An implantable loop antenna with Hilbert curve structures

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Abstract. In this work, an implantable loop antenna with Hilbert curve structures is proposed. This antenna uses Hilbert curves to achieve extremely small electrical dimensions. In addition, we use magnesium instead of copper in the antenna structure, as it is healthier than copper. The proposed antenna covers a frequency band ranging from 765 to 1143 MHz ($S_{11} < -10$ dB), a high efficiency (1.5%), and a maximum realized gain of -15.42 dBi. It is a promising candidate for implantable capsule antenna in medical devices.

1. Introduction

Powered by advanced medical wireless communication systems, implantable antennas attract increasing attention in recent years. Implantable antennas are designed for purposes: (1) monitoring information inside the body of a human or animal, such as stomach endoscopy, heartbeat monitoring, blood glucose level monitoring; (2) wireless power supply for implanted medical devices, such as cochlear implants, pacemakers; (3) locators for protecting animals or studying their behavioral patterns. The wireless transmission of data or energy, reducing the limitations of traditional equipment, has brought great convenience to today's medical treatment. As a key part of the wireless transmission system, implantable antennas become a popular area of research.

Implantable antennas mainly include capsule antennas [1-3] and plane antennas [4-5]. Due to the special application environment, implantable antennas have certain requirements for size and shape. To achieve miniaturization, miniaturized antenna structures such as PIFA (Planar Inverted-F Antennas), loop antennas [1], dielectric resonant antennas [2], spiral antennas [6], dielectric loaded antennas [7], and slit antennas [8] are widely used.

Copper is a commonly used material for metal structures in antennas due to its ductility, low cost and high electrical conductivity. However, according to the International Union for Nutritional Sciences (IUNS), the daily intake of copper for adults is 1.6 - 3 mg. While the daily intake of magnesium is 315-360 mg. Excessive intake of copper can cause liver toxicity and other symptoms. Magnesium, with its high daily intake and its ability to be dissolved and absorbed in the body, is a new alternative to metal materials for implantable antennas [9].
We propose an implantable loop antenna with Hilbert curve structures. Compared to the proposed implantable antenna, this design has the following advantages.

- The antenna achieves a very small electrical size by utilizing the Hilbert curve.
- The antenna achieves a large bandwidth, high gain and efficiency.
- The antenna design is made of magnesium, which can be absorbed by the human body and is non-toxic and non-hazardous.

2. Antenna Design and Analysis

2.1 Hilbert Curve

The Hilbert curve is a fractal pattern of space-filling curves [10] as shown in Figure 1. The plane space is subdivided into $4^n$ squares and the center of each square is connected by a curved line, “$n$” is the order of the curve.

A U-shaped structure of order 1 can be regarded as the smallest unit of the Hilbert curve. To get a Hilbert curve, we execute the following steps:

- Dividing the square equally into $4 \times 4$ small squares;
- Dividing 16 small squares the center line into 4 quadrants: top left, bottom left, top right, and bottom right;
- Plotting order 1 Hilbert curve in each quadrant, as shown in Figure 1(a);
- Keeping the curve of the top left and top right quadrants unchanged, rotate the curve in the bottom left quadrant 90 degrees clockwise and the curve in the bottom right quadrant 90 degrees counterclockwise;
- Connecting curves in four quadrants.

By analogy, Hilbert curves of order 3, order 4 and even higher can be obtained. Theoretically, Hilbert curves can fill the whole space in two, three, and even higher dimensions.

Interpreting a Hilbert curve in terms of a mapping, it can be seen as a mapping of the plane region $[0,1] \times [0,1]$ to the interval $[0,1]$. Taking the order 1 Hilbert curve as an example, using binary, the four small squares are coded as 0.00, 0.01, 0.10, 0.11. And each subsequent increment in order is increased by 2 binary decimal places. The first square (0.00) is subdivided into four squares: 0.0000, 0.0001, 0.0010, 0.0011. By continuously subdividing and encoding each point in the two-dimensional square space, a one-to-one mapping from the plane to the interval is accomplished.

The proposed antenna structure takes advantage of the fractals of the Hilbert curve to reduce the antenna size.

2.2 Antenna configuration

The antenna consists of three order 3 Hilbert curves in series, as shown in Figure 2. The antenna is carved from a 1 mm thick magnesium board with a total length of $D_1$ and a width of $H$. The distance
between each order 3 Hilbert curve is $D_2$ and the width of the curve is $D_3$. After bending, a circular antenna structure with a diameter of $D$ is formed. Therefore, the bent antenna is placed in a ball muscle tissue ($\varepsilon_r \approx 55$, $\sigma \approx 0.948$ at 915 MHz) with a radius of 50 mm.

By optimizing the parameters of the antenna, the optimum dimensions are: $D_1 = 27.5$ mm, $D_2 = 27.5$ mm, $D_3 = 1$ mm, $D = 11$ mm, and $H = 8.5$ mm.

3. Simulation Results and Discussions
The simulation results for the reflection coefficient ($S_{11}$), total efficiency, and gain of the antenna inside the muscle tissue are given in Figure 3. It can be seen that the antenna has a bandwidth of 765 - 1143 MHz ($S_{11} < -10$ dB) and can cover the ISM band (902 - 928 MHz) for medical implants. 41.3% relative bandwidth ensures that the antenna can operate even when the environment changes or processing errors occur. The efficiency of the antenna in the operating band is 1 - 1.6%. The maximum gain of the antenna is -15.42 dBi. Figure 3(d) shows an omnidirectional pattern of this antenna.
To calculate the antenna SAR values, the antenna is placed in spherical muscle tissue with a radius of 50 mm in the simulation, using the standard IEEE/IEC 62704-1 and an input power of 1 W. The simulation SAR results for the antenna SAR values at 915 MHz for an average mass of 1 g and 10 g are shown in Figure 4. From the figure, we can see that the highest SAR values of the antenna are 216 W/kg and 61.8 W/kg respectively.

![Simulation results of the proposed antenna structure: (a) Reflection coefficient; (b) Total efficiency; (c) Realized gain; (d) Radiation pattern at 915 MHz.](image)

![Simulation SAR of the proposed antenna structure.](image)

| Ref     | Relative bandwidth (%) | Size (mm³) | Gain (dBi) | Efficiency (%) |
|---------|------------------------|------------|------------|----------------|
| [11]    | 8.9                    | Ø10 × 5.8  | -21.0      | \              |
| [12]    | 13.0                   | Ø10 × 15   | -24.9      | 0.1            |
| [13]    | 19.0                   | Ø11 × 22   | -22.1      | 0.3            |
| This design | **41.3**              | Ø11 × 9.5  | **-15.4**  | **1.6**        |
Furthermore, the comparison between the related antennas and this design is also given, as shown in Table 1. It is obvious that the performance of this design offers considerable advantages.

4. Conclusion
This paper proposes a broadband, high gain, high efficiency implantable loop antenna with Hilbert curves. The antenna design uses magnesium that is harmless and can be dissolved in the body, making it suitable for implantable medical applications.

Simulation results show that the antenna can work in the ISM band with a bandwidth of 765 - 1143 MHz and cope with the environmental changes that may occur during the implantation process. The antenna gain in the operating band is -15.42 dBi and the efficiency is greater than 1.2 %. Simulation results of the antenna in the muscle tissue model indicate that the design is suitable for implantable antenna applications.

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