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Theoretical Insights and Engineering of Wireless Body-Implanted Bioelectronics

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Abstract—The development and widespread adoption of body-implanted bioelectronics face significant challenges due to limited wireless performance and reliance on batteries. This contribution provides an overview of recent theoretical advancements and practical applications in antenna design for body-implanted bioelectronics. It explores performance indicators, including bandwidth, robustness, radiation efficiency, and the impact of loss mechanisms. Additionally, it discusses the role of antennas in wireless sensing and strategies to mitigate reflection losses, offering insights into efficient and safe power transfer.

Index Terms—Wireless bioelectronics, ingestible devices, implantable devices, in-body antennas, wireless power transfer.

I. INTRODUCTION

Despite their groundbreaking potential, the development of body-implanted bioelectronics and their widespread adoption in medical practice is hindered by limited wireless performances and their reliance on batteries. To achieve long-term operation of these devices and improve their clinical capabilities, efficient and safe wireless data transmission and power transfer through the body tissues is a major challenge [1], [2]. In addition, being the bulkiest component, the batteries dictate the size of bioelectronic devices and require frequent maintenance through invasive surgeries for replacement or recharging, making treatments costly and risky for patients. Battery-free solutions are being explored to address these limitations, including energy harvesting from biological and physical processes [3].

Wireless Power Transfer (WPT) has emerged as a promising solution, where an off- or on-body source sends energy to an implanted receiver. Even though the most common WPT strategies use electromagnetic waves as the energy carried, the choice of the most suitable technique depends on the characteristics of the application. For instance, near-field WPT based on inductive [4]–[11] or capacitive [12], [13] coupling achieves the highest efficiency for powering large, shallow-implanted devices, such as in sub-cutaneous applications. Conversely, far-field techniques [14]–[16] can be an alternative for powering low-consumption telemetry sensors, which are usually deeply implanted or even ingestible. However, achieving near-optimal performance requires WPT strategies [17]–[21] that exploit

the knowledge of electromagnetic propagation in complex media like human tissues. Consequently, mid-field techniques based on reconfigurable transmitters that focus the power pattern towards the receiver are the most suitable for powering miniature, deep-body implanted bioelectronics, enhancing power delivery efficiency while ensuring low electromagnetic exposure levels [22].

Efficient antenna design is essential for enabling wireless data transmission and power transfer, particularly in the field of body-implanted bioelectronics. This contribution aims to provide an overview and explain in an accessible manner recent theoretical advancements and their practical application in engineering antennas for these unique applications.

II. THEORETICAL INSIGHTS, IMPORTANT METRICS, AND CONVENTIONS

The analysis of antenna performance for body-implanted bioelectronics necessitates a clear definition of relevant performance indicators. These antennas operate within lossy and electromagnetically non-deterministic media, which requires a distinct approach to evaluating their intrinsic characteristics. Parameters like impedance bandwidth, radiation efficiency, gain, and robustness could differ when applied to these antennas in comparison to conventional free-space antenna theory.

A. Bandwidth and Robustness

The antenna ability to maintain a good matching (i.e., $|S_{11}| < -10$ dBi) across a wide range of surrounding tissue electromagnetic properties characterizes its robustness. Therefore, a robust design is such that remains operational within the spectrum of tissue properties relevant to its intended application. Conventional wisdom might suggest that employing wide-band antenna designs to accommodate variations in $|S_{11}|$ is one method for detuning mitigation. While wide-band designs are well-suited for high data rates [23], their utilization for enhancing robustness should be approached with caution.

For electrically small resonant antennas, the bandwidth in free space is typically narrow. Placing these antennas within the lossy medium of biological tissues diminishes their Q factor, resulting in a substantial increase in the inversely

proportional quantity: bandwidth. In this context, bandwidth qualitatively signifies the antenna's coupling to surrounding tissues. This may yield designs with a wide bandwidth primarily due to losses in the near-field. Even with this wide bandwidth, variations in tissue properties can significantly impact antenna matching. Conversely, confining most of the near field within the device or tailoring multiple narrow-band resonances to span the expected range of ϵ_r , variations can produce narrow-band yet highly robust designs. Several examples of these approaches can be found in Refs. [24]–[27].

B. Radiation Efficiency, Optimal Frequency, and Losses

The conventional definition of the radiation pattern becomes inadequate when dealing with radiation into a lossy medium, as the antenna far field depends on the choice of coordinate origin. Consequently, the far-field analysis of in-body antennas (i.e., the radiation efficiency and gain) assumes instead that the entire phantom radiates in free space. Given the substantial variations in individual body morphologies, it is difficult to de-embed antenna radiation performance from these non-deterministic factors [28]. Analyzing the antenna within a deterministic anatomical phantom is also impractical: results are strongly dependent on the precise device location and orientation within a given tissue, diminishing result reproducibility and complicating accurate comparisons of antenna performance across different reported antenna designs. For these reasons, and considering the increased computational cost of anatomical phantoms, it is advisable to reserve their use for special cases where a homogeneous model is insufficient to illustrate a particular feature or effect.

Results obtained using a well-characterized and understood phantom shape offer reproducibility and provide deeper insights into antenna intrinsic radiation [29], [30]. Different designs can be evaluated relative to the maximum achievable efficiency derived for this reference phantom. Notably, propagation and reflection losses introduced by the phantom can be separated from intrinsic antenna losses (e.g., near-field and ohmic losses). Both theoretical and realistic antenna models account for the same propagation and reflection losses. A spherical shape serves as a suitable candidate for a standard phantom, introducing isotropic, direction-independent attenuation losses. Spherical symmetry facilitates the construction of computationally efficient theoretical models, such as a spherical wave expansion approach [29] or a 2D-axisymmetric full-wave method [30]. Finally, radiation performance computed within a simple phantom geometries is highly reproducible and relatively straightforward to experimentally verify.

Using two distinct model formulations provided in [29], [30], Fig. 1 illustrates an example of achievable radiation efficiencies and optimal frequency range estimation for an implantable device of specified dimensions (circumradius $a = 10$ mm in this instance) and implantation depth ($d \approx 5$ cm). Note that the similar approaches can be applied to evaluate the optimal operating frequency and the achievable efficiency for small [31] and large animal applications [32], [33].

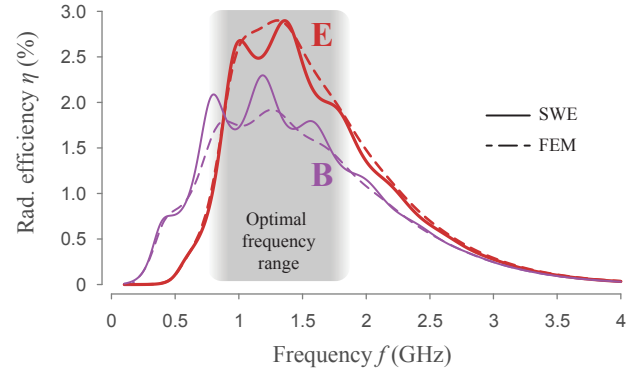


Fig. 1. The optimal frequency range and maximum achievable radiation efficiency $\eta(f)$ of electric (**E**) and magnetic (**B**) equivalent sources of in the spherical muscle-equivalent phantom of 100-mm diameter. The results are computed for a theoretical spherical-wave expansion (SWE) [29] and a realistic full-wave 2D axisymmetric (FEM) models [30].

The radiation efficiency $\eta(f)$ is influenced by the following phantom- and antenna-dependent loss mechanisms [34]:

- 1) Wave attenuation losses, which rise with increasing operating frequency and become the dominant factor for efficiency reduction at $f_0 > f_{\text{opt}}$.
- 2) Wave-impedance mismatch losses at the tissue–air interface, also referred to as *reflection losses* for simplicity.
- 3) Near-field losses, which are typically inversely proportional to f_0 and become dominant at $f_0 < f_{\text{opt}}$.
- 4) Ohmic losses of the antenna, inversely proportional to the frequency. These losses are not considered in the analysis presented in Fig. 1 but could become predominant at $f_0 \ll f_{\text{opt}}$ [35].

C. Near-field Losses as Sensing Modality

The near-field of an implantable or ingestible antenna extends into the surrounding tissue, defining its bandwidth, resonance frequency, and losses. Variation in the electromagnetic properties of the adjacent tissue impact antenna operational parameters, including impedance and efficiency. The impedance variation offers the potential to utilize implantable and ingestible antennas as sensors within bioelectronic devices [36]. Monitoring alterations in antenna parameters resulting from shifts in the near-field provides valuable information about the surrounding environment. Such multiplexed bio-sensing devices as seen in Fig. 2 can be implemented for different purposes in medicine such as wireless endoscopy [37], [38], blood flow sensing and vessel imaging [39], [40], location tracking of ingestible capsules inside the gastrointestinal track [41], [42], and neuro-recording [43], [44].

D. Mitigating Reflection Losses

Wave-impedance mismatch losses at the tissue–air interface, also referred to as reflection losses, could cause 80–99% losses in radiation efficiency of in-body antennas [34]. To mitigate these losses, active or passive approaches could be proposed. Active solutions involve the use of repeater antennas [45], [46] while passive strategies encompass the

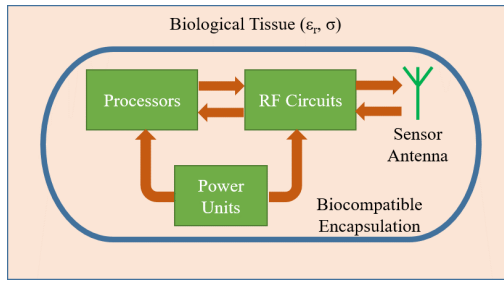


Fig. 2. Model of an implantable or ingestible bio-sensing device.

application of conformal anti-reflection metasurfaces [47], [48] or metamaterial textile plasmonic waveguides for implant-to-implant communications [49].

E. Wireless Powering Strategies

Wireless-powered bioelectronics are commonly based on the techniques summarized in Fig. 3, primarily developed for free-space WPT but modified to address the challenges and requirements of implantable applications. The most employed WPT strategies nowadays are based on near-field coupling and are primarily used for sub-cutaneous applications where the transmitter and receiver are close. However, as this approach is based on inductive [4]–[11] or capacitive [12], [13] coupling, the efficiency sharply reduces as the implantation depth increases or in case of misalignment between transmitter and receiver couplers. On the other hand, radiative or far-field WPT techniques [14]–[16] are less sensitive to misalignments or stochastic variations. However, the power attenuation in the lossy body tissues significantly limits the maximum achievable efficiency levels. In this way, these techniques are best suited for powering low-consumption implants, such as those used for biotelemetry. A more recent development known as mid-field WPT [17]–[21] combines the benefits of near-field coupling and far-field radiation, achieving higher efficiency for deep-body implants by focusing the EM field on the receiver.

Although these traditional WPT strategies have been vastly used in the literature, they still face challenges for efficiently powering miniature and deep-body devices, primarily due to the attenuation and wave scattering in such a complex and heterogeneous media as the human tissues [22]. Additionally, conventional single-antenna WPT systems are sensitive to parameter variations, which implantable devices frequently experience. Therefore, it is crucial to investigate the electromagnetic energy exchange from an on-body transmitter to the in-body receiver to achieve near-optimal WPT performance. In addition, by merging the knowledge of wave scattering in such a complex media with novel physical concepts and engineering techniques, it is possible to achieve optimal electromagnetic focusing from a reconfigurable on-body source to the deep-implanted device. Consequently, this approach paves the way for maximizing power delivery, ideally reaching the theoretical maximum levels while being robust to stochastic variations and minimizing electromagnetic exposure, ensuring, at the same time, efficient operation and the safety of the patient.

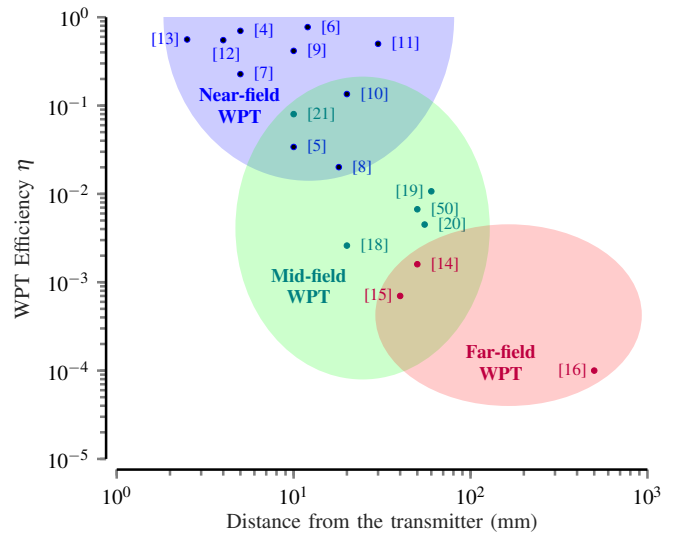


Fig. 3. WPT efficiency η achieved by different implementations found in the literature as a function of the distance range between an off- or on-body transmitter and the in-body receiver.

III. CONCLUSIONS

In this contribution, we overview the interaction between body-implanted antennas and the complex medium of surrounding biological tissue. The dynamic near-field of these antennas impacts critical antenna parameters such as bandwidth, resonance frequency, and losses. Variations in electromagnetic properties within the surrounding tissue create opportunities for these antennas to act as sensors in bioelectronic devices. By monitoring antenna parameter changes in response to near-field coupling with the surrounding medium, we gain insights into the physiological characteristics of adjacent tissues. Successfully identifying wireless powering strategies for specific applications could lead to battery-free operation of implantable devices, facilitating miniaturization and reducing invasiveness. This work highlights the potential of antenna-based sensors and wireless technologies to advance the field of bioelectronics.

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REFERENCES

- [1] A. Kiourti and K. S. Nikita, "A review of in-body biotelemetry devices: implantables, ingestibles, and injectables," *IEEE Trans. Biomed. Eng.*, vol. 64, no. 7, pp. 1422–1430, Jul. 2017.
- [2] D. Nikolayev, M. Zhadobov, R. Sauleau, and P. Karban, "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.
- [3] S. M. Won, L. Cai, P. Gutruf, and J. A. Rogers, "Wireless and battery-free technologies for neuroengineering," *Nat. Biomed. Eng.*, Mar. 2021.
- [4] U. Anwar, Z. Liu, and D. Markovic, "A 6.78-MHz burst-mode controlled inductive wireless power transfer system for biomedical implants with back-channel communication eliminated using transmitter q-factor detection," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 10, no. 5, pp. 6383–6395, 2022.

- [5] C. Kim, J. Park, S. Ha, A. Akinin, R. Kubendran, P. P. Mercier, and G. Cauwenberghs, "A 3 mm × 3 mm fully integrated wireless power receiver and neural interface system-on-chip," *IEEE Trans. Biomed. Circuits Syst.*, vol. 13, no. 6, pp. 1736–1746, 2019.
- [6] M. Schormans, V. Valente, and A. Demosthenous, "Practical inductive link design for biomedical wireless power transfer: A tutorial," *IEEE Trans. Biomed. Circuits Syst.*, vol. 12, no. 5, pp. 1112–1130, 2018.
- [7] Y. Jia, S. A. Mirbozorgi, P. Zhang, O. T. Inan, W. Li, and M. Ghovanloo, "A dual-band wireless power transmission system for evaluating mm-sized implants," *IEEE Trans. Biomed. Circuits Syst.*, vol. 13, no. 4, pp. 595–607, 2019.
- [8] P. Yeon, S. A. Mirbozorgi, J. Lim, and M. Ghovanloo, "Feasibility study on active back telemetry and power transmission through an inductive link for millimeter-sized biomedical implants," *IEEE Trans. Biomed. Circuits Syst.*, vol. 11, no. 6, pp. 1366–1376, 2017.
- [9] S. A. Mirbozorgi, H. Bahrami, M. Sawan, L. A. Rusch, and B. Gosselin, "A single-chip full-duplex high speed transceiver for multi-site stimulating and recording neural implants," *IEEE Trans. Biomed. Circuits Syst.*, vol. 10, no. 3, pp. 643–653, 2016.
- [10] B. Lee, M. Kiani, and M. Ghovanloo, "A triple-loop inductive power transmission system for biomedical applications," *IEEE Trans. Biomed. Circuits Syst.*, vol. 10, no. 1, pp. 138–148, 2016.
- [11] X. Li, C.-Y. Tsui, and W.-H. Ki, "A 13.56 mhz wireless power transfer system with reconfigurable resonant regulating rectifier and wireless power control for implantable medical devices," *IEEE Journal of Solid-State Circuits*, vol. 50, no. 4, pp. 978–989, 2015.
- [12] A. N. M. S. Hossain, P. Mohseni, and H. M. Lavasani, "Design and optimization of capacitive links for wireless power transfer to biomedical implants," *IEEE Trans. Biomed. Circuits Syst.*, vol. 16, no. 6, pp. 1299–1312, 2022.
- [13] R. Jegadeesan, K. Agarwal, Y.-X. Guo, S.-C. Yen, and N. V. Thakor, "Wireless power delivery to flexible subcutaneous implants using capacitive coupling," *IEEE Trans. Microw. Theory Tech.*, vol. 65, no. 1, pp. 280–292, 2017.
- [14] V. Kaim, N. Singh, B. K. Kanaujia, L. Matekovits, K. P. Esselle, and K. Rambabu, "Multi-channel implantable cubic rectenna mimo system with cp diversity in orthogonal space for enhanced wireless power transfer in biotelemetry," *IEEE Trans. Antennas Propag.*, vol. 71, no. 1, pp. 200–214, 2023.
- [15] T. Shaw, G. Samanta, and D. Mitra, "Efficient wireless power transfer system for implantable medical devices using circular polarized antennas," *IEEE Trans. Antennas Propag.*, vol. 69, no. 7, pp. 4109–4122, 2021.
- [16] A. Basir and H. Yoo, "Efficient wireless power transfer system with a miniaturized quad-band implantable antenna for deep-body multitasking implants," *IEEE Trans. Microw. Theory Tech.*, vol. 68, pp. 1943–1953, 2020.
- [17] J. S. Ho, A. J. Yeh, E. Neofytou, S. Kim, Y. Tanabe, B. Patlolla, R. E. Beygui, and A. S. Y. Poon, "Wireless power transfer to deep-tissue microimplants," *PNAS*, vol. 111, no. 22, pp. 7974–7979, 2014.
- [18] S. A. A. Shah and H. Yoo, "Radiative near-field wireless power transfer to scalp-implantable biotelemetric device," *IEEE Trans. Microw. Theory Tech.*, vol. 68, no. 7, pp. 2944–2953, 2020.
- [19] A. Iqbal, M. Al-Hasan, I. B. Mabrouk, A. Basir, M. Nedil, and H. Yoo, "Biotelemetry and wireless powering of biomedical implants using a rectifier integrated self-diplexing implantable antenna," *IEEE Trans. Microw. Theory Tech.*, vol. 69, no. 7, pp. 3438–3451, 2021.
- [20] R. Das and H. Yoo, "A multiband antenna associating wireless monitoring and nonleaky wireless power transfer system for biomedical implants," *IEEE Trans. Microw. Theory Tech.*, vol. 65, no. 7, pp. 2485–2495, 2017.
- [21] Y. Tanabe *et al.*, "High-performance wireless powering for peripheral nerve neuromodulation systems," *PLOS ONE*, vol. 12, no. 10, pp. 1–13, 10 2017.
- [22] 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.
- [23] A. Iqbal, M. Al-Hasan, I. B. Mabrouk, and M. Nedil, "Scalp-Implantable MIMO antenna for high-data-rate head implants," *IEEE Antenn. Wireless Propag. Lett.*, vol. 20, no. 12, pp. 2529–2533, Dec. 2021.
- [24] M. K. Magill, G. A. Conway, and W. G. Scanlon, "Tissue-independent implantable antenna for in-body communications at 2.36–2.5 GHz," *IEEE Trans. Antennas Propag.*, vol. 65, no. 9, pp. 4406–4417, Sep. 2017.
- [25] D. Nikolayev, M. Zhadobov, and R. Sauleau, "Immune-to-detuning wireless in-body platform for versatile biotelemetry applications," *IEEE Trans. Biomed. Circuits Syst.*, vol. 13, no. 2, pp. 403–412, Apr. 2019.
- [26] Y. Feng, Y. Li, L. Li, B. Ma, H. Hao, and L. Li, "Tissue-dependent co-matching method for dual-mode antenna in implantable neurostimulators," *IEEE Trans. Antennas Propag.*, vol. 67, no. 8, pp. 5253–5264, Aug. 2019.
- [27] 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.
- [28] Z. Sipus, A. Šušnjara, A. K. Skrivervik, D. Poljak, and M. Bosiljevac, "Influence of uncertainty of body permittivity on achievable radiation efficiency of implantable antennas—Stochastic analysis," *IEEE Trans. Antennas Propag.*, vol. 69, no. 10, pp. 6894–6905, Oct. 2021.
- [29] A. K. Skrivervik, M. Bosiljevac, and Z. Sipus, "Fundamental limits for implanted antennas: Maximum power density reaching free space," *IEEE Trans. Antennas Propag.*, vol. 67, no. 8, pp. 4978–4988, Aug. 2019.
- [30] D. Nikolayev, W. Joseph, M. Zhadobov, R. Sauleau, and L. Martens, "Optimal radiation of body-implanted capsules," *Phys. Rev. Letters*, vol. 122, no. 10, p. 108101, Mar. 2019.
- [31] M. Gao, J. D. Rosenthal, K. Wu, G. A. Ramírez, Z. Šipuš, S. P. Lacour, and A. K. Skrivervik, "Radiation patterns of RF wireless devices implanted in small animals: Unexpected deformations due to body resonance," *IEEE Trans. Biomed. Circuits Syst.*, 2023.
- [32] S. Benaissa *et al.*, "Design and experimental validation of a multiband conformal patch antenna for animal ingestible bolus applications," *IEEE Trans. Antennas Propag.*, vol. 71, no. 8, pp. 6365–6377, May 2023.
- [33] —, "Propagation-loss characterization for livestock implantables at 433, 868, and 1400 MHz," *IEEE Trans. Antennas Propag.*, vol. 69, no. 8, pp. 5166–5170, Aug. 2021.
- [34] D. Nikolayev, M. Zhadobov, P. Karban, and R. Sauleau, "Electromagnetic radiation efficiency of body-implanted devices," *Phys. Rev. Applied*, vol. 9, no. 2, p. 024033, Feb. 2018.
- [35] J. Liska, M. Gao, L. Jelinek, E. R. Algap, A. K. Skrivervik, and M. Capek, "Upper bound on implantable antennas considering ohmic loss," arXiv:2307.16466, 2023.
- [36] D. Nikolayev, "Biotelemetry device that can be ingested and implanted *in vivo*," US Patent US20210030305A1, Feb., 2021.
- [37] M. Suzan Miah, A. N. Khan, C. Icheln, K. Haneda, and K.-I. Takizawa, "Antenna system design for improved wireless capsule endoscope links at 433 MHz," *IEEE Trans. Antennas Propag.*, vol. 67, no. 4, pp. 2687–2699, 2019.
- [38] J. Wang, M. Leach, E. G. Lim, Z. Wang, R. Pei, and Y. Huang, "An implantable and conformal antenna for wireless capsule endoscopy," *IEEE Antenn. Wireless Propag. Lett.*, vol. 17, no. 7, pp. 1153–1157, 2018.
- [39] Y. Hacohen and S. J. A. Majerus, "A flexible double helix inductive antenna for RFID vascular flow sensing," *IEEE Sens. J.*, vol. 23, no. 17, pp. 19044–19051, 2023.
- [40] S. Ullah and H. Yoo, "High-resolution implantable microcoil antennas for blood-vessel imaging in high-field MRIs," *IEEE Trans. Antennas Propag.*, vol. 69, no. 5, pp. 2560–2570, 2021.
- [41] E. Cil *et al.*, "On the use of impedance detuning for gastrointestinal segment tracking of ingestible capsules," *IEEE Trans. Antennas Propag.*, vol. 71, no. 2, pp. 1977–1981, 2023.
- [42] S. Sharma *et al.*, "Location-aware ingestible microdevices for wireless monitoring of gastrointestinal dynamics," *Nat. Electron.*, vol. 6, no. 3, pp. 242–256, 2023.
- [43] H. Bahrami, A. Mirbozorgi, L. A. Rusch, and B. Gosselin, "Biological channel modeling and implantable UWB antenna design for neural recording systems," *IEEE Trans. Biomed. Eng.*, vol. 62, no. 1, pp. 88–98, 2015.
- [44] A. Iqbal, M. Al-Hasan, I. B. Mabrouk, and T. A. Denidni, "Simultaneous transmit and receive self-duplexing antenna for head implants," *IEEE Trans. Antennas Propag.*, 10.1109/TAP.2023.3312920.
- [45] K. Godeneli, U. Bengi, O. A. Kati, and S. Dumanli, "A wearable dual-mode repeater antenna for implant communications," *IEEE Trans. Antennas Propag.*, vol. 70, no. 2, pp. 868–875, Feb. 2022.
- [46] A. Kiourti, J. Costa, C. Fernandes, and K. Nikita, "A broadband implantable and a dual-band on-body repeater antenna: design and transmission performance," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 2899–2908, Jun. 2014.

- [47] M. Horodyski, M. Kühmayer, C. Ferise, S. Rotter, and M. Davy, "Anti-reflection structure for perfect transmission through complex media," *Nature*, vol. 607, no. 7918, pp. 281–286, Jul. 2022.
- [48] F. Yang, B. O. Raeker, D. T. Nguyen, J. D. Miller, Z. Xiong, A. Grbic, and J. S. Ho, "Antireflection and wavefront manipulation with cascaded metasurfaces," *Phys. Rev. Applied*, vol. 14, no. 6, p. 064044, Dec. 2020.
- [49] X. Tian *et al.*, "Implant-to-implant wireless networking with metamaterial textiles," *Nat. Commun.*, vol. 14, p. 4335, Jul. 2023.
- [50] K. Zhang, C. Liu, Z. H. Jiang, Y. Zhang, X. Liu, H. Guo, and X. Yang, "Near-field wireless power transfer to deep-tissue implants for biomedical applications," *IEEE Trans. Antennas Propag.*, vol. 68, no. 2, pp. 1098–1106, 2020.