a geometrically symmetrical structure in three-dimensional space, which not only ensures the magnetic symmetry of the coronal and sagittal planes, but also improves the strength and uniformity of the magnetic field.

3.3.1. An 8-Channel RF Coil based on Microstrip Yagi-antenna for 7T Magnetic Resonance Imaging:

The structure we propose to study is a radiofrequency coil array consisting of 8 channels. Each channel represents a Yagi antenna, and the array is designed to support a 7 Tesla magnetic resonance imaging (MRI) system for human body imaging as proposed by the article [25]. illustrated in Figure 3.6

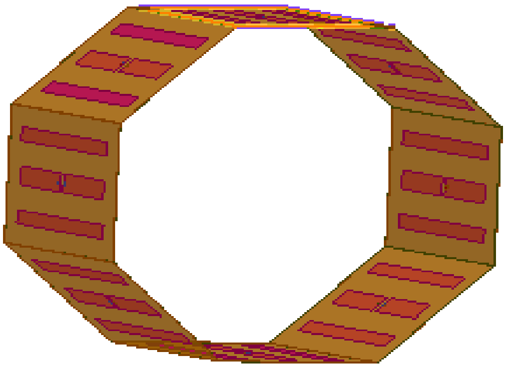

Figure 3.6: An 8-channel RF coil array [25].

3.3.2. Simulation Results:

The geometrical model comprises an eight-channel MTL structure is illustrated in **Figure 3.7**

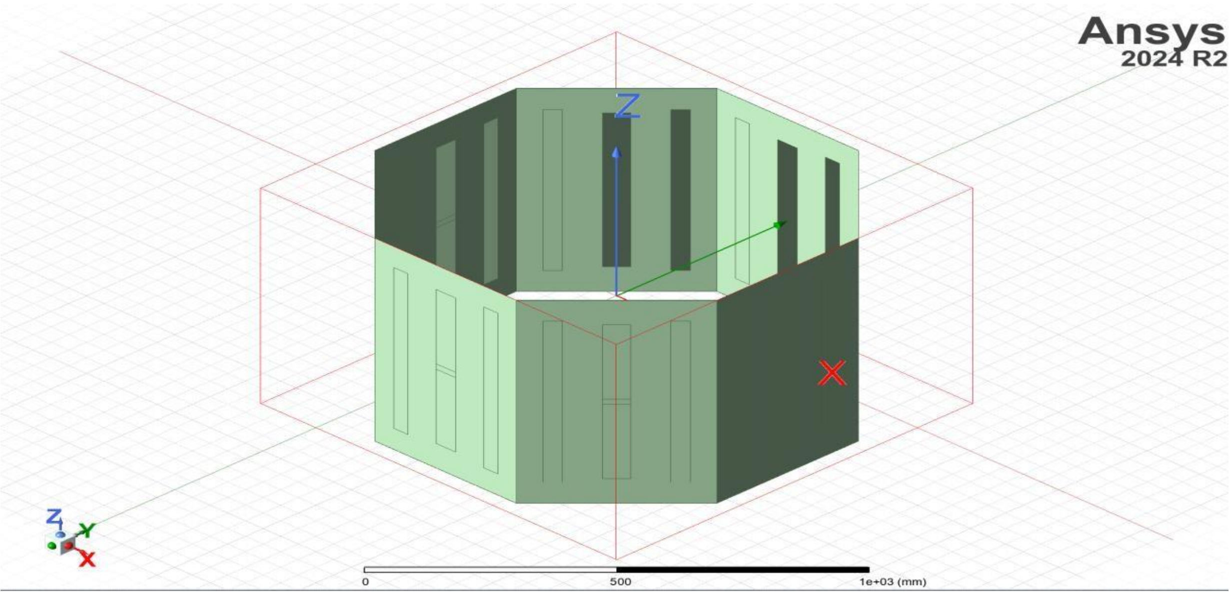

Figure 3.7: The detailed schematic of the eight-channel MTL structure

The simulation of the designed array was carried out using the **FHSS** environment. The variation of the reflection coefficient at the first port as a function of frequency is shown in **Figure 3.8.**

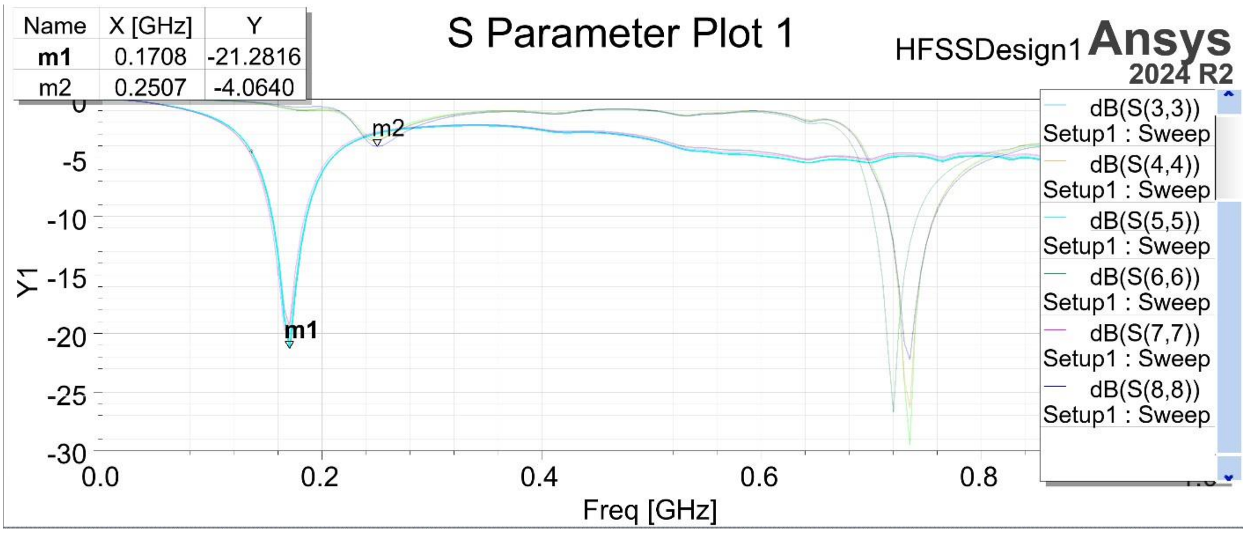

Figure 3.8: The simulated S11 parameters of the eight channel antenna

As can be seen from Figure 3.8, the set of the 8 channels present resonances near 170 MHz and 250 MHz which are below the Larmor frequency 298 MHZ of the 7T MRI system. Later, the actual resonance frequencies of the antenna will be increased to a value of 298 MHz by adding the effect of the presence of the head model.

Figure 3.9 represents the transmission coefficients between the port 1 and the other different 7 ports versus frequency in the frequency band [1- 1000] MHz. Note a very low coupling between the antenna channels, this is shown by a transmission coefficient below – 34 dB in the vicinity of the design Larmor frequency.

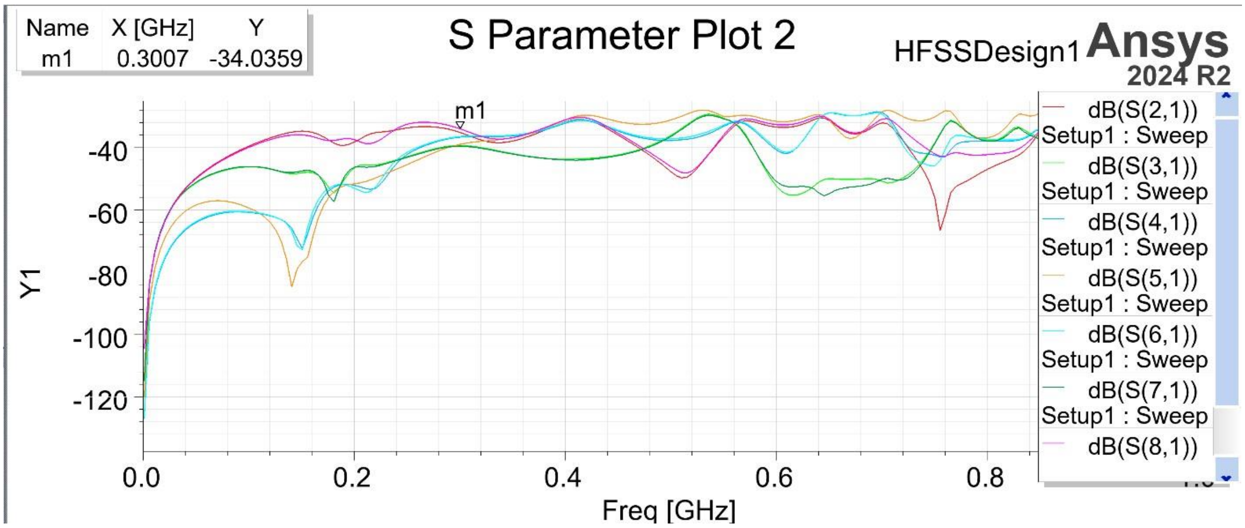

Figure 3.9: The simulated transmission parameters S_{i1} ($i \neq 1$) versus frequency in GHz.

3.3.3. Loaded 8-Channel RF Coil based on Microstri Yagi-antenna for 7T Magnetic Resonance Imaging:

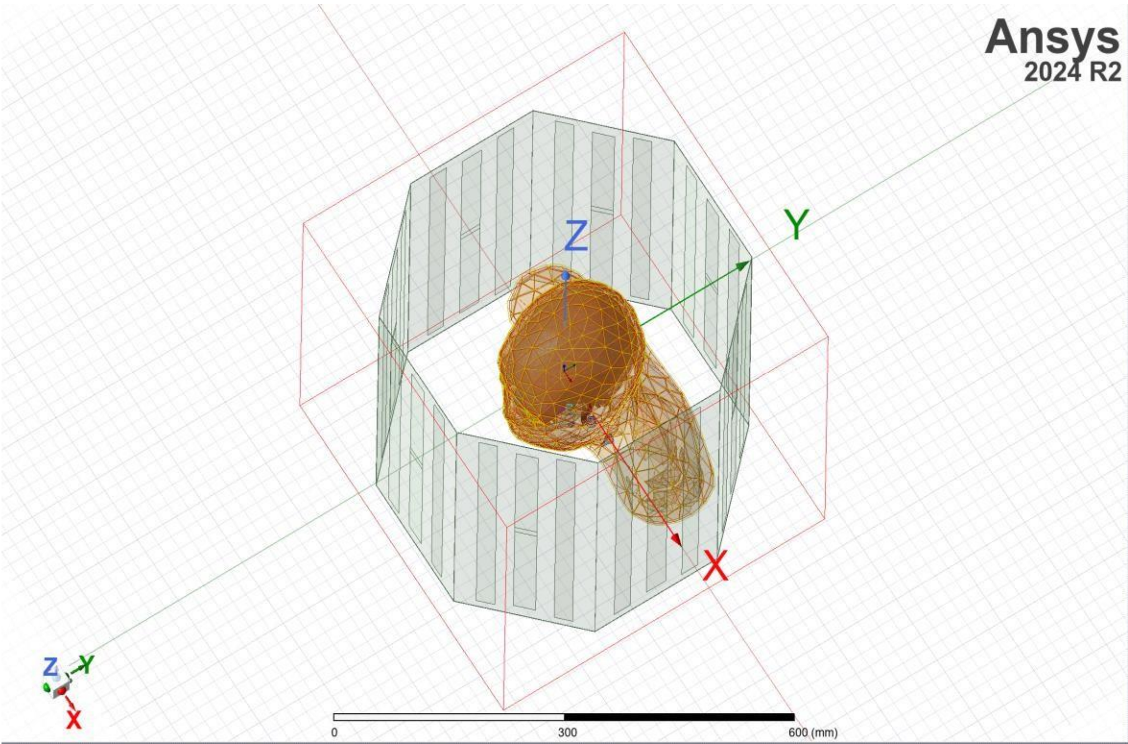

Figure 3.10: The detailed schematic of the eight-channel MTL structure with a Human Head Phantom

3.3.4 Simulation Results

Reflection coefficients

Figure 3.11 shows a pictorial representation of the S_{ii} (i = 1,2,..,8) in decibel versus frequency in MHz of the human head loaded 8 channel MTL dedicated for operation in the 7T MRI system. The resonant frequencies of the single elements are very near to the 298 MHZ 7T MRI system. The individual frequencies of the 8 channels given from the x- axis and rotating counter clock wise are, respectively: 276 MHz with a reflection of 6.67 dB for the first four channels and 331 MHz with a reflection of 1.2 dB for the last four channels.

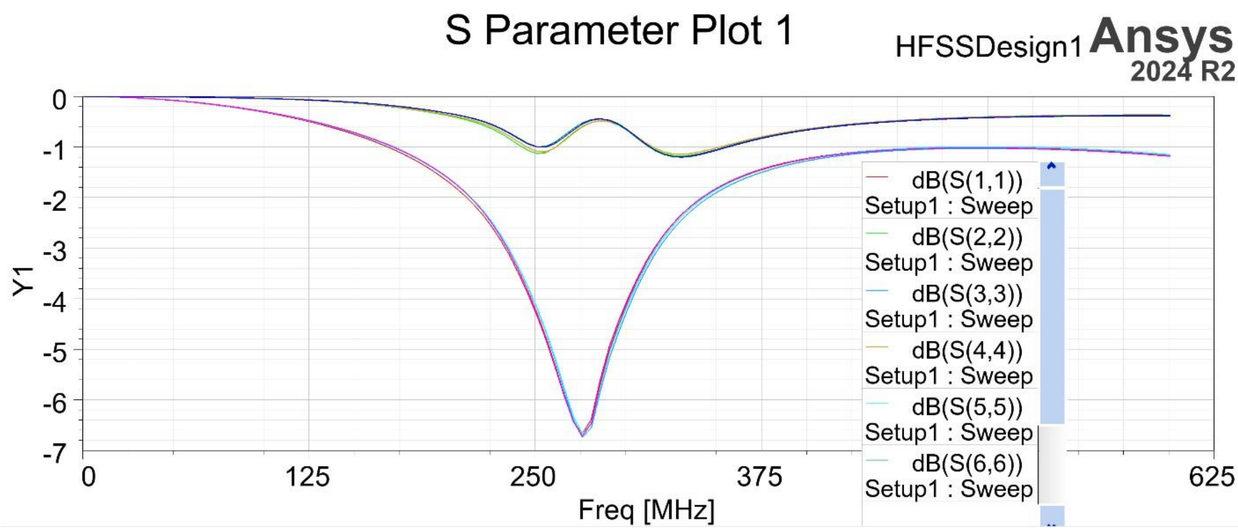

Figure 3.11: The simulated S11 parameters of the loaded 8 channel MTL.

Transmission coefficients

Figure 3.11 represents the transmission coefficients S_{ij} (i,j = 1,2,..,8 and $i \neq j$) of the mutual channels, where we note that the transmission is approximately – 32.0 dB for the (i,j) = (2,1), (3,1), (4,1), (5,1), (6,1), (7,1), (8,1). This transmission coefficient value can reach -64.0 dB for the elements (4,1) which shows a perfect decoupling. The inter-channel decoupling parameter is sought for multichannel MRI systems.

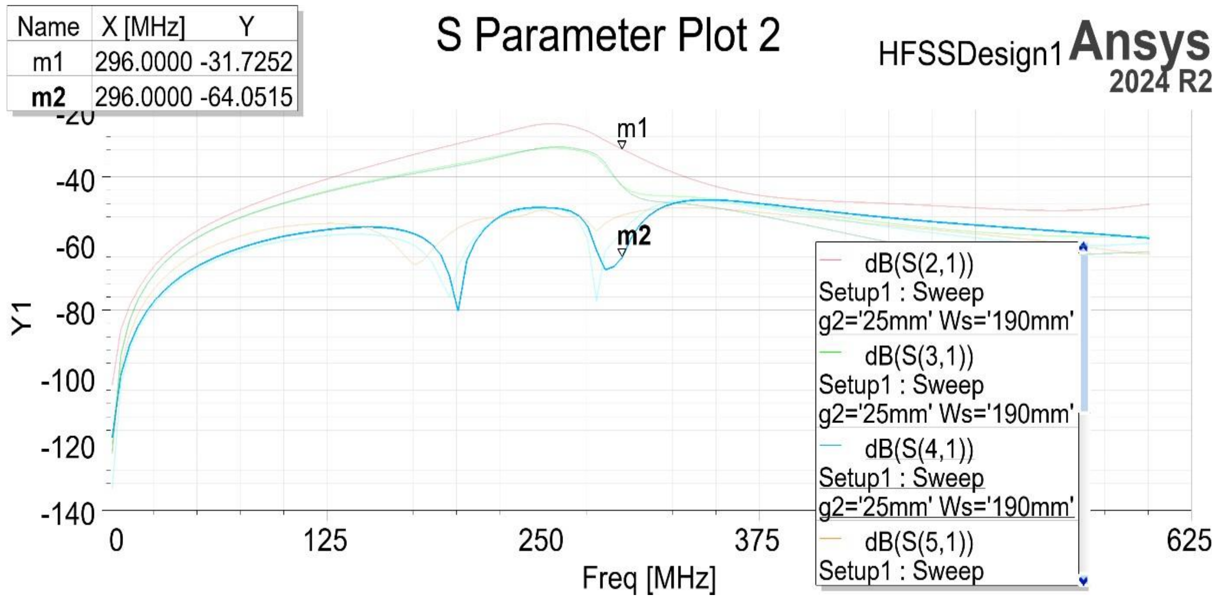

Figure 3.12: The simulated transmission parameters S_{i1} of the loaded 8 channel MTL

Magnetic field distribution B1

The distribution of the magnetic field intensity H = B1/μ_0 inside the loaded 8 channel antenna at the plane z = 0 is presented in Figure 3.13. Note that the field distribution is very homogeneous inside the head tissues. Very sharp spikes representing high values of B1 exist around each conductor.

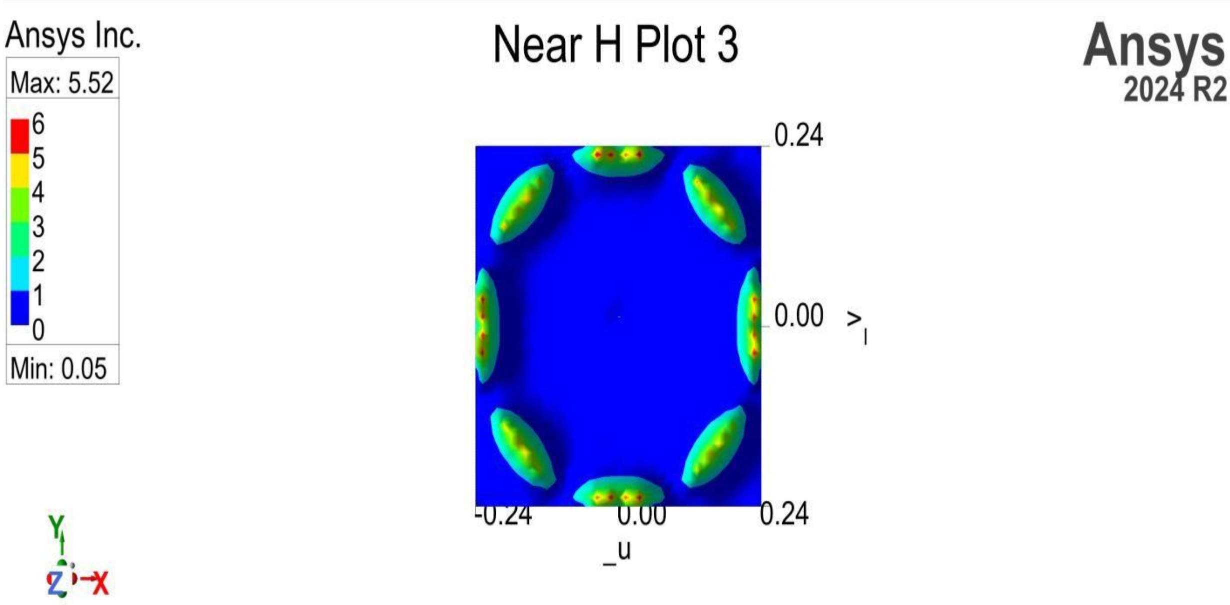

Figure 3.13: Amplitude of the Magnetic field distribution B1 in the plane z = 0.

3.4 Conclusion:

In this chapter, design of an 8 channel microstrip transmission line for the 7 Tesla Magnetic Resonance Imaging system has been presented. The design used a yagi dipole planar antenna as a driven element and two planar dipoles as reflectors to enhance gain. Firstly a single channel unloaded antenna is presented. Secondly, the actual head model extracted from a complete human body model is deployed in the vicinity of the antenna to model the effect of the biological tissues on the radiation of the antenna. Ansys HFSS 2024 R2 commercial electromagnetic software projects and designs have been created to implement the single channel unloaded/loaded antenna. Thirdly, the 8 channel unloaded and unloaded antenna have been designed and simulated using the aforementioned software, where the characteristics of the antenna have been estimated. The simulation results show a very close resonance of the individual antenna elements to the 7 T 298 MHz frequency. Furthermore, the interelement crosstalk (coupling) ranges from -32. dB to -64.0 dB which is an excellent decoupling of the channels. The designed antenna can be a very good candidate for multichannel antennas largely used in MRI systems.

General Conclusion

General Conclusion

In this Master study, we presented the design of a Microstrip Transmission Line RF coil dedicated for high field 7Tesla Magnetic Resonance Imaging system.

Firstly, a general introduction to the study is provided in with the statement of the antenna design problem and the organization of the manuscript chapter by chapter.

Secondly, the magnetic resonance imaging system principles are presented briefly. The magnetic resonance physical phenomenon in Hydrogen atoms is mentioned together with the advantages and disadvantages of MRI. The main blocks of MRI system, their classification as high- and low-field MRI systems are also presented.

Thirdly, the microstrip transmission line theory is outlined as the designed antenna coil uses this planar technology due to its inherent advantages. More specifically, the type of planar antenna is Yagi-dipole with center-fed driven dipole and two dipoles as reflectors to enhance gain.

Fourthly, the chosen type of planar MTL RF coil using Yagi-dipole type is analyzed and designed for the 7T MRI at Larmor resonance frequency of 298 MHz. The design starts from a single channel unloaded, then it has been loaded with the actual model of a human head. The number of channels is increased to reach a complete design of 8 channel loaded antenna. The S-parameters are extracted using Ansys HFSS 2024 R2 software and show actual resonances near 298 MHz with very good reflection and high value of inter-channel decoupling. Very homogeneous magnetic field distribution inside the head tissues are noticed with spiky values around the conductors. This make the antenna as a very suitable candidate for 7T MRI system coil.

Finally, as perspectives for further study, we suggest to increase the number of channel to 16 and 32 to enhance magnetic field homogeneity inside the region where the head is explored. It would also be beneficial to apply a systematic method of optimization to meet the requirements of inter-element decoupling and homogeneity of magnetic field intensity.

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