A Wideband Ultra-Thin Loop-Fed Patch Antenna for Head Implants

Terence S. P. See, Xianming Qing, Wei Liu, Zhi Ning Chen

Abstract—A loop-fed patch antenna that is suitable for head implants is designed at 4 GHz. With a the proposed feeding structure, the ultra-thin antenna features a wide impedance bandwidth and directional radiation pattern in order to maximize the transmission with the receiver and reduce the specific absorption rate (SAR). An antenna prototype with an overall size of $24 \times 10 \times 0.95 \text{mm}^3$ exhibits reflection co-efficient of less than -10 dB, directivity of more than 5 dBi, boresight gain of more than -8 dBi, and low SAR of less than 53 W/kg across the frequency band of 4.1–4.5 GHz.

Index Terms—Differential antenna; patch antenna; head implants; telemetry; specific absorption rate (SAR); ultra-wideband.

I. INTRODUCTION

With the increase in demand for implantable medical devices for diagnostic and therapeutic functions [1–3], the wires that are connected to these devices may come into contact with the skin, which results in patient discomfort and increase the risk of infection. Therefore, the wireless communication for implantable devices has drawn attention from academia and industry as it possesses several advantages, such as minimizing restrictions in daily activities, providing the possibility of remote control and monitoring, and facilitating less invasive surgical procedures [4–5]. As inductive biotelemetry faces the constraints of limited communication range and sensitivity to inter-coil misalignment [6], the antenna-enabled biotelemetry is preferred. However, as these medical devices are used within or at close proximity to the human body, the associated electromagnetic effects due to the interaction between the RF signals and human tissues have led to various regulatory bodies imposing maximum limits for the specific absorption rate (SAR), which determines the amount of RF energy that is absorbed by the human tissues.

The antenna design for head implants is extremely challenging as the small form factor is required, even at low operating frequencies. Moreover, due to the lossy, inhomogeneous, and dispersive surrounding tissues, the impedance matching is often affected. Hence, the antenna needs to be co-designed with its surrounding tissues and bio-compatible casing in order to achieve the optimum efficiency. Moreover, in order to reduce the SAR and enhance the transmission with the external receiver, an antenna with directional radiation is preferred. Another important design consideration is the integration of the antenna with an RF transceiver that is in the form of integrated circuits (IC). It will not be economically viable to fully integrate the antenna on the MMIC semiconductor substrates because of the large estate required by the antennas, especially at low frequencies.

Circular and square stacked planar inverted-F antennas (PIFA) have been proposed for skin implantation and biotelemetry [7–8]. A wide-slot antenna design with a broad impedance bandwidth is also presented for biomedical implants. A spiral antenna with broad bandwidth, bi-directional radiation and circular polarization is also proposed for neuroprosthetic implantable devices [9]. Microstrip patch antennas configurations including spirals and serpentine lines have also been reported [1–2, 7–8, 10–11]. Wideband monopole and dipole antennas for implantable neural recording systems have also been analyzed [12]. However, all these antenna designs have single-ended inputs which are not desirable for the integration with ICs, wherein differential design is commonly applied for high immunity to crosstalk and noise. Adding the balun between the antenna and the IC will result in circuit loss, complicate the system design, and enlarge the size of the implant. Differential antenna designs such as the loop and dipole with omni-directional radiation characteristics are popular candidates for implantation inside the human head but they suffer from the narrow impedance bandwidth [1, 11]. Typically, the differential feeding can be achieved with a pair of open-ended microstrip lines or feeding probes that are excited out-of-phase with respect to each other [13–16].

In this paper, a broadband and ultra-thin loop-fed patch antenna for head implants is proposed. The wide bandwidth can be achieved by utilizing an aperture feeding structure comprising a pair of parallel microstrip lines that is shorted at one end and placed beneath the radiating patches. Together with the presence of the ground plane, the higher directivity and a lower SAR inside the head can be achieved.

II. ANTENNA DESIGN

The antenna design is shown in Fig. 1. It is fabricated on a Ferro A6M ($\varepsilon_r = 5.9, \tan\delta = 0.002$) substrate that is composed of 10 layers implemented using low temperature co-fired ceramics (LTCC) technology. The thickness of each layer is 0.095 mm. The patches are printed on the top layer and each patch measures $9 \times 8 \text{mm}^2$. The size of the substrate and the ground plane is $24 \times 10 \text{mm}^2$. The overall thickness of the antenna is 0.95 mm or 0.03$\lambda_e$, which is ultra-thin. The loop-fed structure is positioned one layer beneath the patches. The width of the microstrip lines is 0.77 mm and the gap between them is 0.7 mm, which provides a differential impedance of about 100$\Omega$. In order to achieve the required impedance matching, the length, width, and separation of the microstrip line beneath the patches are 6.2 mm, 0.9 mm, and 0.35 mm, respectively. The ends of the microstrip lines are shorted to provide the aperture coupling, which broadens the impedance bandwidth. For measurement convenience, a cavity with size...
of 2.2 × 2 × 0.095 mm³ was constructed so that the feed lines are exposed to be soldered to the coaxial cable.

In order to isolate the antenna from the tissue, a casing is required to be constructed to house the antenna. The antenna casing is made of teflon (εᵣ = 2.1, tanδ = 0.0002), which is bio-compatible with the tissues. The thickness of the wall of the casing is 2 mm.

III. SIMULATION MODEL

Since the antenna performance is highly dependent on the presence of the lossy and dispersive tissues around it, it is important to take this issue into account and co-design the antenna with the casing and the surrounding tissues. As shown in Fig. 2, the head is modeled as a three-layered homogeneous structure comprising skin, tendon, and cortical bone. The overall size of the tissues is 125 × 87 × 12.5 mm³, which is based on the size of the top of the head. The top of the casing is 2 mm below the surface of the skin and there is an air gap of 0.5 mm above the antenna. Table I tabulates the thickness and properties (relative permittivity, conductivity, and density) of the tissues at 4 GHz [17], where the properties of the tissues are consistent with those at the top of the head. The antenna was modeled and simulated using the CST Microwave Studio software.

IV. MEASUREMENT SETUP & RESULTS

The measurement was performed using a pair of semi-rigid co-axial cables with the outer conductor soldered together and the inner conductors connected to the microstrip lines as shown in Fig. 3(a) [18–19].

As shown in Fig. 3(b), the antenna that is fully enclosed with the casing is lowered into the liquid, which emulates the skin tissue. Using the Agilent 85070D dielectric probe kit, the measured relative permittivity and loss tangent of the liquid at 4 GHz is 36.6 and 0.6, respectively. The numerical value of the skin tissue obtained from the HUGO model is 36.587 and 0.3 at 4 GHz.

With the differential impedance referenced to 100Ω, the simulated and measured reflection coefficients are shown in Fig. 4. The simulated bandwidth of the antenna for -10 dB reflection coefficient is about 3.76–4.22 GHz while the measured bandwidth is about 4.1–4.5 GHz. The slight upward frequency shift is mainly due to the fabrication tolerance. The average thickness of the fabricated samples is about 0.935 mm, which is slightly smaller than the simulated thickness of
0.95 mm. The measured values in the x and y-directions are generally about 0.7% lower than the design value.

The measured values in the x and y-directions are generally about 0.7% lower than the design value.

---

**Fig. 4.** Reflection coefficient of the antenna.

The HUGO model is used in the characterization of the radiation performance of the antenna. Fig. 5 shows the simulated E-field distribution of the patch antenna at 4 GHz. The simulated radiation pattern of the antenna is shown in Fig. 6, which can be seen that the main radiation is directed outwards from the head. This is desirable in order to increase the signal transmission between the head implant and the external receiver.

---

**Fig. 5.** E-field distribution at 4 GHz.

**Fig. 6.** Radiation pattern of the antenna implanted inside the head at 4 GHz.

---

**V. PARAMETRIC STUDIES**

In order to understand the effects of the microstrip line on the impedance matching, the length ($l_m$) and width ($w_m$) of the microstrip line beneath the radiators, and the gap between the microstrip lines ($g_m$) are varied. As shown in Fig. 9, it can be seen that as the length decreases, the resonant frequency is increased and the matching is improved. On the other hand, the matching is deteriorated with a corresponding increase in the resonant frequency when the width is reduced. When the gap between microstrip lines is increased, the resonant frequency is decreased and the impedance matching is

---

**Fig. 7.** Directivity and gain at boresight of antenna implanted inside the head.

**Fig. 8.** Peak SAR (1-g average) and maximum input power.
improved. From this study, it can be seen that the impedance matching can be optimized by adjusting the parameters of the microstrip line.

more than -8 dBi have been obtained when the antenna was implanted inside the head. Due to the directional radiation property of the antenna, a lower SAR of less than 53 W/kg was achieved. The antenna can be used in head implants for various applications such as bio-telemetry, deep brain stimulation, monitoring, and neural prostheses.

VI. CONCLUSIONS

In this paper, a wideband and ultra-thin loop-fed patch antenna has been presented. The measured results have shown that a wide impedance bandwidth of about 20% has been achieved with the proposed feeding structure. From the simulations, the directivity of more than 5 dBi and gain of

REFERENCES


