Wireless Control of Bacterial Function with Microwave Hyperthermia

(Invited Paper)

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***Abstract*—This study presents a bio-hybrid implant comprising a passive microwave resonator and a colony of engineered *E. coli* that express proteins in response to thermal stimuli. We propose a novel method for wireless control of the genetically modified bacteria using microwave hyperthermia. Synthetic biology has enabled cell-based sensing and actuation; however, the lack of viable wireless communication mechanisms with those cells limits their usage inside the human body. Direct electromagnetic interaction with individual cells would require terahertz and beyond frequencies, which are impractical for in-body use due to high tissue absorption. Instead, we introduce a wireless control strategy based on focused microwave hyperthermia, delivered via an on-body antenna operating between 0.782 GHz and 1.938 GHz. Cellular activation is achieved by localized heating at the implant site, created by the passive resonator. Preliminary results demonstrate that the system can achieve a localized temperature increase of more than 6°C in 5 minutes with 1 W transmit power to activate heat-sensitive genetic circuits, thus establishing a proof-of-concept for wireless thermal control of biological function.**

***Index Terms*—Implantable antennas, bio-hybrid implants, microwave hyperthermia, genetically modified bacteria, implant communications.**

I. Introduction

Implantable electronics have advanced considerably over the past decade, supporting continuous in vivo sensing and actuation through wireless connectivity with external systems. However, most platforms follow a conventional architecture comprising distinct sensing, processing, power, and communication units. These components pose challenges for implantation due to their size, power demands, and potential cytotoxicity. Biocompatibility is typically achieved through inert encapsulation layers, which offer limited long-term safety [1]. Such constraints restrict their applicability in prolonged implantation scenarios.

The authors have been advancing an alternative paradigm to conventional implantable systems by utilizing genetically modified cells for biosensing applications [2]. Building on previous studies involving bio-hybrid implants with molecular-scale sensing capabilities [3], [4], the present work shifts focus toward enabling wireless downlink functionality within similar architectures. We introduce a bio-hybrid implant consisting of genetically engineered E. coli and a passive microwave resonator. Wireless actuation is achieved via an external on-body antenna, eliminating the need for internal active electronics or batteries. The overarching goal is to establish wireless control of protein expression within the body, thereby enabling programmable biological responses. This wireless modulation of bacterial activity offers significant potential for applications such as targeted therapy and drug delivery. As a proof-of-concept, E. coli may be engineered to express glucagon-like peptide-1, offering a biologically integrated approach to reducing insulin dependency.

While synthetic biology allows precise programming of cellular behavior, current wireless control methods lack sufficient penetration for deep-tissue applications. A direct electromagnetic interface with individual cells inside the human body is fundamentally constrained by scale. Direct interaction requires wavelengths comparable to cellular dimensions, necessitating terahertz and beyond frequencies [5]. However, human tissues exhibit high dielectric loss at these frequencies due to their dielectric properties. At 1 GHz, human tissue exhibits permittivity values from 3.5 to 68 and conductivity up to 2.5 S/m. Since conductivity increases with frequency, propagation loss becomes more severe at higher bands, effectively limiting in-body communication to sub-6 GHz frequencies [6]. As a result, in-body wireless communication is practically limited to sub-6 GHz microwave frequencies, which lack the spatial resolution needed for direct cell-level interaction. The proposed system addresses this gap by enabling thermally triggered biological responses.

Conventional thermal therapies primarily target bulk tissue [7]. Previous work has demonstrated various implementations of noninvasive microwave hyperthermia with the common objective of focusing electromagnetic energy on a specific region while avoiding damage to surrounding tissues [8]. Multi-element antenna arrays have been used to target brain tumors, achieving localized heating up to 45°C in both simulations and phantom experiments [9]. Similarly, studies focusing on breast cancer demonstrated that the application of microwave power through focused arrays can increase tumor temperature to 42°C while maintaining healthy tissue at safe levels, typically around 36°C [10]. To improve precision and efficiency, wideband antenna configurations have been introduced, offering broader frequency operation and better focusing performance compared to narrowband systems [11]. More recent work incorporates metasurface structures to enhance field localization in deep tissues, enabling more compact and power-efficient hyperthermia systems [12], [13]. In parallel, electromagnetic fields have also been explored for wireless power transfer (WPT) and communication with implantable systems. Techniques involving conformal antennas, metasurfaces and phased textile-integrated surfaces have shown improved coupling efficiency and deeper energy delivery for implantable systems [14]–[16]. But the utilization of a passive implant resonator for focused microwave hyperthermia has never been proposed in the literature to the best of our knowledge. This is partly due to the fact that superficial hyperthermia, under normal conditions, is a non-invasive procedure. Therefore, thermal focusing with an implant resonator has never been explored.

Here, through a passive resonator, electromagnetic waves are concentrated at the target region, enabling localized temperature elevation at the location of the genetically modified bacteria. This configuration ensures that the temperature increase in the surrounding tissues remains below the safe limit of 43°C during the procedure, while the target temperature is reached at the bio-hybrid implant, as the conductive resonator heats up faster than the surrounding non-conductive medium. This paper demonstrates that a localized temperature increase of more than 6°C can be achieved under 1 Watt input power, sufficient to activate heat-sensitive protein expression.

Section II introduces the bio-hybrid implant and the thermal actuation mechanism of genetically modified bacteria. Section III presents the design of the implant resonator. Section IV focuses on the development of the on-body antenna system optimized for propagation into human body towards the implant. Section V details the wireless communication framework based on microwave hyperthermia. Finally, the conclusion and future prospects are discussed in Section VI.

II. Bio-hybrid Implant

The bio-hybrid implant is a combination of a passive implant resonator and a colony of genetically modified bacteria trapped in a porous membrane together with the resonator as seen in Fig. 1. The overall structure is in the form of a rectangular prism with a 1 mm by 1 mm square cross section which is suitable for minimally invasive insertion.

A. Implant Resonator Design

The implant incorporates a split-ring resonator, which enhances microwave absorption within the bio-hybrid implant. It is designed on an alumina substrate and covered with an interstitial tissue layer representing the genetically modified bacteria, as shown in Fig. 1. The interstitial tissue is modeled using the dielectric properties of extracellular fluid [21]. The overall size of the implant measures 8.5 mm × 1.0 mm × 1.0 mm, containing ring structure with 0.2 mm conductor and 0.2 mm spacing.

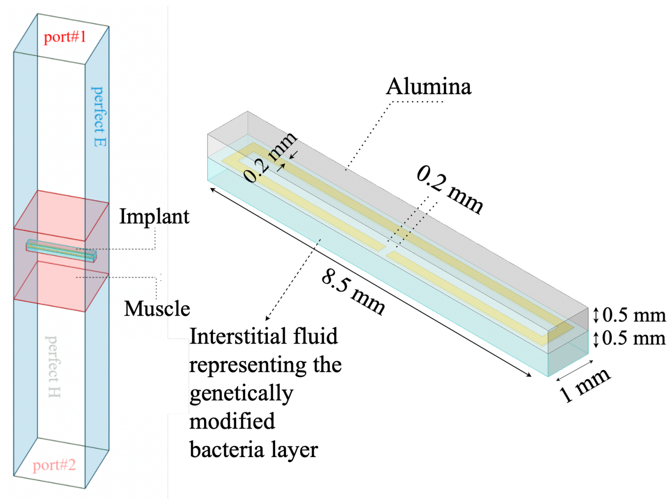

Fig. 1. Simulation model to determine the resonant frequency of the implant (left), Schematic of the embedded split ring resonator integrated into the bio-hybrid implant (right).

The implant is simulated inside a waveguide, as shown in Fig. 1. The conductivity values of muscle tissue and interstitial fluid are set to zero to clearly observe the resonant behavior. As illustrated in Fig. 2, the resonator exhibits a resonant frequency of 1.65 GHz.

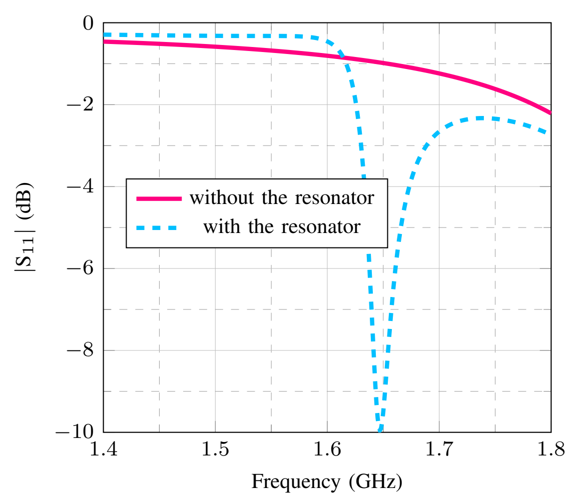

Fig. 2. Comparison of the reflection coefficient of the wavegeuide in the presence and absence of the resonator.

B. Thermally Actuation of Genetically Modified Bacteria

In this study, genetically modified *Escherichia coli* strains engineered to express superfolder green fluorescent protein (sfGFP) in response to elevated temperatures are envisaged to be used. The genetic construct includes a heat-inducible promoter derived from bacterial heat shock response (HSR) elements [17], regulated through a transcriptional repressor system. Under normal growth conditions, a constitutively expressed repressor binds to the operator region of the promoter, inhibiting transcription. Upon thermal stimulation exceeding the threshold (typically around 42 °C), the repressor dissociates, allowing RNA polymerase access and triggering gene expression [18]. This mechanism enables the construction of sharp thermal switches, and the design was implemented to link internal or external heat signals with programmable protein production [19].

This approach enables the development of sharp thermal switches, offering high specificity and reversibility in gene activation. Genetic circuits utilizing this logic have been widely applied in bacteria and phage-derived systems for precise control over protein production. By adjusting the promoter-repressor dynamics and the activation temperature, it becomes possible to fine-tune the system to match specific application needs, including therapeutic protein release and metabolic pathway control.

Thermal actuation provides a non-invasive and reversible means of regulating gene expression in engineered biological systems. Compared to conventional molecular stimulation techniques such as chemical inducers or optogenetics, thermal control offers superior tissue penetration and spatial selectivity, making it highly suitable for in vivo applications [20].

III. On-body Antenna Design

A microstrip-fed wide slot antenna is designed to operate on muscle tissue for superficial hyperthermia application using *HFSS, ANSYS Electronics Desktop* [22], as seen in Fig. 3. The antenna is optimized to maximize propagation into the tissue. A magnetic antenna configuration is selected due to its favorable radiation characteristics near lossy biological media at sub 2 GHz frequency bands [23]. A high permittivity substrate and superstrate are used to minimize reflection at the air body boundary [24]. The high permittivity superstrate also serves as a controlled, low-loss medium that shrinks the near field. This minimizes the near field losses within the lossy human tissues [25].

The on-body antenna is placed on a muscle phantom in which the bio-hybrid implant is located at a depth of 1 cm as seen in Fig. 4. Fig. 5 presents the return loss of the antenna with and without the presence of the bio-hybrid implant. It can be seen that the antenna operates aprox. between 1 GHz and 2 GHz. Wide band operation is critical for cases where the bio-hybrid implant undergoes detuning due to tissue variability. The on-body antenna can transmit at the resonant frequency of the implant resonator. It is worth noting that the resonant frequency of the implant resonator is also visible in the return loss graph of the on-body antenna since the implant is located in its nearfield.

IV. Communication through Microwave Hyperthermia

In order to wirelessly control the bacterial function the on-body antenna should be able to increase the temperature of the bacteria above 42°C while keeping the temperature of the surrounding tissues below safe limits.

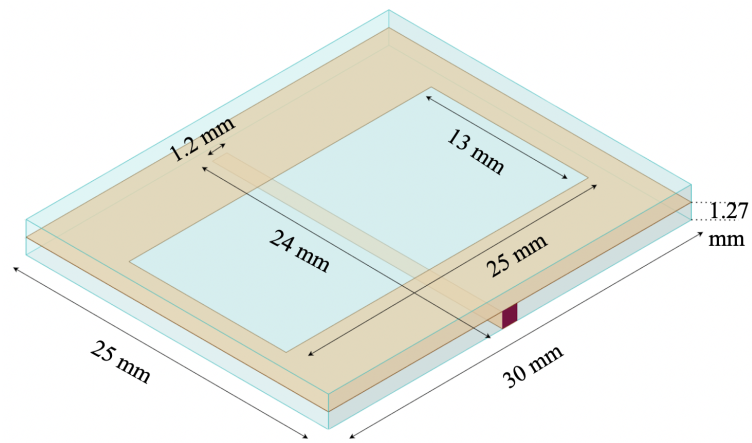

Fig. 3. The on-body slot antenna used to deliver focused microwave energy to the implant. The overall antenna measures 30 mm × 25 mm with a substrate thickness of 1.27 mm and a superstrate layer of 1.2 mm. The rectangular slot at the center is 24 mm × 13 mm with a strip feed offset by 1.2 mm from the slot edge.

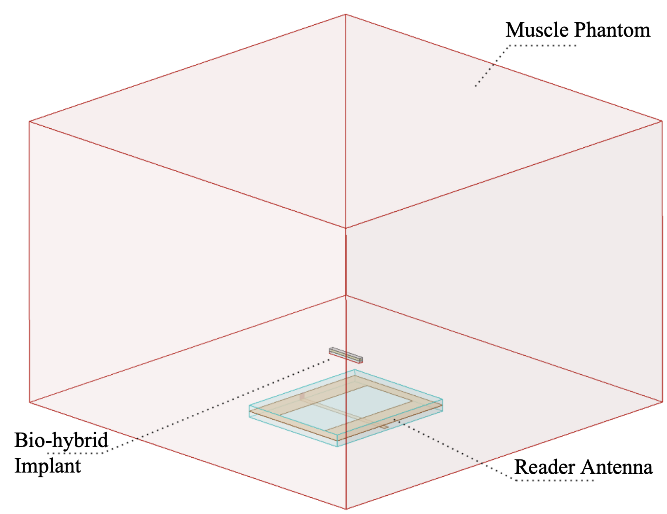

Fig. 4. System-level simulation setup showing the on-body reader antenna placed above the bio-hybrid implant within a muscle-mimicking phantom. The phantom volume is 20 cm × 20 cm × 12 cm.

The thermal simulations are conducted utilizing multi-physics simulation tool at 1.6 GHz. The thermal properties of muscle tissue were defined as: density = 1047 kg/m^3, specific heat capacity = 3600 J/(kg·K), and thermal conductivity = 0.46 W/(m·K). The extracellular fluid was assumed to have the same thermal properties as the muscle tissue.

As seen in Fig. 6, under a continuous wave excitation of 1 W input power at 1.6 GHz for 5 minutes, the average temperature in the extracellular fluid volume reached 43.5°C, with a maximum of 46.1°C. The maximum temperature within the adjacent muscle region remained at 42.8°C, below the safety threshold. In contrast, simulations without the resonator showed significantly reduced heating efficiency: the average

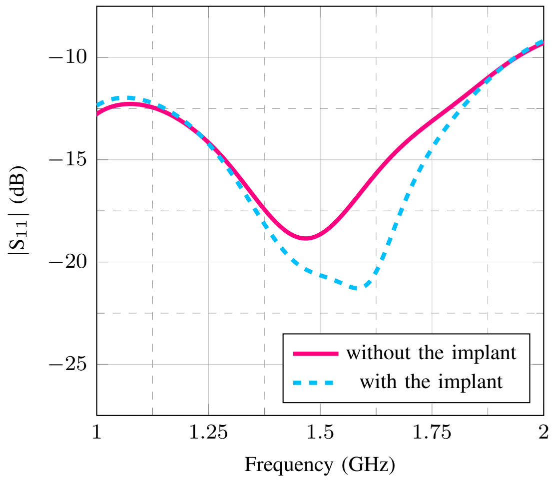

Fig. 5. Comparison of the reflection coefficient of the on-body antenna in the presence and absence of the implant.

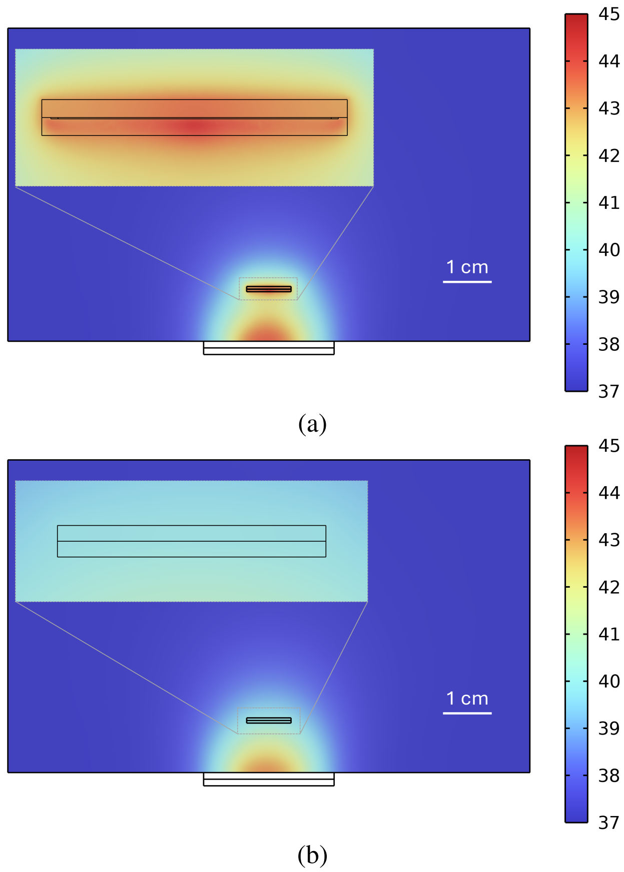

Fig. 6. Thermal map after 5 minutes of electromagnetic heating at 1.6 GHz. (a) with the resonator and (b) without the resonator. The unit is °C.

temperature in the same extracellular fluid volume was 40.0°C, and the maximum only 40.1°C, while muscle temperature rose to 43.3°C, indicating more diffused and less controlled heating. These results confirm that the integrated resonator effectively concentrates electromagnetic energy within the implant volume, improving both heating efficiency and spatial selectivity.

Upon reaching the thermal activation threshold, typically around 42°C, engineered *E. coli* embedded within the implant will initiate the expression of protein. This mechanism effectively translates electromagnetic input into a biological response, forming a unidirectional communication pathway from the external antenna to the internal bio-hybrid system. As such, microwave hyperthermia enables wireless, non-invasive control of synthetic cellular function without requiring any active electronics inside the human body.

V. Conclusion

This study demonstrates a novel method for wireless control of genetically modified bacteria's bacterial function using superficial microwave hyperthermia. The proposed bio-hybrid implant integrates engineered *E. coli* with a passive metallic resonator to enable localized protein expression. Simulation results confirm that the system can produce a controlled temperature increase of more than 6°C at the implant site under an input power of 1 W, sufficient to activate a heat-inducible genetic circuit and initiate expression of a reporter protein. The surrounding tissue remained below the safety threshold of 43°C, validating the spatial selectivity of the proposed approach.

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References

[1] D. Zhang, Q. Chen, C. Shi, M. Chen, and K. Ma, "Dealing with the foreign-body response to implanted biomaterials: Strategies and applications of new materials," *Adv. Funct. Mater.*, vol. 31, no. 4, p. 2007226, 2021, doi: 10.1002/adfm.202007226.

[2] S. D. Oktar, "A System and Method Which Provides Wireless Communication Between Bio-nano Elements and Macro/micro Devices," World Intellectual Property Organization, Patent WO2021126135A1, 2020.

[3] C. Karabulut, A. Bilir, M. E. Lacin, and S. Dumanli, "3D-Engineered Muscle Tissue as a Wireless Sensor: AntennAlive," *IEEE Antennas Propag. Mag.*, vol. 65, no. 6, pp. 28–36, Dec. 2023, doi: 10.1109/MAP.2023.3320589.

[4] A. Bilir and S. Dumanli, "Biodegradable Implant Antenna Utilized for Real-Time Sensing Through Genetically Modified Bacteria," 2024 18th European Conference on Antennas and Propagation (EuCAP), Glasgow, United Kingdom, 2024, pp. 1-4, doi: 10.23919/EuCAP60739.2024.10501075.

[5] J. M. Jornet and I. F. Akyildiz, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band," *IEEE Trans. Wireless Commun.*, vol. 10, no. 10, pp. 3211–3221, Oct. 2011, doi: 10.1109/TWC.2011.081511.101141.

[6] S. Gabriel, R. W. Lau, and C. Gabriel, "The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz," *Phys. Med. Biol.*, vol. 41, no. 11, pp. 2251–2269, 1996.

[7] D. K. Chatterjee, P. Diagaradjane, and S. Krishnan, "Nanoparticle-mediated hyperthermia in cancer therapy," *Ther. Delivery*, vol. 2, no. 8, pp. 1001–1014, 2011, doi: 10.4155/tde.11.72.

[8] J. Wu *et al.*, "Non-invasive differential temperature monitoring using sensor array for microwave hyperthermia applications: A subspace-based approach," *J. Sensor Actuator Netw.*, vol. 14, no. 1, p. 19, 2025, doi: 10.3390/jsan14010019.

[9] Z. Xi *et al.*, "A preclinical system prototype and experimental validation of focused microwave brain hyperthermia," *IEEE Trans. Microw. Theory Techn.*, vol. 73, no. 2, pp. 1147–1157, Feb. 2025, doi: 10.1109/TMTT.2024.3482986.

[10] P. T. Nguyen, A. M. Abbosh, and S. Crozier, “3-D focused microwave hyperthermia for breast cancer treatment with experimental validation,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 7, pp. 3489–3500, Jul. 2017, doi: 10.1109/TAP.2017.2700164.

[11] M. Converse *et al.*, “A computational study of ultra-wideband versus narrowband microwave hyperthermia for breast cancer treatment,” *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 5, pp. 2169–2180, May 2006, doi: 10.1109/TMTT.2006.872790.

[12] M. J. Hajiahmadi, R. Faraji-Dana, and C. Caloz, “Metasurface-based time-reversal focusing for brain tumor microwave hyperthermia,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 12, pp. 12237–12246, Dec. 2022, doi: 10.1109/TAP.2022.3210691.

[13] H. Xiong *et al.*, “Microwave hyperthermia technology based on near-field focused metasurfaces: Design and implementation,” *Adv. Funct. Mater.*, vol. 35, no. 1, Aug. 2024, doi: 10.1002/adfm.202411842.

[14] I. V. Soares *et al.*, “Wireless powering efficiency of deep-body implantable devices,” *IEEE Trans. Microw. Theory Techn.*, vol. 71, no. 6, pp. 2680–2692, Jun. 2023, doi: 10.1109/TMTT.2022.3231492.

[15] I. A. Shah *et al.*, “Flexible metasurface-coupled efficient wireless power transfer system for implantable devices,” *IEEE Trans. Microw. Theory Techn.*, vol. 72, no. 4, pp. 2534–2547, Apr. 2024, doi: 10.1109/TMTT.2023.3319050.

[16] X. Tian *et al.*, “Textile-integrated phased surfaces for wireless networking of bioelectronic devices,” *IEEE Trans. Antennas Propag.*, vol. 72, no. 1, pp. 267–276, Jan. 2024, doi: 10.1109/TAP.2023.3322752.

[17] L. L. Xiong *et al.*, “Tunable temperature-sensitive transcriptional activation based on lambda repressor,” *ACS Synth. Biol.*, vol. 11, no. 7, pp. 2518–2522, Jun. 2022, doi:10.1021/acssynbio.2c00093.

[18] B. Saltepe *et al.*, “Genetic circuits to detect nanomaterial triggered toxicity through engineered heat shock response mechanism,” *ACS Synth. Biol.*, vol. 8, no. 10, pp. 2404–2417, Sep. 2019, doi: 10.1021/acssynbio.9b00291.

[19] D. I. Piraner *et al.*, “Tunable thermal bioswitches for in vivo control of microbial therapeutics,” *Nat. Chem. Biol.*, vol. 13, no. 1, pp. 75–80, Nov. 2016, doi: 10.1038/nchembio.2233.

[20] A. Ping *et al.*, “Targeted Optical Neural Stimulation: A New Era for Personalized Medicine,” *Front. Neurosci.*, vol. 15, p. 1234, 2021.

[21] N. Kuster *et al.*, “Tissue Properties Database,” IT’IS Foundation, Zurich, Switzerland. [Online]. Available: https://itis.swiss/database

[22] ANSYS HFSS, High Frequency Structure Simulator, version 2023 R2, ANSYS Inc., Canonsburg, PA, USA. [Online]. Available: https://www.ansys.com/products/electronics/ansys-hfss

[23] I. V. Soares, M. Gao, E. Cil, Z. Šipuš, A. K. Skrivervik, J. S. Ho, and D. Nikolayev, “Wireless powering efficiency of deep-body implantable devices,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 71, no. 6, pp. 2680–2692, Jun. 2022.

[24] S. Dumanli, “Challenges of wearable antenna design,” in *Proc. 46th Eur. Microw. Conf. (EuMC)*, London, U.K., 2016, pp. 1350–1352.

[25] A. Bilir and S. Dumanli, “Wide-band Dual Port Cross Slot Wearable Antenna for In-body Communications,” in *Proc. 17th Eur. Conf. Antennas Propag. (EuCAP)*, Florence, Italy, 2023, pp. 1–5, doi: 10.23919/EuCAP57121.2023.10133068.