

Miniaturized Laser Induced Graphene Antennas on Edible Substrates towards Ingestible Electronics

Nausheen Nakhawa

New York University Abu Dhabi

Hanan Mohammed

New York University Abu Dhabi

Solomon Serunjogi

New York University Abu Dhabi

Rahul Singh

New York University

Muhammad Abrar Akram

New York University Abu Dhabi

Mahmoud Elbeh

New York University

James Weston

New York University Abu Dhabi

Sohmyung Ha

New York University Abu Dhabi

Mahmoud Rasras

New York University Abu Dhabi

Khalil Ramadi

kramadi@nyu.edu

New York University Abu Dhabi

Article

Keywords: Laser Induced Graphene, ingestible devices, edible electronics, flexible antenna, passive antenna, ingestible substrate, gastrointestinal monitoring, polyimide, Kapton

Posted Date: July 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10395328/v1>

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Additional Declarations: No competing interests reported.

Abstract

Ingestible electronic devices offer significant potential for non-invasive healthcare monitoring. However, current systems often rely on rigid, non-degradable components and complex fabrication processes. In this study, we report a functional, maskless Laser Induced Graphene (LIG) antenna synthesized directly onto an edible material such as potato skin. This device serves as a foundational proof-of-concept for creating functional electronics on highly heterogeneous dietary material. We demonstrate a miniaturized edible antenna within the Industrial, Scientific, and Medical (ISM) band without introducing design complexities. Since the resonant frequency of an antenna is fundamentally governed by its physical dimensions, we optimized the geometry to an ingestible 1 cm² footprint while maintaining operation within the 5.8 GHz ISM band via edge-curvature design principles. We then characterized the platform's transient electromagnetic behavior during *in vitro* testing in a simulated biological environment namely simulated gastric fluid. Over a 24-hour duration, the device exhibited a predictable attenuation in return loss alongside a consistent upward frequency shift, establishing its viability as a telemetry-based sensor for gastrointestinal (GI) monitoring. Other future applications of such an antenna includes a binary loss of signal mechanism for medication tracking or as a scaffold for surface functionalization with target specific bioreceptors for gastrointestinal monitoring. This study demonstrates a simple, scalable and edible antenna based on LIG for health monitoring and diagnostics.

INTRODUCTION

The rapidly developing field of ingestible electronics offers immense potential for noninvasive health monitoring spanning *in vivo* sampling, diagnostics, and targeted therapeutics [1–6]. Such devices can provide access to localized physiological data, microbial metabolic fluctuations or early disease biomarkers in the gastrointestinal (GI) tract [7–10]. However, the widespread clinical translation of ingestible systems is hindered by their reliance on non-degradable and inorganic materials that utilize costly and complex multi-layer fabrication processes. These components are not only costly but also pose risks of internal obstruction and material toxicity requiring a shift toward fully transient or bioresorbable devices made from biocompatible or edible materials where the components perform sensing and subsequently disappear.

For these transient systems to function as active diagnostic tools rather than passive capsules, they must be able to transmit data wirelessly from within the body. Miniaturized edible antennas with minimal footprint could serve as an ideal communication link for this. Fabricating high-performance conductive traces directly onto edible or dietary substrates is challenging as traditional cleanroom-based lithography and metal-ink printing are often incompatible with the irregular and sensitive surfaces of raw food materials. Laser induced graphene (LIG) has emerged as a highly versatile technique for single-step, maskless and scalable photothermal conversion of carbon-rich precursors into highly conductive, porous three-dimensional graphene networks [11, 12]. LIG has been extensively characterized on synthetic polymers such as polyimide [13], as well as a variety of precursors including wood and paper [14–16].

The performance of LIG depends heavily on the chemical properties of the precursor material, in particular the lignin content [14]. A high lignin content within the precursor materials facilitates more effective LIG synthesis and the formation of efficient conductive networks. While LIG has been demonstrated on edible materials such as potato, bread and coconut [15], direct demonstration of functional electronic components such as antennas remains largely unexplored. Developing functional electronics directly on food-based substrates would bypass the need for secondary substrates or carriers, creating a direct path towards edible and scalable platforms (Fig. 1A) [17–19].

In this study, we report a functional, maskless LIG antenna [20, 21] synthesized directly on potato skin (Fig. 1B,1C). Leveraging the high-lignin content of the substrate, we demonstrate an edible antenna with a miniaturized $1 \times 1 \text{ cm}^2$ footprint operating in the 5.8 GHz ISM band. This miniaturization enables integration into standard gelatin capsule while operation within a globally recognized, license-free spectrum supports seamless compatibility with existing short-range healthcare telemetry systems. These LIG-on-potato antennas can serve a dual role; it acts as a primary communication link while the electromagnetic response simultaneously functions as a passive sensing mechanism (Fig. 1A). By integrating an RFID chip, the antenna response can be wirelessly monitored via an external RFID reader and used to monitor the antenna's real time transient behavior, thereby providing a telemetry-based mechanism for monitoring.

RESULTS

Synthesis of LIG-on-Potato Skin

The successful transformation of a dietary substrate into a functional electronic component depends heavily on the precursor's biochemical composition, in particular its lignin concentration. Lignin serves as a critical structural carbon source that facilitates the photothermal conversion into high quality graphene. While previous studies have utilized various edible precursors, including cork (25% lignin), oven-dried bread (18–30%) and coconut shells (30%), we chose the potato skin or periderm of Russet variety potato due to its exceptionally high lignin content (36%) [22–24]. This elevated lignin profile allows for a more efficient, multi-pass laser scribing process required for heterogeneous organic surfaces. Unlike synthetic polyimide, which requires only a single laser pass, the complex nature of the potato skin necessitates a two-step conversion, an initial pass that reduces the complex organic matrix into an amorphous carbon intermediate, followed by subsequent passes that drive the final graphitization [15]. We therefore utilized multiple lasing to achieve a desirable conductive layer. We observed that exceeding three passes resulted in thermal degradation and surface ablation. We also observed that potato skin substrates required a defocused beam (1–2 mm offset) to ensure uniform energy distribution and prevent localized burning of the substrate, in contrast to polyimide which is typically lased at the focal point. By balancing these parameters, we achieved a conductive LIG network directly on the potato skin (Fig. 1B, 1C), providing the robust foundation necessary for the fabrication of antenna geometries.

Morphological and Spectroscopic Characterization of LIG-on-Potato

To validate the structural integrity and chemical composition of the synthesized LIG, we performed morphological and spectroscopic analyses. Scanning electron microscopy (SEM) reveals a highly porous, interconnected 3D network (Fig. 1D) with LIG depth of approximately 30 μm , characteristic of high-quality LIG. Spectroscopic characterization was performed to evaluate the graphitic quality and bonding characteristics of the LIG-on-potato. The resulting spectra (Fig. 1E) exhibits the three signature peaks associated with graphitic carbon namely the D band (1350 cm^{-1}), G band (1580 cm^{-1}) and the 2D band (2700 cm^{-1}) [25, 26]. The D band signifies the presence of defects or disorder within the carbon lattice, while the G band corresponds to the sp^2 hybridized carbon atoms indicative of graphitic content. The 2D band, a second-order overtone of the D band, confirms the formation of a multilayer graphene lattice. Analysis of the peak intensities yielded an I_{2D}/I_G ratio of 0.93, indicating successful reduction and a high degree of graphitization during the laser induction process. Additionally, an I_D/I_G ratio of ~ 1.0 suggests a balanced level of edge-plane defects relative to the graphitic content, a common feature of robust, functional LIG produced from complex natural precursors. These findings confirm that the potato skin can be reliably converted into a high-performance electronic material, providing a sustainable and biodegradable alternative to synthetic substrates. We also fabricated LIG on Kapton to serve as a benchmark for the edible antennas (Figure S1, S2). The morphological and spectroscopic characterization of the LIG on Kapton revealed a well-formed 3D network of porous graphene (Figure S1).

Design and Fabrication of Miniaturized LIG Antennas on Kapton and Potato

To transition the LIG-on-potato material into a functional telemetry tool, the antenna design must satisfy fundamental electromagnetic requirements critical for ingestible electronics, such as the return loss S_{11} and transmission coefficient S_{21} . A return loss exceeding the standard -10 dB threshold is desirable, as it indicates that less than 10% of the input power is reflected, ensuring efficient radiation. The S_{21} measurements provide critical insights into the wireless link budget and the antenna's efficiency in transmitting signals through complex propagation environments. We selected a simple rectangular microstrip patch configuration for the antenna design due to its low-profile, planar nature, and its inherent shielding properties provided by the ground plane, which minimizes signal interference from the underlying biological substrate. The antenna was fed using the microstrip line feed method, utilizing a polyimide Kapton sheet (50 μm thickness) as the benchmarking substrate and copper tape as the ground.

We first simulated the electromagnetic behavior using Ansys HFSS, employing finite element method (FEM) and finite element boundary integral solvers, in order to optimize antenna geometry. Our initial design featured a 2 cm x 2 cm substrate with a graphene patch measuring 1.66 cm x 1.8 cm and an inset width of 1.3 cm. This configuration operated at 4.44 GHz with a gain of 2.51 dBi. We then used

simulations to characterize the edge-curvature effect [27] motivated by classical current-distribution theory for microstrip radiators. Sharp metallic corners introduce localized charge accumulation and electric-field singularities, resulting in increased current crowding, enhanced ohmic dissipation, and stronger excitation of higher-order modes. By replacing abrupt discontinuities with a finite curvature radius, the surface current density becomes more uniformly distributed across the radiating aperture, thereby reducing edge reactance and improving radiation efficiency, lowering antenna quality factor (Q), broadening the impedance bandwidth and improving impedance matching. The Q factor in this case can be represented as

$$Q = \frac{\omega (W_e + W_m)}{P_{\text{rad}} + P_{\text{loss}}}$$

where ω is the angular frequency W_e and W_m are the stored electric and magnetic energies, respectively. P_{rad} and P_{loss} are the total radiated power emitted by the antenna and the total power loss dissipated within the antenna structure.

By varying the upper corner radii from 0.2 cm to 1 cm (Fig. 2), we observed that while higher curvature of 0.6 cm (Fig. 2D) enhanced omni-directionality and beamwidth due to electric field concentration at the edges, the 0.4-cm variant maintained the positive gain (Fig. 2G-I) required for effective wave transmission through lossy media. Thus, we selected the 0.4-cm curved patch antenna design for the LIG antennas (see Figure S2). Further miniaturization of the design to 1 cm² was performed to obtain operation at 5.8 GHz.

Antenna Performance and In Vitro Characterization

We characterized the functional viability of the LIG-on-potato antenna using high-frequency characterization with a vector network analyzer (VNA). A geometrically identical antenna fabricated on Kapton was used as a benchmark reference to confirm that the miniaturized antenna design remains functional on conventional flexible substrates, thereby isolating the effect of the edible substrate on the measured electromagnetic response. VNA measurements of both the LIG-on-potato and LIG-on-Kapton antennas with a 1 cm² footprint under ambient conditions confirmed resonant operation at 5.8 GHz. (Fig. 3A, 3B).

To investigate the impact of various liquid environments on antenna performance, we conducted additional VNA testing with the LIG-on-potato antenna submerged in three relevant media, namely water, saline solution (35 g/L NaCl), and simulated gastric fluid (pH 2.0). In the experimental setup, an external FR4 copper antenna acted as the transmitter while the LIG-on-potato antenna functioned as the receiver, allowing us to evaluate the wireless link budget through S_{21} measurements. The results indicated that ionic concentration significantly influences the electromagnetic properties of the medium. In water, a slight increase in the operating frequency was observed, accompanied by a reduction in return loss (Fig. 3C-E), suggesting improved impedance matching due to dielectric loading. Immersion in simulated

gastric fluid, characterized by a high concentration of hydrogen and chloride ions, demonstrated the most significant reduction in performance. Despite this increase in parasitic absorption and signal reflection, the transmission coefficient S_{21} reached a functional maximum of -25 dB. While this value accounts for environmental interference from surrounding materials like cables and test surfaces, it confirms that a detectable and stable wireless link can be achieved even in the high-conductivity environment of the human gut. Additionally, the linear transfer function was extracted from the experimental data, yielding a sensitivity of $S = \Delta f / \Delta n = 1.42 \text{ GHz/RIU}$ ($R^2 = 0.993$), demonstrating a strong linear relationship between the ionic composition of the surrounding medium and the antenna's resonant frequency response.

Transient Behavior of Edible Antennas

The use of a dietary substrate such as potato skin transforms the antenna from a standard electronic component into a fully edible diagnostic platform. A core advantage of utilizing such materials is their inherent compatibility with the human digestive system, allowing the device to perform telemetry tasks before undergoing safe systemic assimilation. To evaluate the operational window of this edible system, the LIG-on-potato antenna was subjected to a 24-hour study in simulated gastric fluid (SGF) of pH 2.0. The results revealed a controlled evolution of the antenna's electromagnetic profile, with a predictable shift in operating frequency and a transition in reflected power (S_{11}) from an initially optimized -37 dB to approximately -10 dB (Fig. 4A). This behavior is driven by the interaction between the acidic medium and the engineered porosity of the LIG layer, resulting in a performance reduction of approximately 25% after one hour and approximately 50% after 24 hours (Fig. 4B).

Assuming a single-pole resonant response, the quality factor can be estimated using:

$$Q \approx \frac{f_r}{BW_{3dB}} \text{ and, equivalently, } BW_{3dB} \approx \frac{f_r}{Q}$$

where Q is quality factor, f_r is the resonant frequency, the width of the frequency spectrum where the power level drops to half of its peak value at resonance. An approximate quality-factor analysis was performed using the measured reflection coefficient spectra under the assumption of a single-pole resonant response. The unloaded antennas exhibited moderate quality factors ($Q \approx 15\text{--}22$), corresponding to bandwidths of approximately 250–400 MHz near 5.8 GHz. Upon exposure to saline and simulated gastric fluid, the resonance progressively broadened. In SGF, the quality factor decreased to approximately 10 at 5.6 GHz under initial exposure, then declined to approximately 8, 6, and 4 at the 1-hour, 15-hour, and 24-hour timepoints as resonance shifted to the 7–8 GHz range, accompanied by a considerable increase in operational bandwidth from 550–2000 MHz. This behavior is consistent with increased dielectric and conductive losses introduced by ionic absorption into the porous graphene network. Although the decrease in Q lowers frequency selectivity, the accompanying bandwidth increase improves robustness against fabrication variability and environmental detuning. The observed

transition from a relatively narrow-band resonator to a broader-band response therefore provides an additional sensing metric correlated with substrate degradation and fluid exposure.

DISCUSSION

This work demonstrates a miniaturized, functional antenna fabricated directly onto a natural, edible substrate using potato skin. Through a maskless laser scribing process, localized thermal energy carbonizes the potato epidermis into a conductive, three-dimensional porous graphene network, thereby avoiding the bulky and complex fabrication processes associated with traditional photolithography. However, implementing functional microwave designs on biological substrates introduces distinct RF engineering challenges, particularly when constraining the device geometry to a compact 1 cm^2 footprint in order to operate within the ISM band. Unlike smooth, isotropic synthetic polymers like Kapton, which are among the established substrates for laser-induced graphene (LIG) electronics, natural materials present a highly heterogeneous surface topology. Overcoming this heterogeneity requires the precise optimization of laser processing parameters, including power, scan speed, defocus, and laser passes. Restricting fabrication to this operational window is critical as insufficient laser exposure results in incomplete graphitization and increased sheet resistance, whereas excessive exposure damages the organic substrate, thereby increasing the surface roughness or damaging the intended antenna geometry. Consequently, these fabrication parameters directly influence the impedance matching, current distribution, resonant frequency, and overall radiation efficiency of the antenna.

By patterning miniaturized conductive graphene antennas onto potato skin, we show that ingestible electronics can be simplified. Although LIG generally has lower conductivity than bulk metals, it provides sufficient conductivity for many low cost and flexible wireless applications. The main significance of these LIG-based edible antennas is that they combine acceptable antenna performance with a simple and cost-effective fabrication technique. Here we demonstrate that the edible antennas are capable of supporting RF current flow and functioning as radiating elements at 5.8 GHz with a return loss from -12 dB to -40 dB . We observed that the variations in return loss of different antenna batches were mainly due to antenna measurement factors such as contacts, cable positioning, and parasitic effects introduced by the connector and feed line.

The performance of the exposed or non-encapsulated antenna within simulated gastric fluid (SGF) over a 24-hour period demonstrates a dynamic behavior that can be effectively exploited as a passive sensing mechanism. The observed time-dependent attenuation along with the upward frequency shift can be explained by the physical interaction between the acidic fluid and the porous, foam-like morphology of the LIG structure. As SGF penetrates the substrate's cellular structure, the effective relative permittivity of the surrounding dielectric matrix changes dynamically. This fluid absorption alters the substrate's effective capacitance, thereby driving the resonant frequency upward. Additionally, the penetration of highly ionic gastric fluid into the porous LIG network changes the overall sheet resistance and introduces significant dielectric losses, leading to the observed signal attenuation. This platform leverages these material-induced modifications to enable passive sensing. By tracking shifts in resonance and signal

degradation, environmental exposure, and degradation state, local physiological transitions can be monitored, demonstrating its potential as a telemetry-based sensor for gastrointestinal (GI) monitoring.

This platform could be further developed from a purely passive element into a controllable wireless communication device during GI transit. Using encapsulation layers such as cellulose-based or pH-sensitive coatings could allow to control over when the antenna becomes exposed to the surrounding environment. This controlled dissolution enables a transition from communication to sensing, accompanied by corresponding changes in the signal response, which could be used to track the device as it moves through the gastric and intestinal environment. More broadly, this platform offers flexibility in how the device is used. The onset of exposure can be delayed or tuned depending on the coating, allowing for applications that require either extended stability or activation at specific locations in the GI tract.

The porous nature of LIG also opens up possibilities for further functionalization, for example, by incorporating bioreceptors for targeted sensing. For practical reasons, modifying the operating frequency and surface chemistry will be essential for broadening clinical utility. Although the 5.8 GHz band is advantageous for keeping the physical footprint minimal, high-frequency microwave signals face severe attenuation when traveling through lossy biological media. To ensure reliable signal propagation from deep within the human body to external receivers, future designs must shift toward sub-GHz bands such as the 400 MHz or the 915 MHz ISM band. Although lower frequencies require a larger effective electrical length, the high surface-area-to-volume ratio characteristic of porous LIG opens up extensive opportunities for surface functionalization.

CONCLUSION

We demonstrate the successful fabrication of functional wireless antennas directly on heterogeneous, edible substrates utilizing a maskless laser writing technique. By converting the natural carbon components of organic precursors into conductive graphene networks, this platform establishes a viable alternative to conventional ingestible electronics, avoiding the use of rigid and non-biodegradable silicon components. The observed behavior of the antenna in simulated gastric fluid proves that controlled material degradation can be effective as a passive sensing mechanism to monitor physiological environments. When combined with smart, pH-sensitive encapsulation coatings, this approach offers a highly adaptable framework capable of balancing stable wireless communication with targeted environmental sensing during gastrointestinal transit. We show how edible materials can serve as viable platforms for functional electronics, combining simple fabrication with inherent biodegradability. In addition, the demonstration of a compact 1-cm² LIG-on-Kapton antenna highlights the broader applicability of this approach for portable and wearable devices.

METHODS

Fabrication of LIG-on Potato Skin and Kapton

LIG antennas were fabricated using a laser scribing tool (FLUX Beam box Pro CO2 laser cutter) on both potato skin and Kapton (DuPont Kapton polyimide sheet with a relative permittivity of 3.4 and loss tangent of 0.002). The laser parameters were carefully optimized, with power set to 16–17% at a speed of 130–140 mm/s with multiple passes. Pretreatment of the potato skin with a fire retardant prepares the surface for multiple lasing. Applying the laser 2–3 times yields a more desirable conductive layer. However, exceeding three passes results in thermal degradation and surface ablation. In addition to these parameters, the potato substrate required a defocused beam (1–2 mm offset) to ensure uniform energy distribution and prevent localized burning of the substrate in contrast to polyimide which is typically lased at the focal point.

Antenna Measurement

The functional viability of the LIG-on-potato antenna was demonstrated using high-frequency characterization using a vector network analyzer (VNA) (Keysight N5247A PNA). Prior to the measurements, the VNA was calibrated over a frequency range of 1–10 GHz using a Keysight N4694D electronic calibration (e-cal) module, with the calibration reference plane defined at the SMA connector ends of the coaxial cables. For both the LIG-on-Kapton and LIG-on-potato antennas, a copper tape ground plane was attached to the reverse side of the substrate. Due to the irregular and heterogeneous surface of the potato skin, direct soldering of the SMA connector was not feasible; instead, silver conductive paint was applied to ensure reliable electrical connectivity between the SMA center pin and the antenna inset feed point. The antenna was then connected to the VNA using Keysight N4697J flexible test cables to minimize signal loss and phase instability across the measurement frequency range. S-parameter measurements (S_{11} and S_{21}) were first recorded under ambient, dry conditions to characterize the antenna's electromagnetic behavior. For the liquid immersion testing, a custom acrylic enclosure was designed with a precision cutout sized to accommodate the antenna aperture. The LIG-on-potato antenna was suspended within this cutout such that it was surrounded by the test liquid on all sides without making direct contact with the container walls, ensuring uniform dielectric loading. An external FR4 copper antenna was positioned outside the enclosure and served as the transmitter, while the LIG-on-potato antenna acted as the receiver, enabling S_{21} transmission coefficient measurements across the liquid environments. All liquid tests were conducted at room temperature.

Scanning Electron Microscopy (SEM)

The LIG samples were mounted on an SEM stub using copper tape and imaged using a ThermoFischer Quanta 3D microscope with a primary electron energy of 2–5 kV.

Raman Spectroscopy

The spectroscopic characterization was performed using a confocal Raman microscope (WITec Alpha 300R) with a laser excitation source of 633 and 532 nm using a 20 × and 10 × objective lens for LIG-on-potato and Lig on Kapton respectively to capture spectra within the 1000 to 3000 cm^{-1} wavenumber range.

Declarations

Author Contribution

Conceptualization, H.M. and K.B.R.; methodology, N.N., H.M., S.S., R.S., M.A.A and M.R.; software, N.N., and R.S.; investigation, N.N, H.M, S.S, R.S, M.A.A, M.E., J.W; resources, K.B.R, S.H., M.R.; data curation, N.N, H.M; writing – original draft, H.M; writing – review & editing N.N, H.M., S.S, R.S, S.H, M.R and K.B.R.; supervision, K.B.R. and M.R.; project administration, K.B.R. Authors N.N and H.M have contributed equally.

Acknowledgement

This work was supported by New York University Abu Dhabi (NYUAD) and carried out using the Core Technology Platform resources at New York University Abu Dhabi. We would also like to acknowledge the Micro and Nanoscale Bioengineering Lab under Prof. Yong-Ak Song for the laser cutter utilization.

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Figures

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Figure 1

Legend not included with this version.

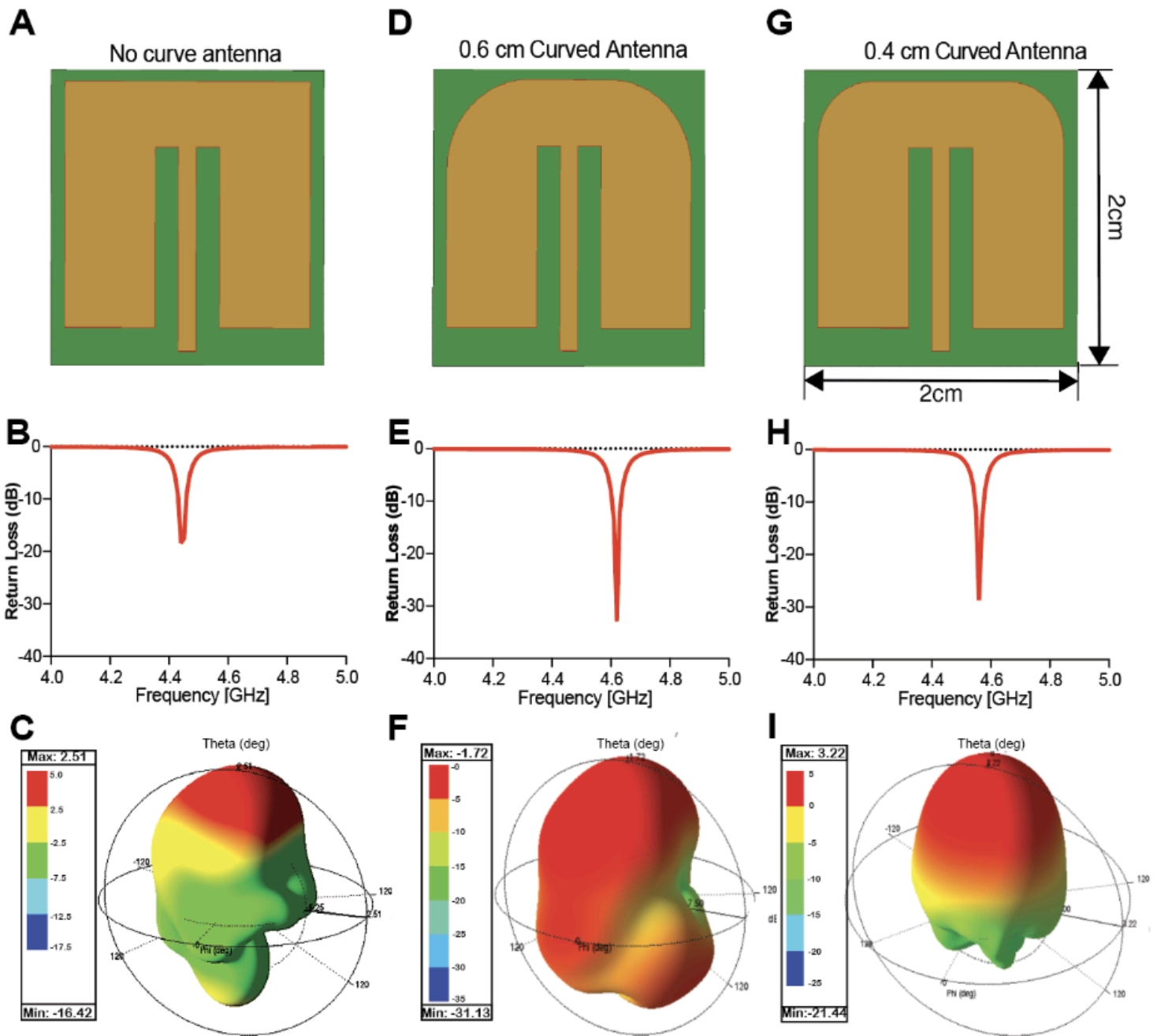


Figure 2

Figure 2 (A) Straight antenna design with (B) corresponding operating frequency and (C) simulated gain (in dBi). (D) Curved antenna with 0.6cm curved antenna with (E) operating frequency and (F) simulated gain (in dBi). (G) Curved antenna with 0.4cm curved antenna with (H) operating frequency and (I) simulated gain (in dBi).

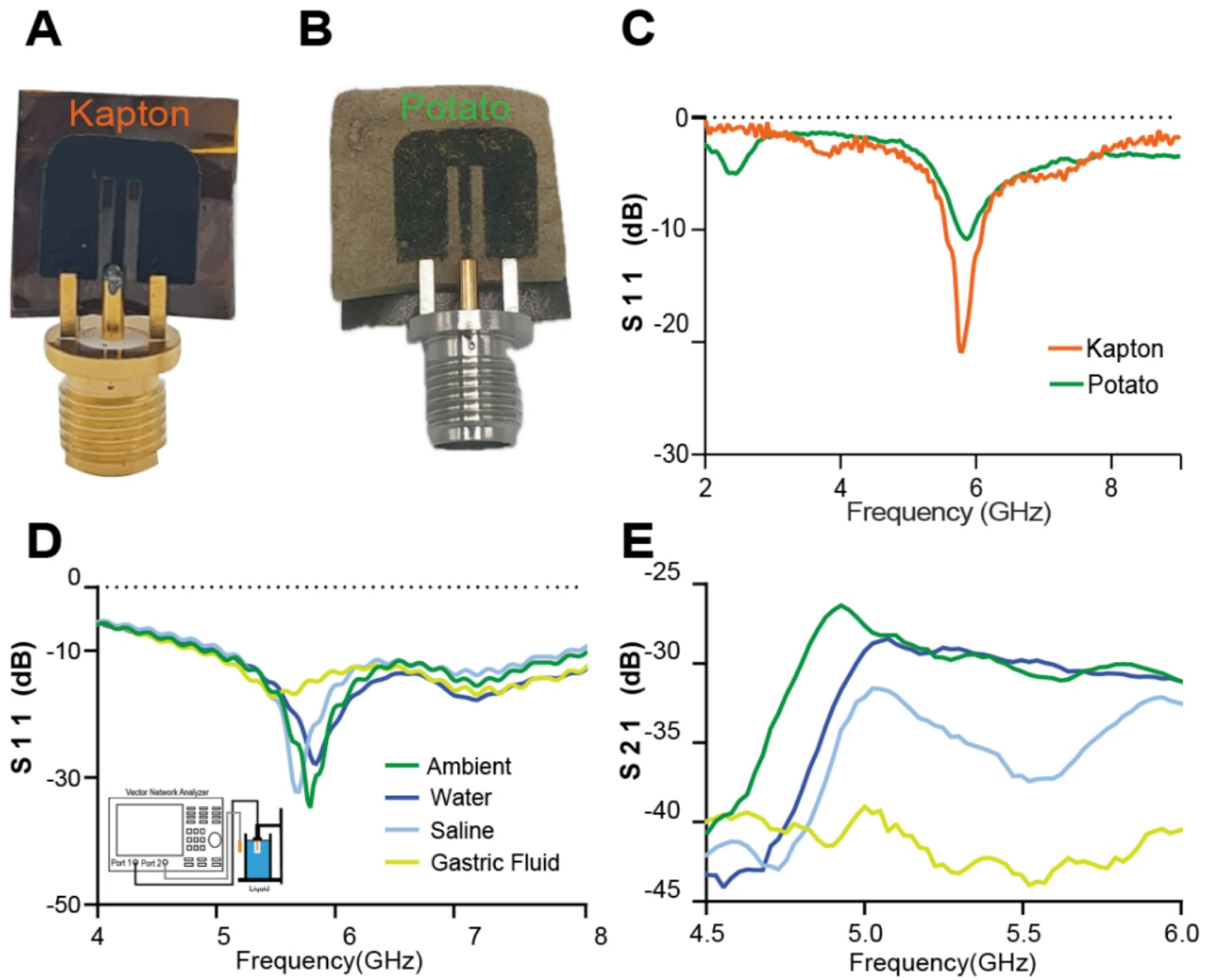


Figure 3

Figure 3. LIG antenna on (A) Kapton and (B) potato skin. (C) Reflection coefficient (S_{11}) of 1 cm x 1 cm antenna on Kapton and potato skin, (D) Reflection coefficient (S_{11}) on LIG on potato antenna in various media, (E) Transmission coefficient (S_{21}) of LIG on potato antenna in various media

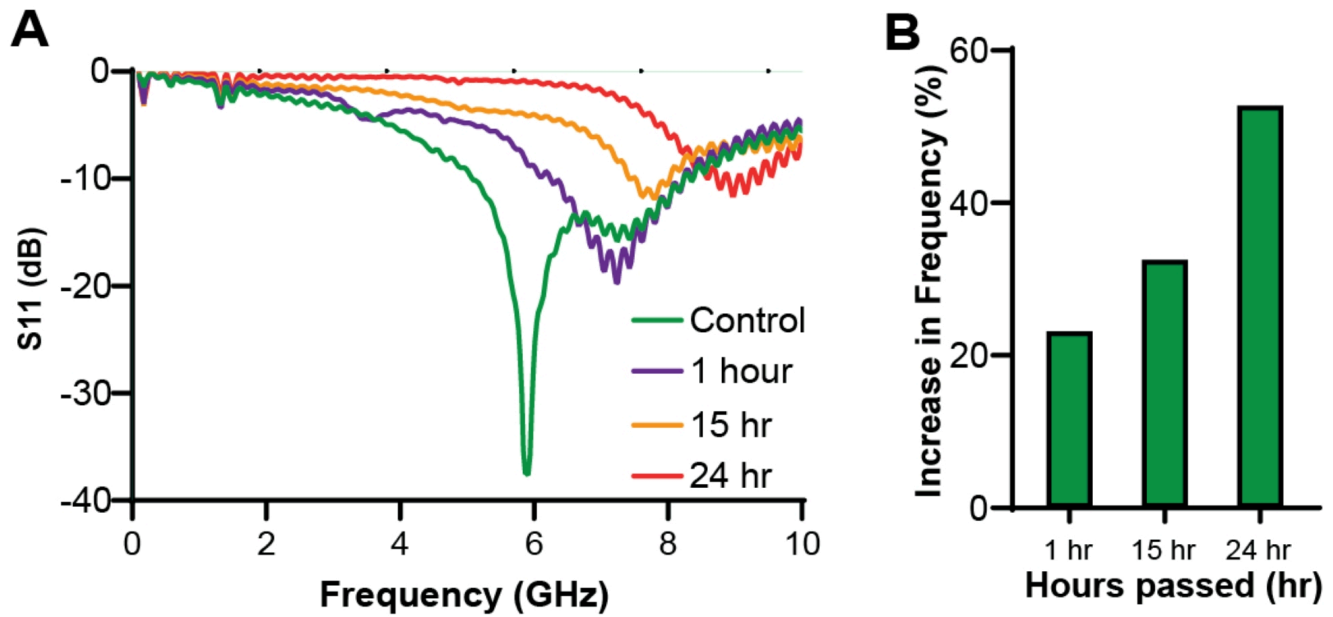


Figure 4

Figure 4 (A) Reflection coefficient (S_{11}) of LIG antenna on potato in simulated gastric fluid (SGF), (B) Time-dependent changes in operating frequency over time as LIG degrades in SGF.

Supplementary Files

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