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Design of Ultra Wideband Antenna for Wireless Endoscopy

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ABSTRACT: The Ultra-Wide band antenna is really good for endoscopy applications. This Ultra-Wide band antenna design is great because it works well with the endoscopy applications. It has impedance matching and this is very important for the Ultra-Wide band antenna. The Ultra-Wide band antenna also has gain and good radiation characteristics. The Ultra-Wide band antenna is small. This is very useful for capsule integration. To make the Ultra-Wide band antenna work well the designers used a substrate that is safe for people. They also did simulations to see how the Ultra-Wide band antenna would work. They looked at things like S-parameters. Gain and radiation patterns. They made sure the Ultra-Wide band antenna was safe by checking the SAR safety limits. The designers tested the Ultra-Wide band antenna using a phantom that is like human tissue. The results of the test were very good. The Ultra-Wide band antenna worked well. The Ultra-Wide band antenna is very good for medical imaging systems that're minimally invasive. It can send a lot of data quickly. This is very useful for the medical imaging systems. The Ultra-Wide band antenna is a tool, for wireless endoscopy applications.

Keywords: Ultra wideband, Antenna, Endoscopy, Wireless capsule, VSWR, Gain, Radiation

1. Introduction

Wireless endoscopy, also known as capsule endoscopy, is a modern and minimally invasive method for examining the gastrointestinal (GI) tract. Unlike traditional endoscopy, which involves inserting a flexible tube through the mouth or rectum, wireless endoscopy requires swallowing a small capsule. This capsule has a tiny camera, light source, battery, sensors, and a wireless module. As it travels through the digestive system, it captures thousands of high-resolution images and sends them wirelessly to an external receiver worn by the patient. Medical professionals later review these images to identify problems such as bleeding, ulcers, tumors, or inflammatory diseases. This method improves patient comfort, reduces risks, and allows for viewing areas that are difficult to see using standard techniques. A key part of the wireless capsule endoscopy system is the antenna. The antenna sends image data from inside the body to an external monitor. Since the capsule operates in a complex biological environment, the antenna requires careful design to ensure reliable communication. It needs to be compact enough to fit inside the capsule, which is usually just a few millimeters in size. At the same time, it should offer stable radiation characteristics, good impedance matching, and consistent signal strength, even with constant movement and random positioning inside the body. Ultra-Wideband (UWB) technology has emerged as a promising choice for wireless endoscopy. UWB systems operate over a wide frequency range, allowing for high-speed data transmission with low power consumption. This is especially crucial for sending high-resolution images or possibly real-time video. UWB signals also experience less interference from other medical devices and penetrate human tissues better than narrowband systems. The broad bandwidth enhances signal reliability and minimizes issues related to multipath fading within the body. However, designing a UWB antenna for biomedical use presents several challenges. Human tissues like skin, fat, and muscle have high dielectric constants and conductivity, which can absorb electromagnetic waves and decrease antenna performance. To tackle this, the antenna must maintain good impedance matching across the operating band, even in lossy environments. Radiation patterns should remain stable and ideally be omnidirectional or wide-beam to ensure continuous communication, regardless of the capsule's orientation. Additionally, biocompatible materials need to be used for safe long-term contact with body tissues. This project focuses on designing, simulating, and evaluating the performance of a compact UWB antenna specifically for wireless endoscopy. The aim is to achieve wide bandwidth, stable radiation performance, acceptable gain, and efficient impedance matching while ensuring safe operation inside the human body. Through detailed electromagnetic simulations and performance analysis, we will confirm the proposed antenna’s suitability for reliable biomedical wireless communication.

2. Literature Review

A. Mohan and N. Kumar (2025) created a compact wideband implantable antenna that functions in the 2.45 GHz ISM band for wireless capsule endoscopy. Their antenna worked well in biological tissues. It had good impedance matching and met Specific Absorption Rate (SAR) safety limits. The design aimed to ensure effective communication inside the body while prioritizing patient safety.

A. Alshammari, A. Iqbal, R. B. Simorangkir, and I. B. Mabrouk (2024) developed an ultra-miniaturized dual-band implantable antenna for wireless capsule endoscopy. Their antenna supports several frequency bands to improve telemetry reliability. The design achieved good impedance matching in human tissue, kept SAR levels low, and had a compact size suitable for capsule integration.

B. Thyla, P. K. Jaya Soumeyaa, T. Jennifer, S. Maharishi, and V. Thulasi Bai (2023) suggested a compact Ultra-Wideband (UWB) antenna for wireless capsule endoscopy applications. Their work aimed to make the antenna small enough for capsule integration while maintaining a wide impedance bandwidth. The proposed design displayed better radiation characteristics in the human tissue environment, allowing for reliable communication inside the body.

K. Ladic, K. Sayrafian, D. Simunic, and K. Yazdandoost (2023) studied wireless channel behavior for UWB communication during capsule endoscopy. Their research examined key factors like path loss, delay spread, and fading effects inside the human body. This work provided helpful insights into how UWB signals act in biological tissues, aiding in the development of reliable high-speed capsule communication systems.

L. Chang, A. Iqbal, A. Basir, R. B. V. B. Simorangkir, and I. Ben Mabrouk (2024) presented a conformal MIMO UWB antenna for high-speed telemetry in capsule endoscopy systems. Their work aimed to improve data rates, isolation, and diversity performance using MIMO technology. The conformal design allowed for better integration within the capsule and increased communication reliability.

R. Govindan et al. (2023) introduced the design and analysis of a conformal MIMO ingestible bolus sensor antenna for wireless capsule endoscopy. Their study demonstrated better data reliability through MIMO diversity techniques and evaluated both on-body and in-body performance. The antenna maintained stable radiation characteristics, even with changes in capsule orientation within the body.

3. Proposed Methodology

This project focuses on designing, simulating, and evaluating the performance of a compact ultra-wideband (UWB) antenna for wireless endoscopy applications. We use ANSYS High Frequency Structure Simulator (HFSS) as the main tool because it provides precise electromagnetic analysis

3.1 Antenna Design

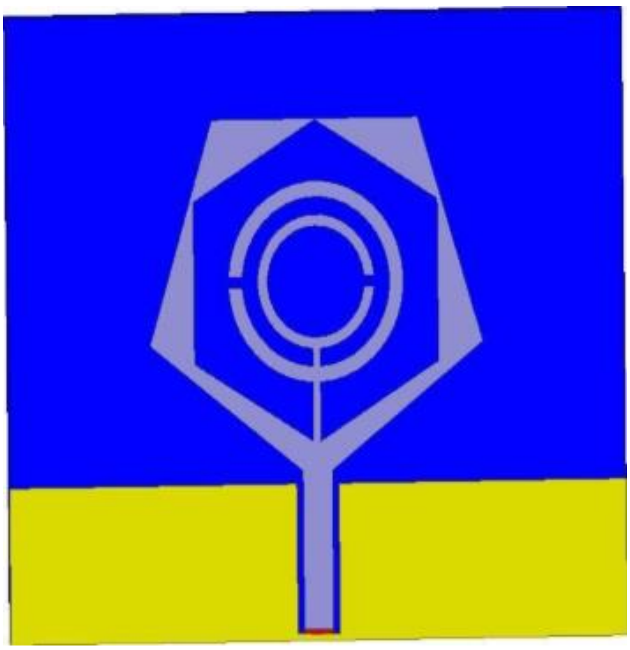


Figure 1: *Antenna Design*

First, we choose a compact antenna structure that meets the size requirements of a capsule endoscope. We select a suitable substrate material with low dielectric loss to ensure effective radiation. The antenna geometry is designed for UWB operation by incorporating features like slots or modified ground structures to improve bandwidth.

3.2 HFSS Modeling and Simulation

We model the designed antenna in ANSYS HFSS, using a three-dimensional electromagnetic structure. We excite the antenna with a lumped port or wave port and apply the right boundary conditions. HFSS simulations are conducted across the UWB frequency range to assess the antenna characteristics.

3.3 Performance Analysis

We evaluate key antenna parameters, including return loss (S11), voltage standing wave ratio (VSWR), bandwidth, radiation pattern, and gain, based on the simulation results. We optimize the antenna by adjusting the design parameters to achieve better impedance matching and wider bandwidth.

3.4 In-Body Analysis

To examine the antenna's performance inside the human body, we create a simplified human tissue model using layers with appropriate dielectric properties, such as skin, fat, and muscle. We place the antenna within the tissue model and run simulations to analyze the frequency shift, radiation behavior, and efficiency.

3.5 Optimization and Verification

Based on the simulation results, we optimize the antenna dimensions to enhance overall performance. We validate the final antenna design by ensuring it meets UWB bandwidth requirements, shows stable radiation characteristics, and adheres to SAR safety standards.

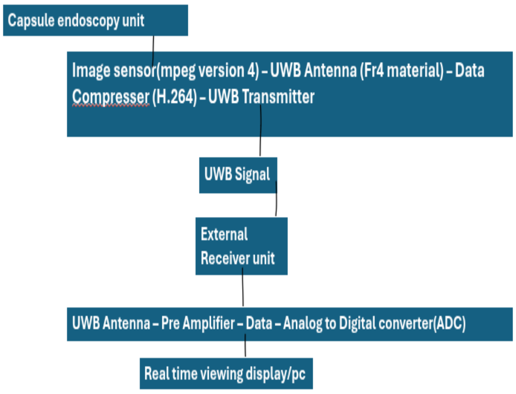


Figure 2: Block Diagram of the Ultra-Wideband Antenna for Wireless Endoscopy

➢ Inside the Body, Capsule Endoscopy Unit

The capsule endoscopy unit is swallowed by the patient and travels through the gastrointestinal (GI) tract. It has everything needed to capture images and send them wirelessly. The unit operates in a small, power-efficient way to ensure it works well inside the human body.

➢ Image Sensor

The image sensor captures continuous images of the internal GI tract and converts the visual information into electrical signals. These images are taken at regular intervals to ensure a complete view of the digestive system.

➢ Data Communication Module

The captured image signals are processed and converted into digital data. This module prepares the data for wireless transmission by encoding and formatting it properly. It makes sure data handling inside the capsule is reliable and efficient.

➢ UWB Antenna, Inside Capsule

The UWB antenna is a key part of the system. It sends the processed image data wirelessly from inside the body to the external receiver. The antenna is designed to be compact and provide a wide bandwidth. It maintains proper impedance matching with low return loss and ensures stable performance even in the lossy environment of human tissue.

➢ UWB Transmitter

The UWB transmitter modulates the processed data onto an ultra-wideband signal. UWB technology allows high data rate transmission with low power use and minimal interference. The transmitted signal carries high-resolution image information.

➢ External Receiver Unit

The external receiver unit is worn outside the patient's body. It picks up the UWB signal sent from the capsule. This unit has several sub-components:

➢ UWB Antenna:

Captures the transmitted signal.

➢ Low Noise Amplifier (LNA):

Boosts weak received signals while reducing noise.

➢ Recovered Data Module:

Processes and reconstructs the received image data.

➢ Real-Time Viewing Display, Recorder Unit

The recovered data goes to a display or recording unit. Doctors can view the captured images in real-time or save them for later analysis. This assists in diagnosing gastrointestinal disorders accurately.

4. System Architecture

4.1 Software Architecture

The High-Frequency Structure Simulator (HFSS) is used to design and analyze UWB antennas for wireless endoscopy applications. HFSS is a full-wave electromagnetic simulation tool based on the Finite Element Method (FEM). It delivers precise results for antenna parameters like return loss, VSWR, radiation pattern, gain, and SAR. Using HFSS allows for evaluating antenna performance in both free space and human tissue models. This software provides a detailed look at the antenna's behavior in a lossy biological environment. It is ideal for designing compact UWB antennas for in-body medical applications.

4.2 Capsule Endoscope Unit

The capsule endoscope is a small, swallowable device that moves through the gastrointestinal tract. It has a miniature camera for capturing images, illumination LEDs for lighting, a control and processing unit, a battery for power, and a compact UWB antenna. The UWB antenna transmits image data from inside the human body to an external receiver. Because of size limits, the antenna is designed to be compact while still providing wide bandwidth and stable radiation characteristics in the lossy body environment.

4.3 UWB Antenna Module

The UWB antenna is built into the capsule and works across a wide frequency range to support high-speed data transmission. The antenna provides omnidirectional radiation, ensuring reliable communication no matter how the capsule is positioned inside the body. Its performance is optimized for efficiency within human tissue while meeting safety standards.

4.4 External Receiver Unit

The external receiver unit is placed outside the patient's body. It includes a UWB receiving antenna, receiver circuitry, and a data processing system. This unit collects signals sent from the capsule, processes the received data, and reconstructs images for medical analysis.

4.5 Data Processing and Display

The received image data goes to a computer or monitoring system, where it is decoded, stored, and displayed for medical professionals. This allows for real-time or near real-time observation of the gastrointestinal tract.

4.6 Overall System Operation

When the capsule endoscope is swallowed, it continuously captures images and transmits them wirelessly through the UWB antenna. The external receiver collects the signals and forwards the data for processing and display. The use of UWB technology ensures low power consumption, a high data rate, and minimal interference. This makes the system suitable for wireless endoscopy applications.

4.7 HFSS Section

- Create a New Project

Open HFSS and start a new project. Right-click on the project and select Insert HFSS Design to begin a new 3D antenna design.

- Define Substrate Material

Choose a suitable substrate material, like FR4 or Rogers, from the HFSS material library. Set its thickness, dielectric constant, and loss tangent.

- Design Antenna Geometry

Use HFSS 3D modeling tools to create the antenna patch and ground plane. Add features like slots, stubs, or defected ground structures to improve UWB bandwidth. Make sure the dimensions fit the size constraints of capsule endoscopy.

- Assign Conductors and Boundaries

Set the patch and ground to Perfect Electric Conductor (PEC) or Copper. Apply a radiation boundary around the antenna to simulate free-space conditions.

- Assign Excitation

Place a lumped port or wave port at the antenna's feeding point. Set the port impedance to 50 Ω for proper matching.

- Set Solution Setup

Define the solution setup for frequency analysis. Set the operating frequency range based on UWB requirements, for example, 3 to 11 GHz. Enable frequency sweep for wideband analysis.

- Run Simulation

Click Analyze to run the HFSS simulation. HFSS calculates antenna parameters such as S-parameters, radiation pattern, and gain.

- Analyze Results

Check the return loss (S11) to make sure it is below –10 dB in the UWB band. Evaluate VSWR, gain, radiation pattern, and bandwidth. Look for any frequency shifts or performance issues.

➢ In-Body Simulation

Create a basic human tissue model (skin, fat, muscle) in HFSS. Place the antenna inside this tissue model. Analyze the frequency shift, radiation efficiency, and gain within the tissue environment.

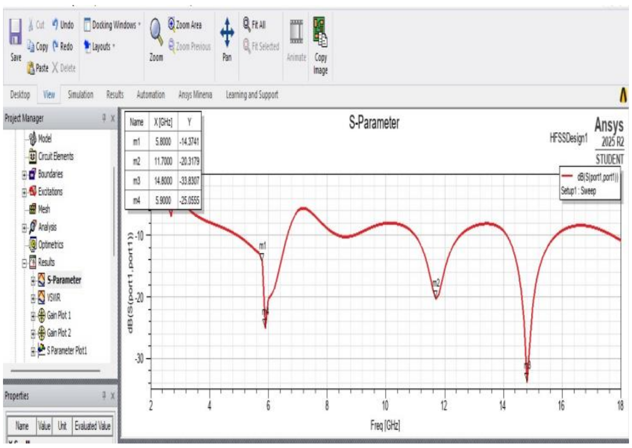
➢ Optimization

Adjust the antenna dimensions, shape, or substrate to enhance performance. Rerun the simulations until the antenna satisfies the UWB bandwidth, VSWR, gain, requirements.

5. Results and Discussion

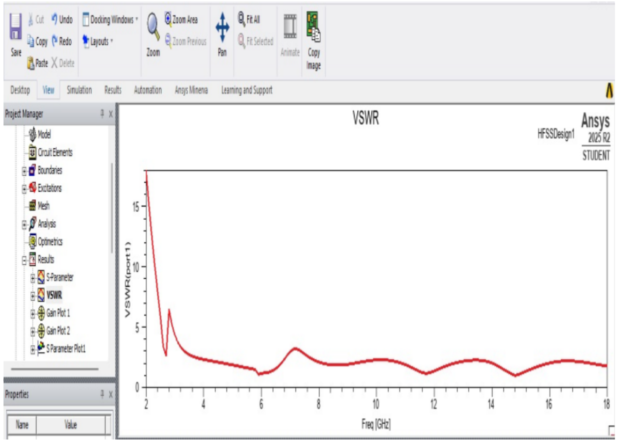
The proposed ultra-wideband (UWB) antenna was simulated using ANSYS HFSS. The key performance parameters—return loss (S11), VSWR, bandwidth, gain, radiation pattern evaluated.

5.1 Return Loss (S11) Analysis



Name	X[GHz]	Y
m1	5.8000	-14.3741
m2	11.7000	-20.3179
m3	14.8000	-33.8307
m4	5.9000	-25.0555

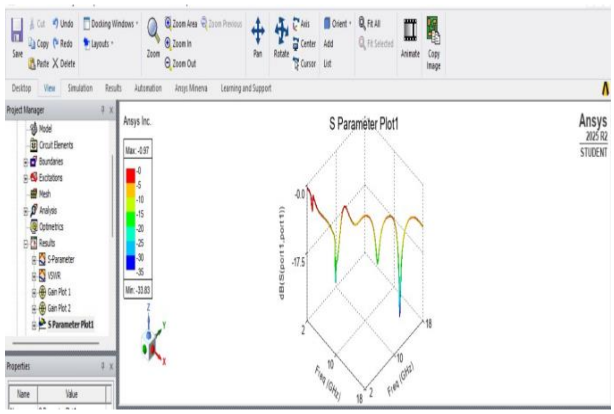
5.2 VSWR Analysis



The VSWR remains below 2 across the UWB frequency band, confirming good impedance matching.

VSWR slightly increases in the tissue model, but still remains within acceptable limits.

5.3 Gain Analysis



Gain is acceptable for short-range in-body communication.

Slight reduction in gain inside tissue is expected due to absorption losses.

5.5 Radiation Pattern

Free Space Radiation Pattern:

Nearly omnidirectional in the horizontal plane (H-plane), ensuring continuous communication regardless of capsule orientation.

Discussion

The antenna achieves wide bandwidth (3–11 GHz), suitable for high-data-rate wireless endoscopy.

Impedance matching and VSWR remain good both in free space and inside tissue.

Gain and radiation patterns are sufficient for reliable in-body communication.

6. Conclusion

The current work designed and analyzed a compact Ultra Wideband (UWB) antenna for wireless endoscopy applications. The focus was on achieving a wide impedance bandwidth, stable radiation patterns, low return loss, acceptable gain, and reliable VSWR performance. The simulated results show that the proposed antenna achieves a return loss below -10 dB across the ultra-wideband frequency range. This indicates efficient impedance matching and minimal signal reflection. The VSWR values stay close to one throughout the operating band, confirming stable power transfer between the antenna and the feeding network. Additionally, the gain characteristics are suitable for short-range in-body communication, ensuring reliable transmission of medical images and data from within the human body to an external receiver. The radiation pattern analysis reveals nearly omnidirectional characteristics, which is crucial for capsule-based endoscopic systems where antenna orientation cannot be controlled. These results confirm that the proposed antenna design meets the essential performance requirements for integration into compact wireless endoscopy capsules.

The significance of this work lies in its potential for non-invasive medical diagnostics, where compact and efficient antennas are vital for real-time internal imaging and patient monitoring. The antenna's compact size and wide bandwidth make it relevant for modern biomedical telemetry systems. However, some limitations remain, such as reliance on simulation-based validation and the need for further experimental verification in real biological environments to account for tissue absorption and detuning effects. Future work may focus on fabrication and practical measurements in phantom or in-vivo conditions, improving gain without increasing antenna size, and enhancing biocompatibility for safe long-term use. Overall, the proposed UWB antenna shows promising performance for wireless endoscopy applications and provides a solid foundation for further research and practical integration into medical devices.

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