Multilayer Ultra-Miniature Loop Antenna for Insertable Pill Application

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***Abstract*— An ultra-miniaturized multilayer loop antenna for insertable pill applications is presented. The antenna is designed for the Medical Device Radiocommunications service (MedRadio 401–406 MHz) and makes use of the three metal layers of the antenna board to increase its electrical length within a compact size of 16.2 mm^2 (3.3 × 4.9 mm). The realized gain is –38.3 dBi in ⌀10-cm muscle-equivalent spherical phantom, and the radiation efficiency reaches 0.06%. Antenna adaptation to manufacturing (extra Rogers 2929® substrate layer and vias diameter increased) resulted in an efficiency of 0.05%. Finally, different approaches are discussed to increase the antenna efficiency while keeping the space constraint unchanged.**

***Index Terms*— insertable antennas, miniature antenna, biotelemetry, in-body wireless communication, MedRadio**

I. INTRODUCTION

Wireless capsule endoscopy is a technology used clinically for diagnosis and assistance with treatment decisions [1]–[2]. The insertable pills use wireless radio frequency (RF) links to transmit bio-signals from inside the human body to an external receiver over a link distance of a few meters.

The design of the capsule antenna plays a major role in building up this communication link. However, the losses and strong heterogeneity of the human body degrades the antenna radiation efficiency and affects the pattern, which makes the antenna design very challenging. Miniaturization is also a great challenge to be addressed for electronic devices insertable in the human body. The insertable antenna has to be small in size and operate at a relatively low frequency MedRadio 401–406 MHz. For the current antenna application in this paper, the space allocated to the antenna does not exceed 16.2 mm^2 (3.3 × 4.9 mm).

According to the layout of the antenna in a capsule, we can divide the capsule antennas in two major types, namely, planar [3] and conformal structures [4]. The conformal structures can make full use of the capsule space and adhere to the inner/outer surface of a capsule shell, which minimizes the antenna footprint in the capsule. However, integrating the conformal antenna in a multi-component capsule can be very challenging and requires additional modifications that affect other capsule electronics. Various types of planar and conformal designs have been introduced recently [4].

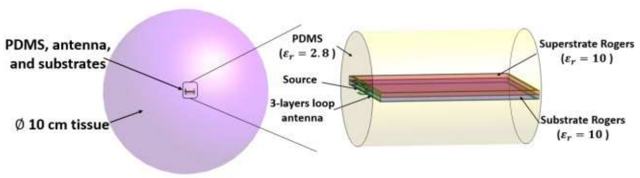

Fig. 1: Numerical model of the three-layer loop antenna inside the PDMS (filling material) and the tissue model.

However, none of the proposed designs fits the space constraint of 3.3 × 4.9 mm at MedRadio bandwidth (401–406 MHz). Considering the space constraint and the frequency, loop antennas, due to their predominantly magnetic near field, may provide higher in-body efficiencies than dipoles, monopoles, or patch antennas [6].

Here, we introduce a multilayer loop antenna suitable for insertable pill applications. The designed antenna has ultra-miniature dimensions with enhanced efficiency (considering the frequency of 401–406 MHz and the space constraint). The remainder of this paper is organized as follows. Section II gives an overview of the simulation platform and the numerical model with definition of the application constraints. Section III presents the three layers loop antenna and shows the antenna performances. Section IV shows the design adaptation to manufacturing and feeding solutions. Finally, Section V discusses different strategies to increase the antenna efficiency while keeping the space constraint unchanged.

II. SIMULATION PLATFORM AND NUMERICAL MODEL

Full wave numerical simulations have been used to design and investigate the multilayer loop antenna. We used two simulation platforms: Sim4Life (finite-difference time-domain: FDTD) [7] and Feko (method of moments: MoM) [8]. The numerical model is shown in Fig. 1. The body tissue was modeled by a homogeneous spherical phantom with a diameter of ⌀10 cm as proposed in [4, 9]. Its dielectric properties are those of the muscle at 401–406 MHz (ε_r = 57.1, σ = 0.796 S/m). The substrate and the superstrate (5 × 3.5 × 0.127 mm) have the electromagnetic properties of the Rogers

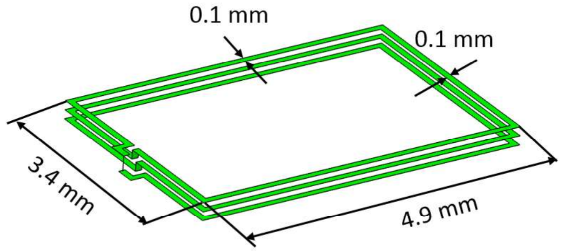

Fig. 2: Dimensions of the three-layer loop antenna model.

6010 DK10® (ε_r = 10, tan δ = 0.002). The antenna along with substrate/superstrate are encapsulated inside a polydimethylsiloxane (PDMS) filling material modeled as a cylinder of 5 × ⌀3.5 mm having the relative permittivity of 2.8. FDTD solver used hardware acceleration (NVIDIA) reducing significantly the simulation time to less than 3 hours per simulation.

III. Three-Layer Loop Antenna Design

Considering the presented constraints, the optimal choice was to design a loop antenna (magnetic antenna) and increase its electrical length. Meandering the loop antenna resulted in efficiency losses due to formation of canceling currents. Thus, we opted for a multilayers loop antenna for enhanced efficiency. The three-layer loop antenna design is shown in Fig. 2. The metallization layers of the antenna (3.3 × 4.9 × 0.254 mm, Fig. 2) were modeled as a perfect electric conductor (PEC) with a strip width of 0.1 mm.

First, we validated the antenna design using two different simulation platforms. Fig. 3 shows the input impedance of the three-layer loop antenna in Feko and Sim4Life. The results are in good agreement between the two numerical methods (FDTD and MoM) with a maximum relative variation of 3.2 % in the 390–410 MHz range.

We matched the antenna at 400 MHz and bandwidth of 4 MHz (50 Ω) using LC matching circuit with the following values: L = 26.88 nH and C = 4.6 pF). Fig. 4 shows the antenna performance in terms of the reflection coefficient $|S_{11}|$. The realized gain is G = –38.3 dBi in muscle-equivalent spherical phantom of ⌀10 cm, and the radiation efficiency reaches 0.06%.

IV. Design Adaptation to Manufacturing and Feeding Solution

Two main adaptations needed to be applied in order to fit the antenna design to fabrication constraints. First, the via of 0.1 mm in Fig. 2 has to be changed to a 0.2-mm round via hole with a 0.4-mm round pad. Second, an extra Rogers 2929® layer (ε_r = 2.94 ± 0.05) of 50 µm is needed to be added as a film adhesive system to glue the two Rogers 6010 DK10® layers. The adapted antenna design is shown in Fig. 5. A co-planar wave-guide is used to feed the antenna using the space of 3.5 × 5 mm. The trace width is 0.5 mm with a ground plane spacing of 0.3 mm. Design adaptation resulted in a reduced efficiency of 0.05% (instead of 0.06% for the initial design).

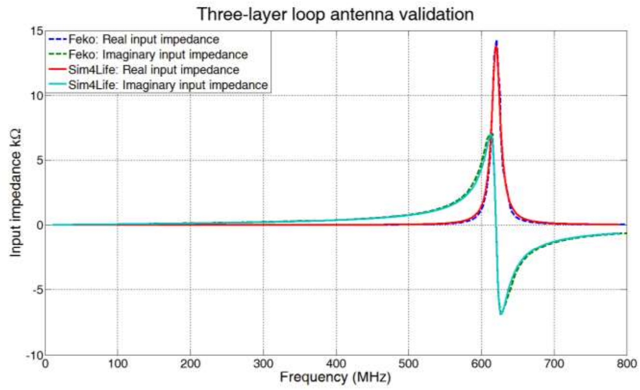

Fig. 3: Input impedance of the three-layer loop antenna simulated in FEKO and Sim4Life without matching circuit

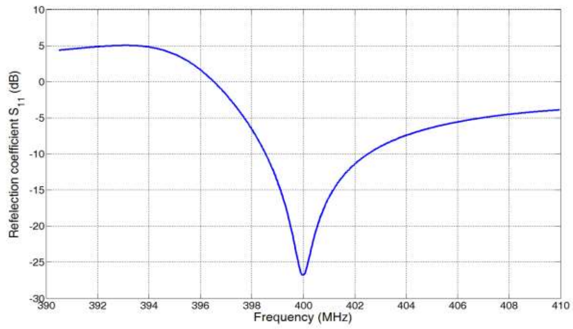

Fig. 4: Reflection coefficient of the three-layer loop antenna. Resonance frequency of 400 MHz and -10 dB bandwidth of 4 MHz.

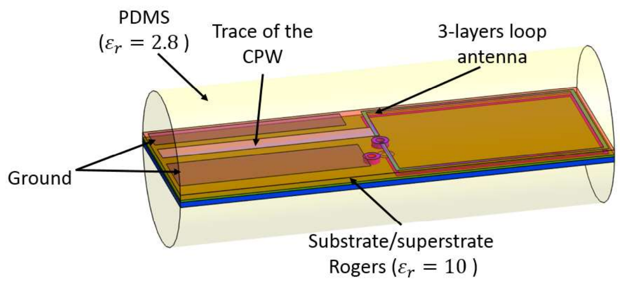

Fig. 5: Adapted model of the three layers loop antenna showing the 0.2-mm vias and the extra 50 µm Rogers 2929® layer.The CPW is used in the 5 × ⌀3.5 mm

V. Discussion and Conclusion

A three-layer loop antenna for insertable pill application was designed and adapted for manufacturing. The antenna has ultra-miniature dimensions and a radiation efficiency of 0.05%. The antenna is in the manufacturing process and the experimental characterization results will be presented at the conference.

Taking into account the insertable pill size antenna constraints (3.5 × 5 mm) discussed in Section II, and considering the operating frequency of 403 MHz and the bandwidth of 6 MHz, we deal with electrically small antenna (ESA) limitations as $ka < 0.5$, where k is the wavenumber and $a \approx 3$ mm is the antenna circumradius [4]. Considering a cylindrical capsule filled with PDMS (ε_r = 2.8), an implantation depth of 5 cm (a homogeneous spherical phantom with a diameter of ⌀10 cm), a frequency of 401 MHz, and a 0.5-mm- thick capsule shell, Nikolayev *et al.* [9] showed that the fundamental bounds on efficiency are $\eta_{TE} \approx 0.3$ % and $\eta_{TE} < 0.01$ % for ideal magnetic and electric antennas, respectively. These results assume no material losses, no feed and mismatch losses, optimal current distributions, and optimal usage of the available space [9]. The antenna designed in this paper can be optimized using different approaches. First, filling the in-body capsule with high-permittivity material instead of the PDMS improves the maximum achievable radiation efficiency. Nikolayev *et al.* [4] used the pure water, with high permittivity (ε_r = 78.4) at 434 MHz. Solid high-permittivity (and low loss) materials can be used for the industrial implementation (ceramic-powder loaded polymer [10] or epoxy [11]). Second, the use of a biocompatible encapsulation may help decouple the antenna from the surrounding tissue and can facilitates the antenna matching without using the LC circuit [4]. A good candidate material is Al_2O_3 (ε_r = 9.9, tan δ = 0.0001) [12] as practically lossless, biocompatible, and widely available commercially in various shapes and sizes. Future work includes the antenna manufacturing and radiation performance measurements to validate the numerical model.

References

[1] G. Iddan, G. Meron, A. Glukhovsky, and P. Swain, “Wireless capsule endoscopy,” *Nature*, vol. 405, no. 6785, pp. 417–418, May 2000.

[2] G. Ciuti, A. Menciassi, and P. Dario, “Capsule endoscopy: From currentachievements to open challenges,” *IEEE Rev. Biomed. Eng.*, vol. 4, pp. 59–72, 2011.

[3] L. Xu, Y. Guo and W. Wu, "Miniaturized dual-band antenna for implantable wireless communications," IEEE Antenn. Wireless Propag. Lett., vol. 13, pp. 1160–1163, 2014.

[4] D. Nikolayev, M. Zhadobov, L. Le Coq, P. Karban and R. Sauleau, "Robust ultra-miniature capsule antenna for ingestible and implantable applications," IEEE Trans.Antennas Propag., vol. 65, no. 11, pp. 6107-6119, Nov. 2017.

[5] D. Nikolayev et al., “Antennas for ingestible capsule telemetry,” in Advances in Body-Centric Wireless Communication: Applications and State-of-the-Art, London, UK: IET, 2016, pp. 143–186.

[6] D. Nikolayev, M. Zhadobov, P. Karban and R. Sauleau, "Conformal antennas for miniature in-body devices: The quest to improve radiation performance," URSI Rad. Sci. Bull., vol. 2017, no. 363, pp. 52–64, Dec. 2017.

[7] Sim4Life, Zurich Med Tech. www.zurichmedtech.com/sim-4life/. Visited on October 2019.

[8] FEKO, Altair, https://altairhyperworks.com/product/FEKO. Visited on October 2019.

[9] D. Nikolayev, W. Joseph, M. Zhadobov, R. Sauleau, and L. Martens, “Optimal radiation of body-implanted capsules,” Phys. Rev. Lett., vol. 122, no. 10, p. 108101, Mar. 2019.

[10] S. Koulouridis et al., “Polymer–ceramic composites for microwave applications: Fabrication and performance assessment,” IEEE Trans. Microw. Theory Tech., vol. 54, no. 12, pp. 4202–4208, Dec. 2006.

[11] S. Lee *et al.*, “A study on dielectric constants of epoxy/$SrTiO_3$ composite for embedded capacitor films (ECFs),” *IEEE Trans. Adv. Packag.*,vol. 30 no. 3, pp. 428–433, Aug. 2007.

[12] F. Merli *et al.*, “Design, realization and measurements of a miniature antenna for implantable wireless communication systems,” *IEEE Trans. Antennas Propag.*, vol. 59, no. 10, pp. 3544–3555, Oct. 2011.