

Laser Induced Graphene Patterned on Potato Skin Enables Functional Radiofrequency Antenna Operation

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

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Abstract

Laser-induced graphene (LIG) enables the maskless formation of conductive carbon structures, but the translation of LIG patterns on food-derived materials into functional components remains underexplored. Here, we fabricate miniaturized LIG antennas directly on potato skin and evaluate whether this irregular, heterogeneous substrate can support a well-defined resonant radiofrequency (RF) response. A multipass, defocused laser process produced an approximately 30 μm thick porous graphitic network, with Raman spectra exhibiting the characteristic D, G, and 2D bands. A miniaturized $1 \times 1 \text{ cm}^2$ antenna incorporating a curved patch geometry and inset microstrip feed was designed to achieve resonance in the 5.8 GHz industrial, scientific, medical (ISM) band and benchmarked against an identical-geometry LIG antenna fabricated on polyimide (Kapton). Vector network analyzer measurements confirmed resonant operation near 5.8 GHz for antennas fabricated on both substrates. In a transmitter-receiver configuration, the LIG-on-potato antenna produced a detectable transmission response while immersed in water, saline, and simulated gastric fluid. Measurements conducted over 24 h of exposure to simulated gastric fluid (SGF) revealed progressive changes in resonant frequency, reflection coefficient, bandwidth, and apparent quality factor. These results demonstrate that LIG patterned directly on a heterogeneous food-derived substrate can support a miniaturized resonant RF component and establish a proof-of-concept platform for future food-derived wireless electronics.

INTRODUCTION

Laser-induced graphene (LIG) is a direct, maskless technique for photothermally converting carbon-rich precursors into conductive, porous, three-dimensional graphene networks^{1–3}. Since its original demonstration on polyimide, LIG has been developed into functional electronic components, including antennas, supercapacitors, and sensors, on synthetic substrates. LIG synthesis has subsequently been extended to a range of natural precursors, including wood, paper, cork, coconut, bread and potato with the resulting material properties depending strongly on precursor composition, surface conditions, and laser-processing parameters^{4–7}.

Within this broader class of natural precursors, food-derived substrates remain underexplored as platforms for functional LIG electronics. Previous studies have produced LIG patterns on potato, bread, and coconut, confirming that conductive structures can be formed directly on these materials. However, these investigations have focused primarily on LIG formation, material characterization, and electrical conductivity rather than quantitatively validated component-level performance. Resonant RF operation from an antenna patterned directly on a heterogeneous food-derived substrate has not been quantitatively demonstrated so far. This distinction is important as conductivity alone does not establish whether a patterned material can function as an RF component, whose performance depends jointly on conductor geometry, electrical properties, substrate characteristics and fabrication uniformity.

Achieving component-level operation is particularly challenging on biological materials. Unlike smooth and compositionally uniform polymer films, food-derived substrates exhibit spatial variations in surface

topology, moisture content, thickness and chemical composition. These variations can consequently affect the structural and electrical properties of the resulting LIG. They can also compromise the geometrical consistency required to obtain a predictable resonant response. Quantitative RF measurements are therefore needed to determine whether LIG patterned directly on a food-derived substrate can support a well-defined resonant response.

One prospective application for such material platforms is in the field of ingestible electronics (Fig. 1A). Such components could support minimally invasive *in vivo* sensing, diagnostics, and targeted therapeutic delivery^{8–16}. For applications requiring the transmission of data or physiological information from within the gastrointestinal tract, a compact wireless communication interface is required¹⁷. Antennas fabricated directly on food-derived substrates could ultimately contribute to such an interface while reducing reliance on a separate synthetic carrier for the radiating element^{18–20}. Their incorporation into complete ingestible systems would, however require further integration with communication, sensing, power and packaging components.

RF antennas provide a useful test of the transition from conductive material to functional component because their resonant frequency and impedance response depend jointly on conductor geometry, conductivity, substrate properties and fabrication uniformity. Here, we address this materials-to-component transition by evaluating whether LIG patterned directly on potato skin can support resonant RF operation. Using a maskless, multipass defocused laser process, we fabricate a $1 \times 1 \text{ cm}^2$ LIG antenna designed to operate in the 5.8 GHz ISM band (Fig. 1B, C). Laser-processing conditions are selected to convert the carbon-rich potato-skin surface into conductive LIG. The resulting antenna is benchmarked against an identical-geometry LIG antenna fabricated on Kapton providing a reference for comparing the RF response of the heterogeneous food-derived platform with that of an established synthetic LIG substrate.

We further characterize changes in the electrical and electromagnetic response of the LIG-on-potato antenna during exposure to simulated gastric fluid. Simulated gastric fluid (SGF) was selected to examine the antenna's response under conditions relevant to potential ingestible applications. The time-dependent resonant response is used to examine how RF behavior evolves under physiologically relevant SGF exposure. These measurements also suggest potential dual functionality; the structure can operate as a resonant RF component, while changes in its electromagnetic response may provide an indication of its exposure or transient material state (Fig. 1A). Future integration with an RFID chip could enable this response to be interrogated wirelessly using an external reader. We demonstrate proof-of-concept of a component level RF operation on a food-derived LIG substrate and characterize its time-dependent electromagnetic response during exposure to simulated gastric fluid.

RESULTS

Synthesis of LIG-on-Potato Skin

The successful transformation of a food-derived substrate into LIG 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 natural 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%)^{21–23}. 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 graphitization⁵. 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).

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) exhibit 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})^{24,25}. 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. LIG was also fabricated on Kapton to serve as a benchmark for the LIG-on-potato 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

We selected a 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 effect²⁶ 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 cm^2 was performed to obtain operation at 5.8 GHz.

Experimental RF Performance of LIG-on-Potato Antennas

To transition the LIG-on-potato material into a functional RF component, the antenna design must satisfy fundamental electromagnetic requirements relevant for compact, high frequency device design such as the return loss S_{11} and transmission coefficient S_{21} . A commonly used impedance-matching criterion is $S_{11} < -10$ dB, which indicates that less than 10% of the incident power is reflected at the antenna port. Although this criterion does not independently establish radiation efficiency, it confirms that most of the incident power is accepted by the antenna. The S_{21} measurements provide insight into end-to-end wireless transmission through the surrounding propagation environment. As S_{21} also depends on

antenna separation, alignment, impedance matching, cables and propagation losses, it is interpreted as a system-level transmission response rather than a direct measurement of antenna efficiency.

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 substrate on the measured electromagnetic response. VNA measurements of both the LIG-on-Kapton and LIG-on-potato 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 such as cables and test surfaces, it demonstrates detectable transmission between the external antenna and the LIG-on-potato antenna in an acidic ionic medium mimicking gastric-fluid conditions. 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.

Time-Dependent Electromagnetic Response in Simulated Gastric Fluid

The porous, three-dimensional architecture of LIG makes its electrical and electromagnetic properties inherently sensitive to fluid infiltration, offering a route to correlate material-level degradation with measurable changes in resonant behavior over time. To evaluate this behavior, 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 may be driven by the interaction between the acidic medium and the

engineered porosity of the LIG layer, resulting in a 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 patterned 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 cm² footprint in order to operate within the ISM band. Additionally, unlike smooth, isotropic synthetic polymers like Kapton, which are among the established substrates for laser-induced graphene (LIG) electronics, food-derived materials present a highly heterogeneous surface topology. The LIG processing window was therefore selected by controlling laser power, scan speed, focal offset, number of passes and minimal curvature variation of the substrate. We observed that insufficient exposure produced incomplete carbonization and discontinuous patterns, whereas excessive exposure caused surface ablation and distorted the intended antenna geometry. Defocusing the laser reduced localized burning, while repeated exposure promoted the formation of a continuous conductive region. These observations highlight the importance of controlling laser-processing conditions when fabricating geometrically sensitive RF components on heterogeneous food-derived substrates.

Although LIG generally has lower electrical conductivity than bulk metals, its direct formation on a substrate can eliminate the need to deposit or transfer a separate conductive material for the radiating pattern. Lower conductivity may increase conductor losses and limit radiation efficiency; yet the resonant response demonstrated here shows that potato-derived LIG provides sufficient conductivity to support component-level RF operation at 5.8 GHz. Both the LIG-on-potato antenna and the identical-geometry LIG-on-Kapton reference exhibited resonance near the intended operating frequency, with minimum S_{11} values ranging from approximately -12 to -40 dB across the measured devices. These results demonstrate impedance-matched resonant operation below the commonly used -10 dB criterion. The observed variation in S_{11} likely reflects a combination of substrate heterogeneity, fabrication variability, electrical contacts, cable positioning, and parasitic effects associated with the connector and feed line. Because these contributions were not independently quantified, the differences cannot be attributed exclusively to either the food-derived substrate or the measurement setup. The significance of the LIG-on-potato antenna therefore lies in combining measurable RF functionality with a direct, maskless fabrication process on a heterogeneous food-derived substrate. The transmitter-receiver measurements provide additional evidence of RF functionality. A detectable S_{21} response was measured when the LIG-on-potato antenna was immersed in water, saline, and simulated gastric fluid. In simulated gastric fluid, the peak S_{21} value was approximately -25 dB, demonstrating detectable coupling between the external transmitter and the immersed LIG-on-potato receiver under the specified experimental conditions.

Having established resonant operation and detectable transmission, we next examined the response of the exposed LIG-on-potato antenna during 24 h of immersion in simulated gastric fluid. The resonant frequency, S_{21} , bandwidth and apparent quality factor changed progressively with exposure time. This dynamic electromagnetic behavior demonstrates that the antenna response depends on its duration of exposure and suggests that it could potentially be used as a passive indicator of fluid exposure or changes in the material state. Here, the observed time-dependent attenuation along with the upward frequency shift could be due to the physical interaction between the acidic ionic 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 may alter the substrate's effective capacitance, thereby driving the resonant frequency upward. Additionally, the penetration of highly ionic gastric fluid into the porous LIG network could change the overall sheet resistance and introduces significant dielectric losses, leading to the observed signal attenuation. Because these properties were not measured independently during immersion, their individual contributions cannot be resolved from the present RF measurements. In particular, the upward frequency shift should not be attributed solely to a change in effective permittivity because dielectric loading and physical changes to the antenna may exert competing effects on the resonance. The decrease in apparent quality factor and accompanying broadening of the resonance provide additional measures of the evolving electromagnetic state of the antenna. Although a broader bandwidth can reduce sensitivity to frequency detuning, the observed broadening occurred together with attenuation and weaker impedance matching and should not be interpreted as improved antenna performance.

Instead, the combined changes in resonant frequency, signal magnitude, bandwidth, and apparent quality factor characterize the time-dependent response of the antenna during simulated gastric-fluid exposure.

Taken together, the exposure-dependent response suggests potential dual functionality. The LIG-on-potato structure can operate as a resonant RF component, while changes in its electromagnetic response may provide an indication of its exposure history or transient material state. Integration with an RFID chip or another wireless readout system could enable this response to be interrogated remotely, providing a potential route toward telemetry-based monitoring. Additional functionality could be introduced through encapsulation and surface modification. Cellulose-based or environmentally responsive coatings could regulate when the antenna becomes exposed to its surroundings, enabling a transition from a protected resonant state to an exposure-responsive state. The timing of this transition could potentially be adjusted through coating composition and thickness for delayed or location-dependent activation. Furthermore, the porous LIG surface could support functionalization with selective recognition elements for targeted sensing. Together, these opportunities illustrate how the demonstrated antenna could be extended toward controllable and multifunctional food-derived wireless components.

In the case of intra-body applications, 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 could allow for surface functionalization.

CONCLUSION

This study demonstrates the translation of laser-induced graphene on a food-derived substrate from conductive-pattern formation to functional component-level RF operation. To our knowledge, this is the first demonstration of a functional antenna patterned directly on a food-derived substrate. The maskless, multipass laser process converted potato skin into a porous graphitic network that was patterned into a miniaturized $1 \times 1 \text{ cm}^2$ antenna operating near the 5.8 GHz ISM band. An identical LIG-on-Kapton antenna provided a reference on an established synthetic substrate, while reflection and transmitter-receiver measurements confirmed resonant operation and detectable end-to-end RF transmission from the LIG-on-potato antenna.

The *in vitro* measurements further showed that the antenna's resonant frequency, S_{11} , bandwidth, and apparent quality factor evolved progressively during 24 h of exposure to simulated gastric fluid. These exposure-dependent changes demonstrate that the electromagnetic response of the antenna is sensitive to changes in its surrounding environment and support its potential use as a passive indicator of fluid exposure or transient material state. The combination of miniaturized RF functionality and an

environment-dependent resonant response distinguish this work from previous studies limited primarily to LIG formation and conductive patterning on food-derived materials. Future integration with RFID electronics, selective recognition elements, and encapsulation strategies could enable wireless interrogation, targeted sensing, and controlled operation in more complete ingestible systems.

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 antennas 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

COMPETING INTERESTS

The authors declare no competing interests.

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.

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Data Availability

All data reported in this paper will be shared by the corresponding author upon request.

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Figures

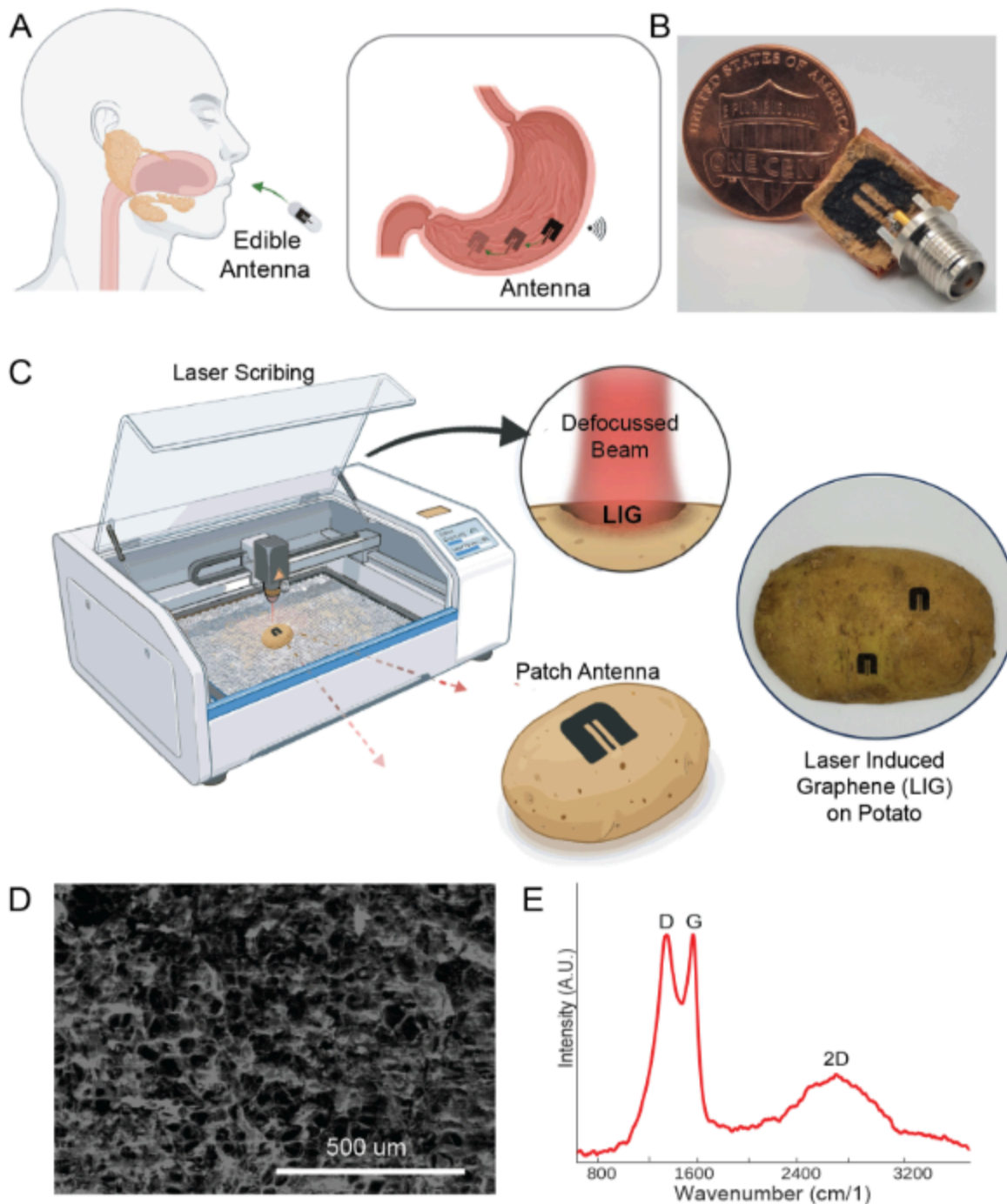


Figure 1

Fabrication and characterization of the LIG-on-potato antenna.

(A) Conceptual illustration of a laser-induced graphene (LIG) antenna fabricated on a food-derived substrate and its potential use as an ingestible radiofrequency (RF) component in the gastric environment. (B) LIG antenna patterned on potato skin with a connector for RF measurements. (C) LIG antenna scribed on potato skin (inset showing defocused laser beam for optimal scribing). (D) scanning electron microscopy (SEM) image of LIG on potato skin. (E) Raman spectrum of LIG on potato skin

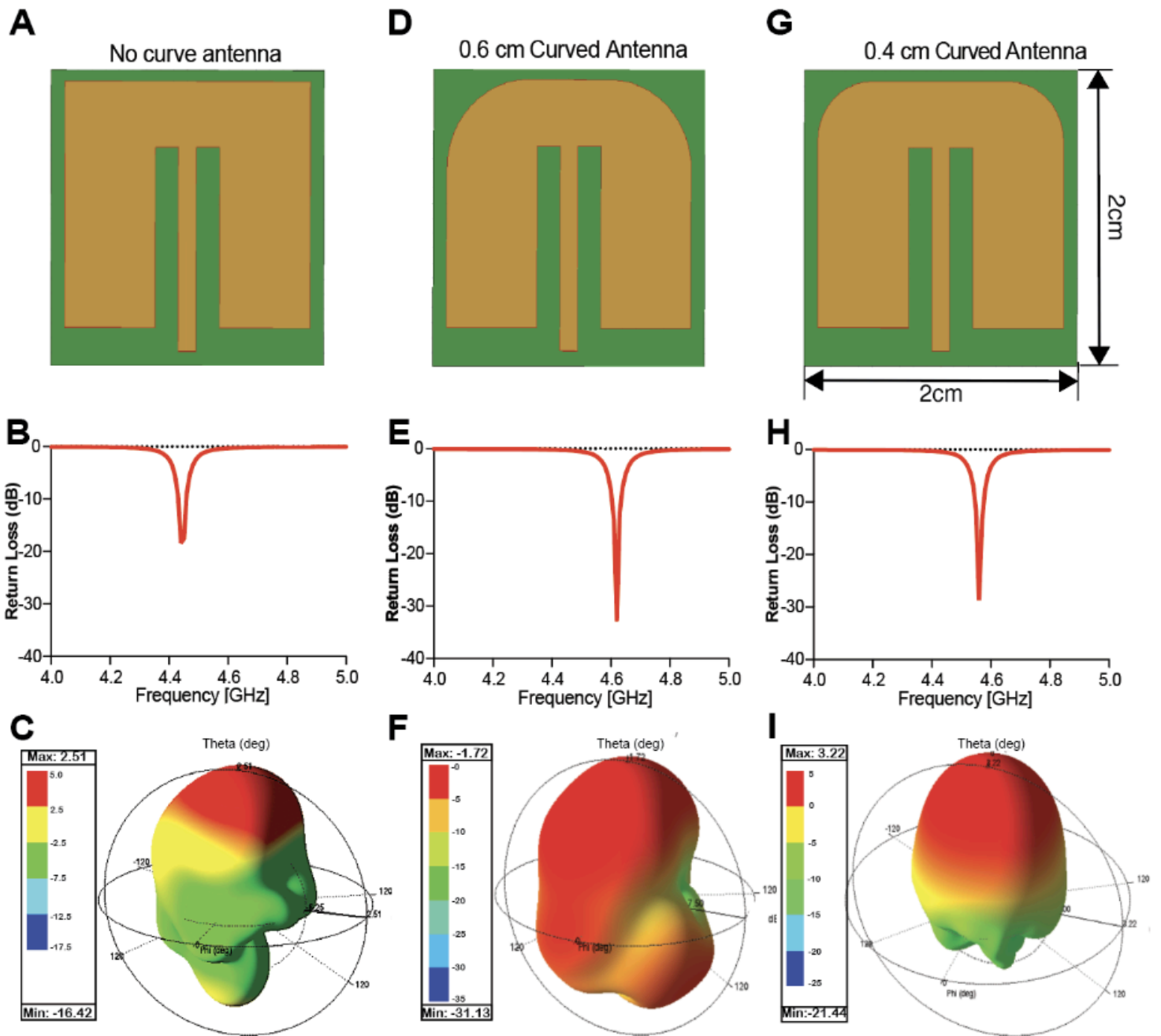


Figure 2

Simulated antenna designs and RF characteristics.

(A) Straight-edged antenna design with its corresponding (B) simulated frequency response and (C) simulated gain (in dBi). (D) Curved antenna design with a corner radius of 0.6 cm with its corresponding (E) simulated frequency and (F) simulated gain (in dBi). (G) Curved antenna design with a corner radius of 0.4cm, with its corresponding (H) simulated frequency response and (I) simulated gain (in dBi).

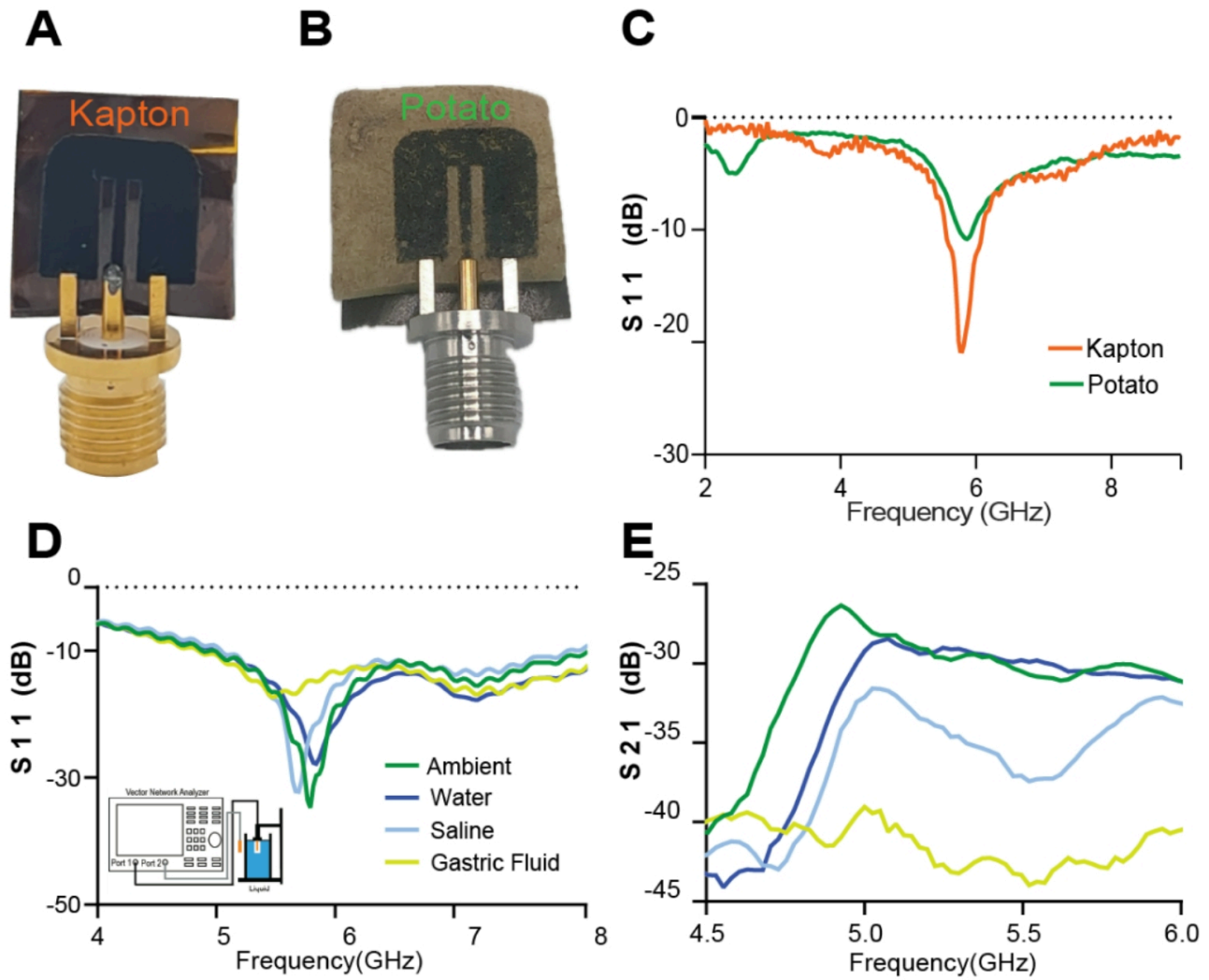


Figure 3

Experimental RF performance of LIG antennas.

Images of the LIG antenna fabricated 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.

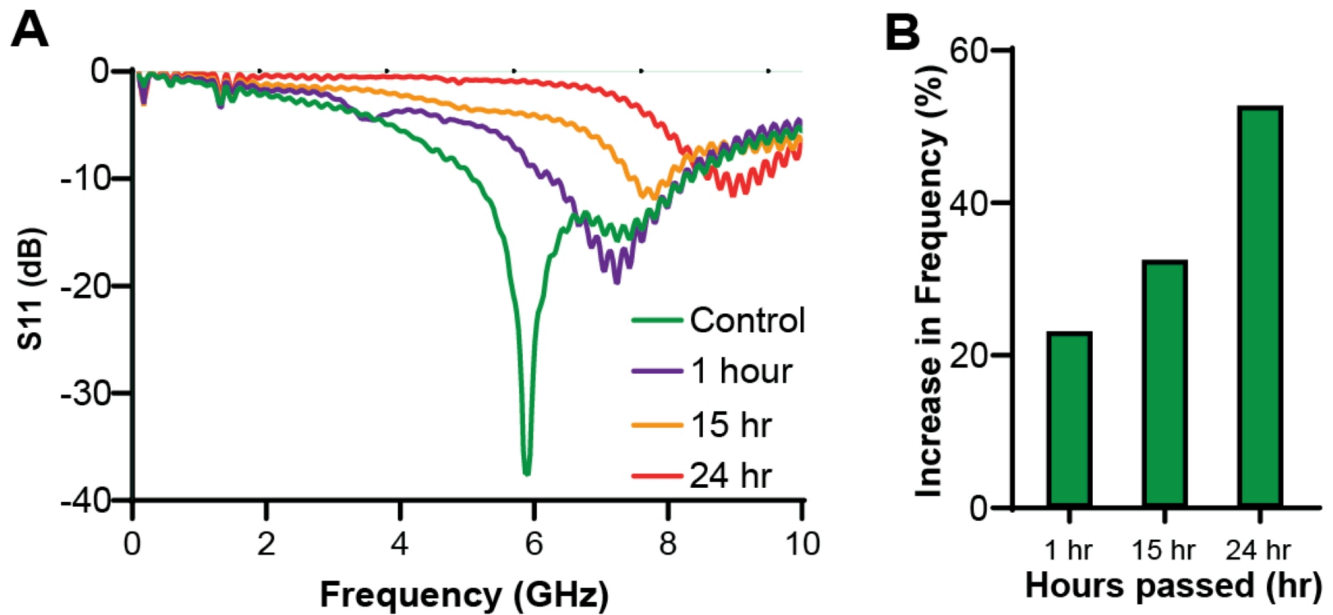


Figure 4

Time-dependent RF response during simulated gastric-fluid exposure.

(A) Reflection coefficient (S_{11}) of the LIG-on-potato antenna during exposure to simulated gastric fluid (SGF). (B) Change in resonant frequency as a function of SGF exposure time.

Supplementary Files

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