

Eco-Sustainable RFID Antennas on Plasticized Starch Enabled by RF-Optimized Laser-Induced Graphene Transfer

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Abstract—The increasing demand for sustainable RFID and sensing systems drives the transition toward biodegradable materials and low-energy fabrication. Conventional conductors and petroleum-based polymers (e.g., PET, PI) ensure high performance but lack environmental compatibility. This work introduces a near-metal-free fabrication process for conductive and biodegradable antennas based on Laser-Induced Graphene (LIG) transferred onto Plasticized Starch (PS). Since PS is unsuitable for direct laser-writing, a LIG master acts as a transfer matrix. Conductive patterns are imprinted onto the PS film through a low-temperature curing and peeling process. A parametric analysis identifies the optimal curing conditions, assessing the morphological homogeneity and the electrical stability of the transferred traces. Results demonstrate a sheet resistance as low as $4.8 \Omega/\text{sq}$ with nearly 100% geometrical integrity and excellent adhesion. As a demonstrator, a C-dipole antenna for smart packaging is fabricated and tested, exhibiting high robustness against repeated bending and reliable operation in realistic scenarios. Applied to food-filled packages, the antenna provides a read range of 45–60 cm, in the worst case scenario, which is compatible with proximity identification on smart shelves. By combining a bio-derived substrate with a carbon-based conductor, this platform eliminates the need for metal-plastic separation, significantly reducing the complexity of end-of-life recovery.

Index Terms—Laser-Induced Graphene (LIG), Plasticized Starch (PS), Sustainable Electronics, RFID Antennas, Sensor, Smart Packaging.

I. INTRODUCTION

The rapid expansion of the Internet of Things (IoT) across industrial domains such as manufacturing, healthcare, agri-food, automotive, and logistics has accelerated the deployment of Radio-Frequency Identification (RFID) technologies as a core enabler for large-scale identification and sensing [1], [2]. At the same time, this widespread diffusion has raised increasing concerns regarding the environmental footprint associated with both production and end-of-life management of RFID labels. Recent assessments indicate that the integration of RFID tags in large-scale supply chains, such as medical and pharmaceutical logistics, already contributes to non-negligible

CO₂ emissions on a yearly basis [3]. As a result, the development of sustainable materials and fabrication processes for RFID devices has emerged as a relevant research challenge.

As RFID labels are composed of a dielectric substrate, a conductive radiating trace, and a microelectronic chip, the development of environmentally sustainable devices must address all material constituents of the tag, rather than focusing on a single component. In particular, the substrate and the antenna conductor, which together determine both the electromagnetic performance and most of the environmental footprint of the device, must be jointly redesigned through eco-compatible materials and fabrication processes. Concerning the dielectric substrate, polyethylene terephthalate (PET), polyimide (PI), and polyvinyl chloride (PVC), that are typical substrates for RFID antennas, are progressively being replaced by paper-based materials [4], [5], which already provide advantages in terms of recyclability and end-of-life management. With the aim of further reducing environmental impact, more recent research efforts are extending this trend toward bio-based alternatives, including chitosan [6], gelatin [7], cellulose derivatives [8]. However, when conventional metallic conductors are applied onto biodegradable substrates, the resulting structures are metal-dielectric laminates, which complicate recycling and end-of-life handling. Recent studies have explored carbon-based inks, such as graphene nanoplatelets and carbon nanotube dispersions, as well as polymer-based conductors cross-linked to biodegradable matrices [9], [10], [11]. Despite their potential, most of these approaches still rely on wet-chemical processing steps, which limit process sustainability and scalability.

Along this line, the plasticized starch (PS) polymer can be considered a particularly promising candidate for the substrate as the main constituent can be obtained also from agro-industrial residues of potato and rice processing. In addition to direct agricultural sources, indeed, starch can be recovered from by-products such as washing water and peeling scraps [12], which can be converted into powders and reused, supporting circular-economy [13]. Owing to their bio-origin and relatively low-temperature processing, PS films can be produced with limited energy input and reduced reliance on additional chemical treatments.

From the conductor perspective, the Laser-Induced Graphene (LIG) technology could be exploited for the fabrication of sustainable circuits enabling dry, mask- and chemical-free patterning of conductive elements.

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Representative applications of LIG processing include sensors [14], energy harvesters [15], and, more recently, antennas [16]. Laser-induction enables the direct conversion of carbon-rich precursors into graphene-based conductive patterns [17]. When combined with biodegradable substrates, the intrinsic biocompatibility of LIG [18] further supports simplified end-of-life handling, potentially allowing the disposal of the substrate-conductor system without any separation step. Typical LIG precursor materials include, PI, poly-ether-ether-ketone (PEEK), polysulfone (PSU), but also paper [19], wood [20], fabric, and even food [21], [22]. Unfortunately, the high temperatures involved in the photothermal conversion either ablate the precursor or produce highly-defective graphene, whose sheet resistance ($\propto \text{k}\Omega/\text{sq}$) is not suitable for antenna applications. Hence, to the best of the authors' knowledge, no examples of full-LIG antennas by direct engraving of biodegradable substrates are present in the literature. To overcome this limitation, transfer-based processes have been proposed, primarily for sensing applications [23]. In these approaches, a starch solution is cast onto a laser-processed polymeric master and peeled off after curing, demonstrating that conductive carbon patterns can be embedded into biodegradable films. However, the prior work has focused mainly on material transfer and sensing functionality, with limited attention to the electromagnetic requirements of wireless devices. In particular, the starting LIG traces were not optimized to maximize the electrical conductivity, yielding sheet resistance values on the order of $10^3 \Omega/\text{sq}$, far above the few ohms-per-square required for efficient radiation in wireless systems [16]. Moreover, unlike millimeter-scale sensors, centimeter-scale RF antennas rely on continuous and defect-free conductive traces, since even small discontinuities can perturb the surface current distribution and degrade radiation performance.

In this work, departing from the state of the art and extending the preliminary results reported in [24], we address the formation of the PS-LIG composite specifically tailored for wireless applications. With this aim, the contribution is twofold: *i*) the process parameters are optimized to preserve the sheet resistance of the initial LIG trace upon the transfer, reduce the dielectric losses of the PS film, and prevent the formation of defects during the transfer, and *ii*) the temporal stability of the composite material is experimentally evaluated as a relevant indicator of process robustness. The PS-LIG composite formation process is experimentally validated through a representative RFID antenna for smart packaging applications. The demonstrator is used not only to characterize the electromagnetic performance of the antenna, but also to assess the robustness of the material platform against mechanical deformation and variable environmental conditions.

The paper is organized as follows. Section II introduces the constituent materials and describes the LIG transfer process onto plasticized starch substrates. Section III addresses process optimization, with particular emphasis on the role of curing time at fixed temperature, and quantitatively evaluates the resulting material through radio-frequency characterization of the PS dielectric properties and the electrical performance of the transferred graphene patterns. Section IV discusses the

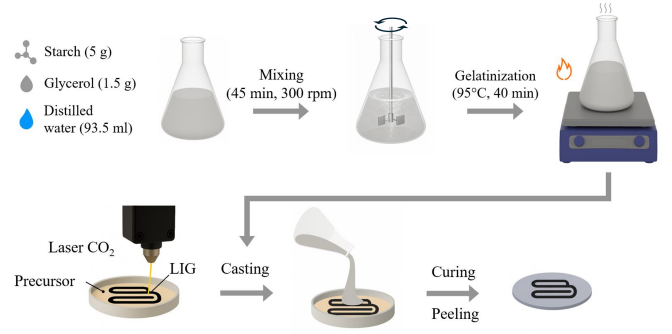


Fig. 1: Schematic illustration of the solvent-casting-based transfer process used to embed the LIG pattern into the PS film.

hygroscopic properties and the temporal stability of the PS film. Finally, Section V presents the application demonstrator obtained through the optimized fabrication.

II. MATERIALS AND TRANSFER PROCESS

A. Laser-Induced Graphene (LIG) Master

The graphene transfer relies on a PEEK film (Goodfellow [25]) with thickness $t = 125 \mu\text{m}$, used as the master for graphene transfer. Compared with other laser-compatible polymers, such as polyimide, PEEK conversion to LIG requires less energy, and returns a morphologically compact graphene pattern (Table S1 and Fig. S1 of SI). This directly impacts the final electrical properties of the transferred conductor since the initial conductivity of the LIG on the master precursor is higher, and the more extent contact area between the hosting polymer and the LIG flakes increases the robustness of the bond [26]. As a result, the transferred graphene forms a completely embedded and continuous conductive network.

B. Plasticized Starch (PS)

PS films are prepared as in [27] starting from a water-based mixture composed of 5 wt% potato starch (Paneangeli, Italy), 1.5 wt% glycerol as plasticizer, and 93.5 wt% distilled water¹. The constituents are poured into a glass flask and magnetically stirred at 300 rpm for 45 min to ensure homogeneous dispersion of the starch granules and ease the initial swelling phase. The suspension is then heated to 95°C for 40 min to promote starch gelatinization and plasticization, yielding a transparent high-viscosity fluid for casting. Hence, the PS solution is poured into circular silicone molds and cured at 50°C in static air [27], [28].

C. LIG Transfer

The integration of the LIG pattern onto the PS film is achieved through a solvent-casting-based transfer process as in [29], [30]. The procedure (Fig. 1) exploits the transition

¹The relevant amount of water is required to promote swelling of the starch granules, disrupt their hierarchical semi-crystalline structure, and release the polysaccharide chains, thus enabling starch gelatinization and the formation of a homogeneous plastic matrix

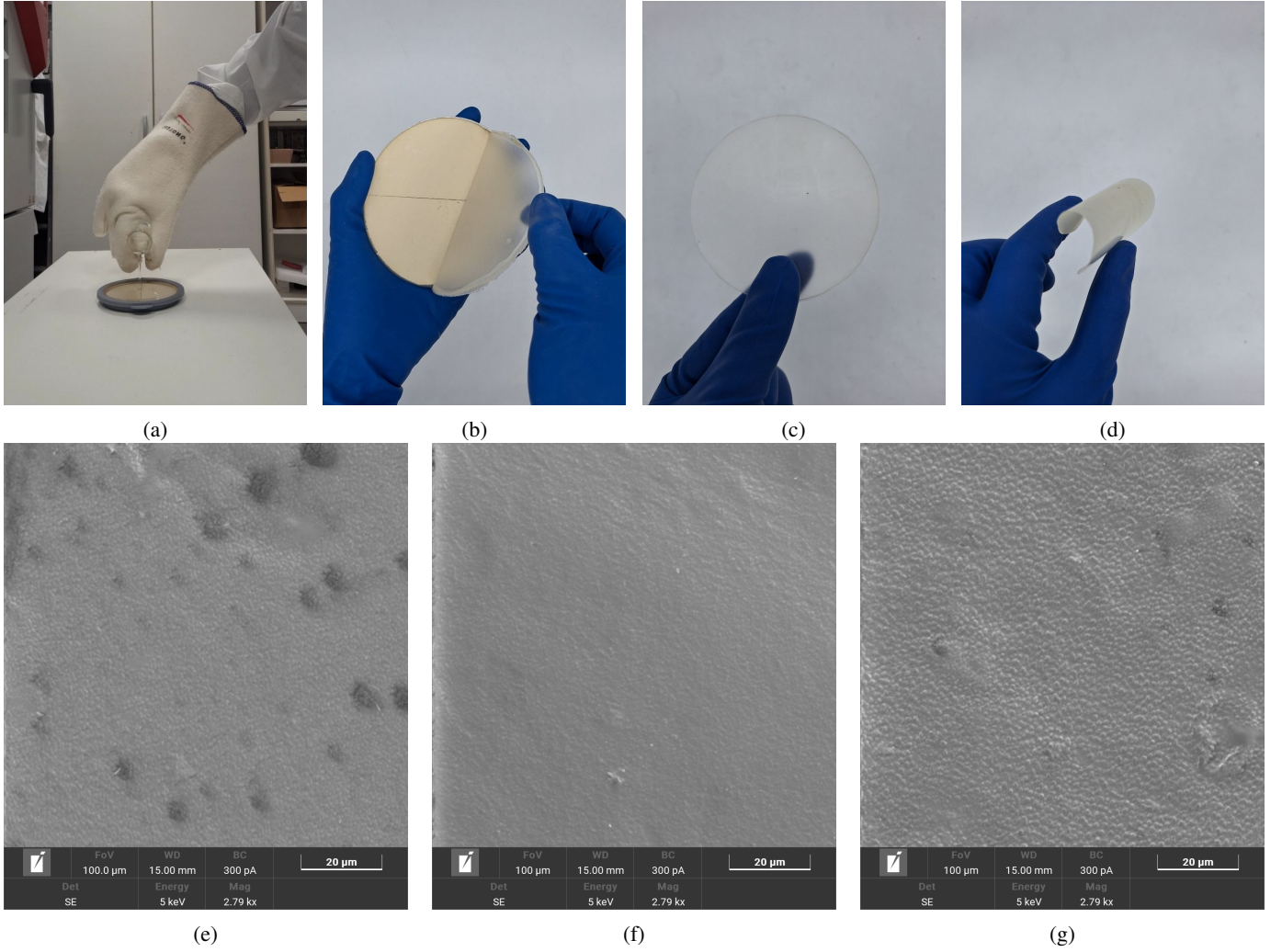


Fig. 2: Snapshots of (a) liquid mixture casting, (b) post-curing peeling, (c) formed PS film, and (d) flexibility test. Scanning Electron Microscope (SEM) images of the bare PS film after (e) $\tau_C = 2$ days, (f) $\tau_C = 3$ days, and (g) $\tau_C = 4$ days.

from a high-viscosity fluid to a bulky plasticized starch film mechanically embedding the conductive LIG network without the use of adhesives or metallic interlayers.

Upon stirring and heating, the high-viscosity starch-glycerol mixture is poured directly onto the laser-patterned LIG master ensuring complete coating of the conductive regions. In this phase, the high-viscosity PS solution infiltrates the porous structure of the LIG layer. The mixture is then cured at fixed temperature, T_C , during a time τ_C to be investigated next, to promote solvent evaporation, consolidation of the starch matrix, and stabilization of the embedded conductive pattern. Lower curing temperatures, including room-temperature conditions, contribute to an increased risk of residual moisture retention and biological degradation (e.g., mold formation). Upon completion of the curing phase, the master substrate is mechanically peeled off, allowing separation of the self-standing PS film with the LIG pattern transferred and embedded within its surface. The resulting composite film is flexible and electrically conductive, and can be directly used as antenna for RFID and sensing structures.

III. PROCESS CHARACTERIZATION

The optimization of the transfer process must account that, since the target application is a passive wireless system, the ultimate figure of merit is the radiation gain of the antenna, which inherently depends on multiple material- and process-related parameters.

Radiation gain is jointly influenced by: *i*) the sheet resistance of the conductive pattern forming the antenna, which governs ohmic losses; *ii*) the dielectric loss tangent, $\tan\delta$, of the PS substrate, which controls dielectric dissipation, and *iii*) the integrity of the transferred LIG pattern that affects current distribution.

To quantify the quality of the transferred LIG, we introduce two figures of merit: the *Transfer Loss*, T_L , which describes the electrical degradation of the transferred conductor with respect to the pristine LIG, and the *Transfer Integrity*, T_I , which quantifies the geometrical completeness of the transferred pattern.

T_L is defined as the increase in sheet resistance between the LIG on the master $R_{S,0}$, and the transferred LIG on the PS film, $R_{S,PS}$, after peeling

$$T_L = R_{S,PS} - R_{S,0}. \quad (1)$$

Denoting with A_0 the area of the LIG pattern on the master and with A_{PS} the trace that has been correctly deposited on the PS, T_I is defined as:

$$T_I = \frac{A_{PS}}{A_0} \quad (2)$$

The transfer integrity is experimentally computed through optical analysis of high-resolution images of the transferred LIG squares. After binarization, non-transferred regions appear as white areas within the nominally black LIG pattern.

The aforementioned figures of merit $\{\tan\delta, T_L, T_I\}$ are evaluated versus the curing time τ_C . Preliminary experimental observations indicated that PS films cured for 24 h remain significantly moist, leading to incomplete mechanical stabilization and increased dielectric losses, and were therefore excluded from the analysis. The parametric investigation is thus restricted to curing times $\tau_C = \{2, 3, 4\}$ days. For each curing time, three samples were fabricated and measured.

A. PS Electrical Characterization

PS samples were fabricated by casting the gelatinized starch solution into a flat circular silicone mold of 100 mm diameter (Fig. 2a), with an initial casting thickness of approximately 10 mm. The cured mixture was hence peeled-off as illustrated in Fig. 2b, and flexible self-standing films were obtained (Fig. 2c, 2d). The dry thickness was measured in 3 different positions for each sample, and the average value ($t \approx 200 - 300 \mu\text{m}$ regardless of the curing time) corresponds to an approximate height reduction of 97% w.r.t. the initial casted volume (Table I). Scanning Electron Microscope (SEM) images of the films for different curing times are reported in Fig. 2e-2g. Notably, for $\tau_C = 2$ days some agglomerates are visible, probably due to the non-complete curing of the mixture. For $\tau_C = 4$ days the surface appears rougher than the $\tau_C = 3$ days case, that, instead, is clear and smooth.

The dielectric characterization of the material was performed on bare PS films, i.e., on samples without any transferred LIG pattern, so that the extracted permittivity and loss tangent can be unambiguously attributed to the starch-based substrate. These measurements were carried out using the ring resonator technique [31], which provides reliable estimation of dielectric parameters in the frequency range relevant to UHF RFID applications.

The values of relative permittivity ϵ_r and loss tangent $\tan\delta$ are hence estimated by parametric identification starting from the measured transmission coefficients, $|S_{21}|$, of the microstrip ring resonator loaded with the PS films in between the bottom and top layer. Fig. 3 illustrates the setup and compares the $|S_{21}|$ for different curing times. Table I summarizes the extracted values averaged over three samples. Notably, τ_C mainly affects the relative permittivity, whereas the loss factor stays constant ($\tan\delta \approx 0.3$) and comparable to that of typical food-derived dielectrics [32].

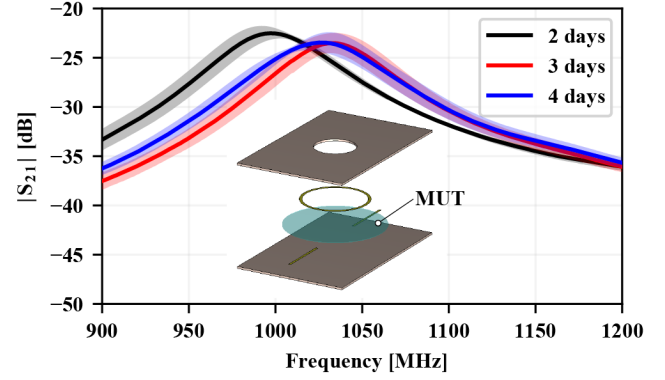


Fig. 3: Measured transmission coefficients of the PS-loaded ring resonator for different curing times. Shaded areas indicate the measurement dispersion. Sketch of the measurement setup in the inset.

TABLE I: MEASURED THICKNESS AND ESTIMATED DIELECTRIC PROPERTIES OF PS SAMPLE FOR DIFFERENT CURING TIMES.

τ_C [days]	2	3	4
t [μm]	252.2 ± 26.4	261.1 ± 35.2	245.6 ± 50.0
ϵ_r	4.2 ± 0.2	3.0 ± 0.2	3.2 ± 0.2
$\tan(\delta)$	0.3 ± 0.0	0.3 ± 0.0	0.2 ± 0.1

B. LIG transfer Characterization

To evaluate the figures of merit of the transfer, LIG square patterns with side dimensions of $10 \text{ mm} \times 10 \text{ mm}$ were first laser-synthesized on the PEEK precursor (master) by a CO_2 infrared laser cutter (Trotec Speedy 100) - Fig. 4a. Laser scribing was performed with 5.0 W power, a scan speed of 11.2 cm/s, and a focal offset of -2.0 mm . Above parameters were selected to achieve an optimal electrical conductivity ($2 < \sigma < 4 \text{ kS/m}$) as well as a thick and robust LIG layer ($50 < t < 100 \mu\text{m}$) with a compact morphology (Fig. 4c) to ease the transfer step [33]. The gelatinized PS solutions, obtained after the three curing intervals ($\tau_C = \{2, 3, 4\}$ days), were cast, as before, onto the laser-patterned master placed on the bottom of the circular mold. The PS film was then left to cure at the prescribed temperature (50°C) for the different times.

Before LIG transfer, the sheet resistance of each LIG master was measured following the four-points method [34] by means of the Ossila Four-Point-Probe system, to provide a reference value under identical laser-writing conditions. After completion of the curing, the self-standing PS film was removed from the mold and the PEEK master was mechanically peeled off, yielding a PS-LIG composite film with the conductive pattern transferred and embedded at the surface. The resulting PS film with integrated LIG traces (Fig. 4b) exhibits high uniformity and homogeneity, with a flat surface morphology and no evidence of edge effects, cracks, or local defects. The SEM scan (Fig. 4d) highlights marked morphological differences with respect to the pre-transfer case, as the exposed

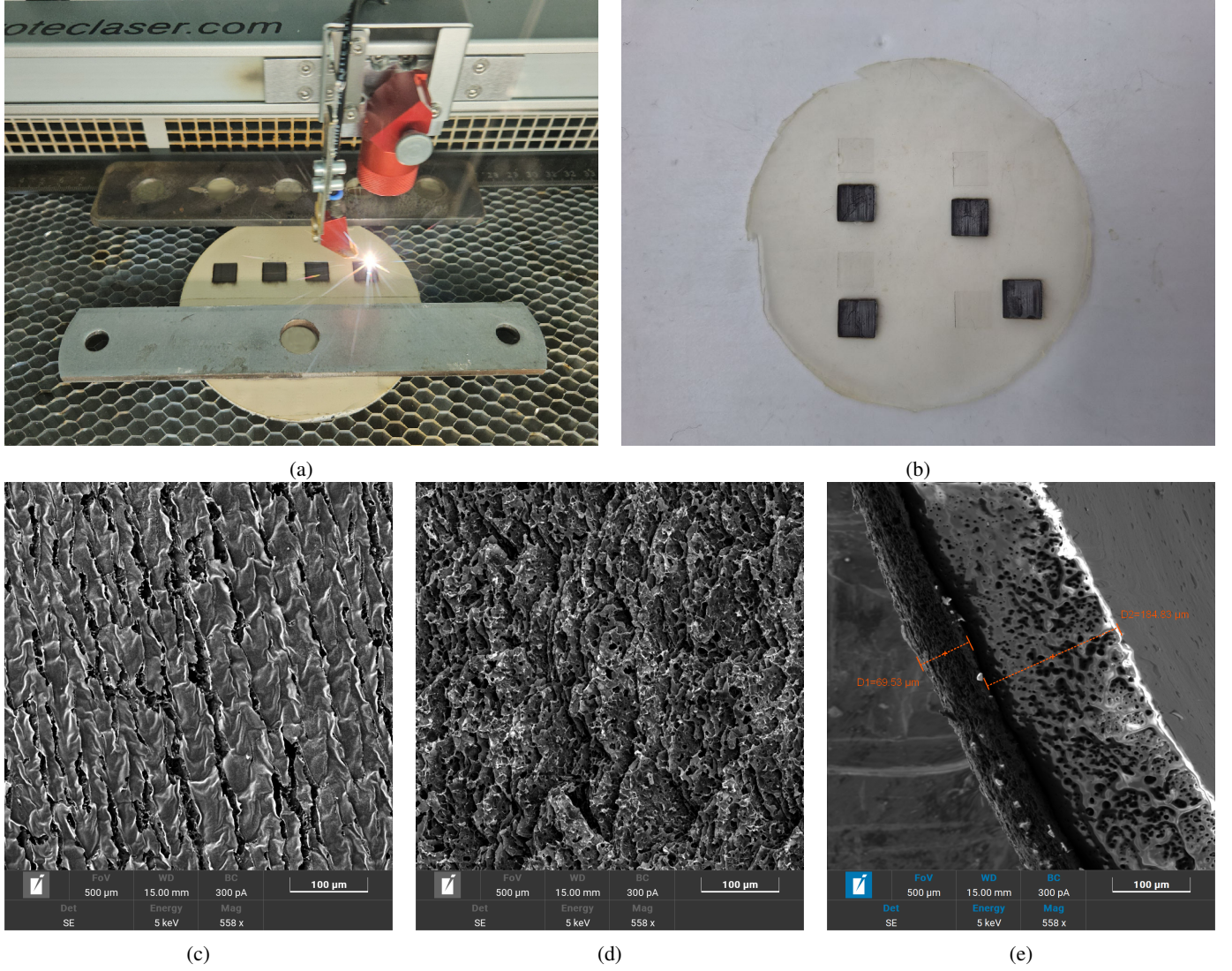


Fig. 4: (a) Snapshot of the synthesis of LIG squares patterns on PEEK precursor. (b) Photo of the transferred traces on PS film. SEM image of (c) the LIG trace on the PEEK precursor, (d) the transferred conductor in the PS film, and (e) the cross-section of the LIG-PS complex.

surface of the conductor after transfer corresponds to the interface originally facing the inner PEEK precursor. Cross-sectional analysis (Fig. 4e) confirms that the transferred LIG trace is fully embedded within the PS matrix, occupying approximately 25% of the overall film thickness.

The measured figures of merits reported in Table II highlight a high degree of repeatability in the laser writing process, since the sheet resistance values measured on the different LIG masters are closely clustered. After transfer, the sheet resistance of the LIG patterns shows only a moderate loss with respect to the initial master values (just 2 – 3 Ω/sq after transfer). A clear dependence on curing time is observed: samples cured for 2 days exhibit higher transferred sheet resistance, while improved electrical performance is obtained for curing times of 3 days, with practically no degradation of sheet resistance. Apparently, there is no benefit from longer curing times. Concerning the transfer integrity, it remains close to 100% for all curing conditions, indicating that the transfer

TABLE II: ELECTRICAL CHARACTERIZATION OF THE LIG TRANSFERRED ONTO PS FILMS

τ_C [days]	$R_{S,0}$ [Ω/sq]	$R_{S,PS}$ [Ω/sq]	T_L [Ω/sq]	T_I [%]
2	5.8 ± 0.7	7.5 ± 1.1	1.7	99
3	4.3 ± 0.2	4.6 ± 0.3	0.3	99
4	5.5 ± 0.8	6.3 ± 0.2	0.8	99

process preserves the integrity and continuity of the conductive patterns once a minimum curing threshold is exceeded.

IV. HYGROSCOPIC PROPERTIES & TEMPORAL STABILITY

This section evaluates the hygroscopic properties and the long-term stability of the material by monitoring the dielectric response of PS films over the time. The PS substrates were initially stored under uncontrolled ambient storage conditions for more than 30 days until the residual moisture completely

TABLE III: ABSOLUTE VALUES OF ϵ_r AND $\tan(\delta)$ OF PS SAMPLES ($\tau_C = 3$ days) AFTER RE-HYDRATION. RELATIVE VARIATIONS W.R.T. POST-CURING VALUES IN THE BRACKETS.

Hours	ϵ_r ($\Delta\%$)	$\tan(\delta)$ ($\Delta\%$)
0	5.5 ± 0.0 (+83.3%)	0.5 ± 0.0 (+66.7%)
24	4.8 ± 0.3 (+61.1%)	0.3 ± 0.0 (-3.8%)
42	3.5 ± 0.3 (+15.6%)	0.2 ± 0.0 (-33.4%)
121	2.0 ± 0.0 (-33.3%)	0.1 ± 0.0 (-66.6%)
336	2.0 ± 0.0 (-33.3%)	0.1 ± 0.0 (-66.6%)
504	2.2 ± 0.0 (-30.0%)	0.1 ± 0.0 (-66.6%)

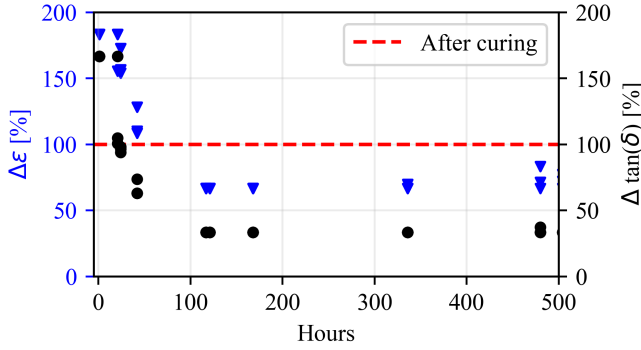


Fig. 5: Temporal variation of the dielectric response of PS films ($\tau_C = 3$ days) after re-hydration and exposure to ambient temperature and humidity.

evaporated and substrates were dry. Then, the samples were inserted in a climatic chamber for 6 hours at $RH = 80\%$ for re-hydration. Finally, upon their removal, the dielectric properties were monitored periodically for 21 days by the same ring-resonator-based procedure described in Section III.A. The experiment was performed on samples cured for 3 days by assuming the same trend for different- τ_C samples.

After re-hydration, the films were stored under laboratory ambient conditions, with no humidity control, during which residual water progressively evaporated until reaching an equilibrium with the surrounding environment. Fig. 5 and Table III report a significant increase in both the relative permittivity and dielectric loss tangent ($\epsilon_r = 5.5$, $\tan(\delta) = 0.5$) w.r.t. the post-curing values in Table I, due to the high-RH exposure during re-hydration. Then, a pronounced variation of both ϵ and $\tan(\delta)$ (approx. 50% reduction) occurs within the first 48 hours, which can be due to the rapid evaporation of loosely bound water. After the first two days, their temporal variation appears more moderate, and, over the following two weeks, the dielectric permittivity remained nearly constant, indicating a progressive stabilization of the material in its dry state.

This behavior suggests that, when exposed to high-RH environments, PS films reach a quasi-stationary dielectric state under ambient conditions, right after 48 hours. It is worth noting that the gradual loss of residual water leads to a net reduction of the dielectric loss tangent that is beneficial for RF applications.

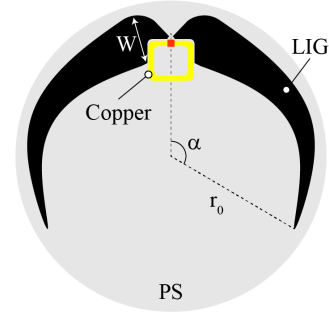


Fig. 6: Layout and main geometrical parameters of the tapered C-shaped LIG dipoles.

V. EXAMPLE OF APPLICATIONS

The proposed PS-LIG technology is demonstrated through a representative RFID antenna for smart packaging applications. The device is characterized in terms of both electromagnetic performance and robustness against humidity variations and repeated mechanical deformation.

A. Layout and Numerical Simulations

Previous studies on LIG antennas have shown that, due to the finite conductivity of LIG, wide traces are generally beneficial to reduce ohmic losses and improve radiation efficiency [16]. However, increasing the patterned area also increases the thermal load induced by laser processing on the polymeric precursor. Large laser-written regions may therefore promote substrate deformation or non-planarity of the LIG master [35], making the transfer step more critical. Accordingly, to balance electromagnetic performance and manufacturability, the antenna layout (Fig. 6) consists of a C-shaped dipole whose trace width is tapered along the angular coordinate α by the way of the equation:

$$W(\alpha) = W(1 - \frac{\alpha}{\alpha_{max}}) \quad (3)$$

where W is the reference trace width in the region closest to the coupling loop. This geometry maximizes the conductor width near the antenna input, where the current density is the highest and ohmic losses are critical, while progressively reducing the trace width toward the antenna extremities, where the current is lower. To preserve the planarity of the LIG trace without compromising the performance W has been set to 10 mm.

The LIG dipole is fed by a small rectangular copper loop mounting the RFID microchip. The metallic module can be readily detached and reused with a new LIG-PS antenna, reducing material waste and simplifying the recycling process. Additionally, the loop, defined by the geometrical parameters $\{a, b\}$ and by a trace width $w_L = 1$ mm, provides the impedance transformation required for conjugate matching. The loop hosts the RFID IC, Magnus S3 by Axzon, with an input impedance at 900 MHz equal to $Z_{IC} = 2.6 - j74.4 \Omega$, and power sensitivity $p_0 = -16$ dBm [36]. The IC features a self-tuning mechanism, which dynamically adjusts its input

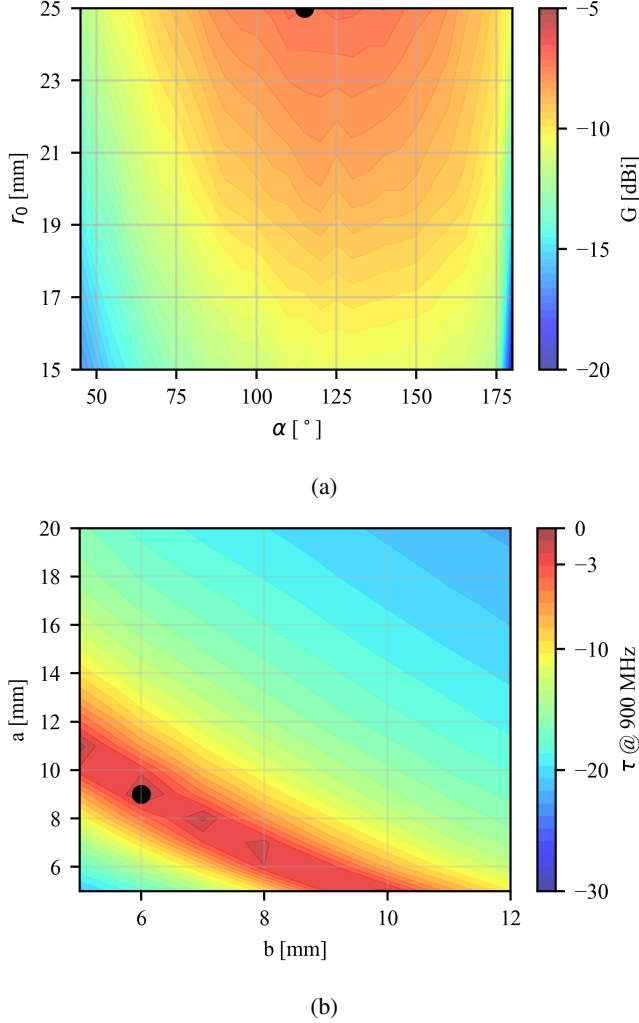


Fig. 7: Contour plots of (a) the radiation gain as a function of the dipole radius, r_0 , and tapering angle, α , and (b) power transfer coefficient at 900 MHz as a function of the metallic loop parameters. The black marker indicates the optimal solutions.

susceptance by controlling an internal ladder capacitor network to compensate for external perturbations affecting the antenna [37]. This operation is digitally encoded in a 11-bit code, namely the Sensor Code (SC) backscattered to the user that is related to the change of the antenna susceptance. Moreover, this IC also integrates an on-chip solid-state temperature sensor, providing digital temperature readings over the -40 °C to $+85$ °C operating range with precision and accuracy of 0.2 °C [38].

The design parameters of the antenna are the internal radius r_0 , the tapering angle α , and the loop form factor $\{a, b\}$. They are optimized sequentially in two steps (Fig. 7a) by means of parametric simulations in CST Microwave Studio 2025 to maximize the performance of the antenna in the far-field region.

In the first step, the radiation gain, G , of the antenna is maximized by tuning the internal radius in the range $15 \text{ mm} < r_0 < 25 \text{ mm}$ and the tapering angle in the

TABLE IV: OPTIMAL GEOMETRICAL ANTENNA PARAMETERS AND COMPUTED PERFORMANCE AT 900 MHz.

r_0 [mm]	α [°]	a [mm]	b [mm]	G [dBi]	τ [-]
25	115	9	6	-11.7	1.0

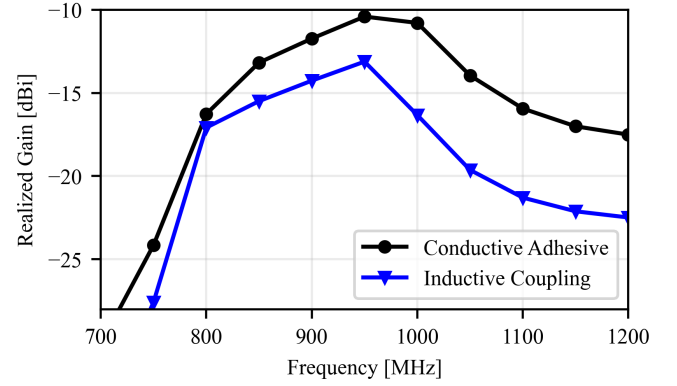


Fig. 8: Realized gain of the optimized antenna when the feeding loop is either electrically connected (black) or inductively coupled (blue) to the LIG trace.

interval $45^\circ < \alpha < 180^\circ$. In a second step, the dimensions of the rectangular metallic loop are adjusted to maximize the power transfer coefficient between the antenna and the RFID IC. The electromagnetic model of the antenna uses the material parameters extracted for the PS-LIG composite obtained after $\tau_C = 3$ days of curing. The transferred LIG trace is modeled with the Leontovich impedance condition as in [39] by considering the sheet resistance $R_{s,PS} = 5 \Omega/\text{sq}$. The PS substrate (thickness $t = 300 \mu\text{m}$) is described by the experimentally extracted dielectric properties $\epsilon_r = 3.0$, $\tan(\delta) = 0.3$. The resulting optimal geometrical parameters, the corresponding radiation gain in the broadside direction and power transfer coefficient are reported in Table IV.

Finally, two different feeding methods of the optimized geometry have been comparatively evaluated. The first option relies on the electrical connection between the metallic loop and the LIG radiator by means of a conductive adhesive (i.e. direct connection); in the second case, instead, the two elements are separated by a thin PI layer ($125 \mu\text{m}$) and the loop feeds the LIG dipole by inductive coupling. As shown in Fig. 8, the direct connection ensures a 3-dB improvement in performance thanks to the more efficient current injection on the LIG trace.

B. Fabrication & Test

The PS-LIG antenna was assembled by means of the procedure described in Section II.C, whereas the copper loop was fabricated by mechanical etching of copper foils on a polyimide film. Upon manual alignment, the metallic loop and the LIG one were connected by means of a conductive epoxy glue (CW2400 by Chemtronics [40]). Fig. 9a and 9b show the peeling procedure and the final prototype, respectively. To assess the repeatability of the fabrication process, three

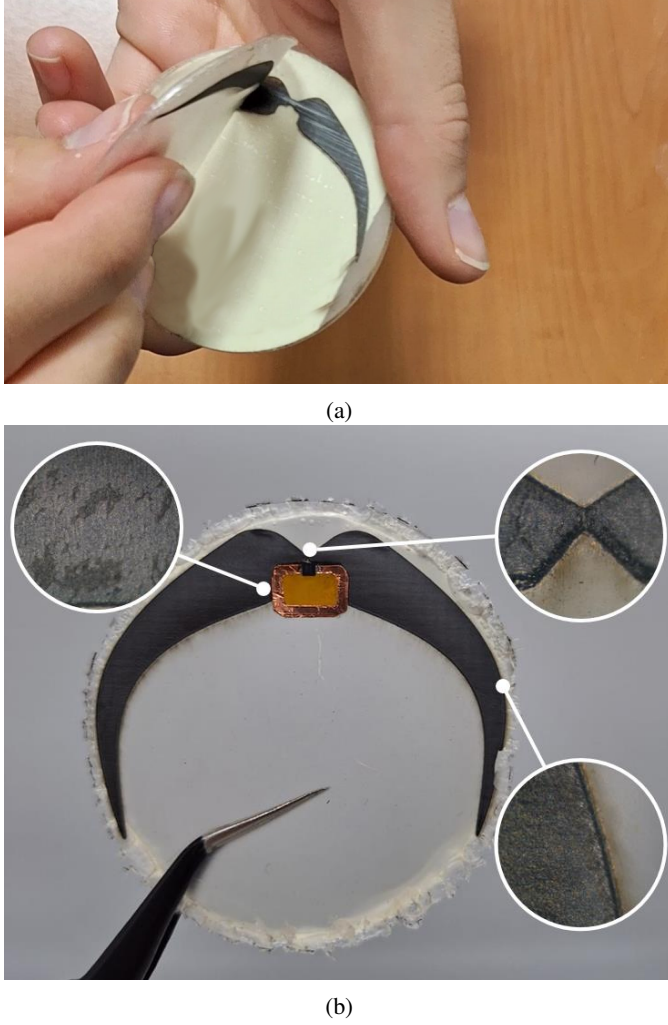


Fig. 9: (a) Peeling of the PS film embedding the LIG antenna. (b) Photo of the assembled free-space LIG antenna. Details (40x magnification) of the embedded LIG trace in the insets.

replicas of the device were experimentally characterized in terms of power transfer coefficient and realized gain, G_r . The former was estimated by measuring the antenna's input impedance by means of a Vector Network Analyzer (VNA) and a differential probe [41]; the realized gain, instead, was calculated by means of the turn-on power method [42] implemented in the TagFormance Pro Station (Fig. 10). As illustrated in Fig. 11a and 11b, the measured τ and realized gain are attenuated by ≈ 1.5 dB w.r.t. the simulated curve in the band of interest, probably due to a non-optimal connection between the LIG radiator and the metallic loop. Nevertheless, they are consistent with the simulated trends with G_r ranging from approximately -14 dBi at 870 MHz to -11 dBi at 950 MHz. The dispersion among the three replicas remains below 1 dB across the investigated band, confirming the repeatability of the fabrication process. Assuming a circularly polarized reader antenna with EIRP=3.28 W, corresponding to the maximum value allowed in Europe, the estimated maximum read distance is approximately 150 cm. This range could be doubled by using identification-only RFID ICs with higher sensitivity,

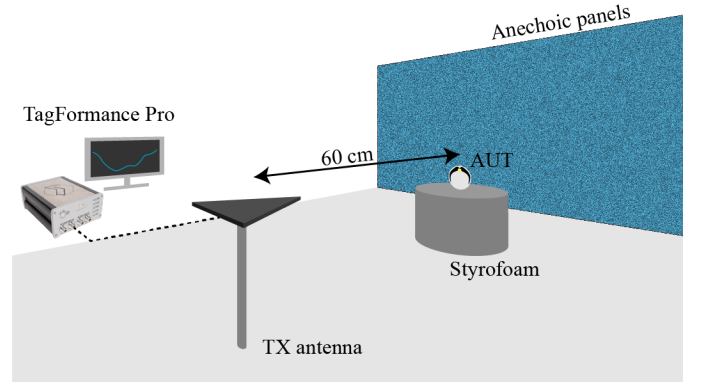


Fig. 10: Illustration of the TagFormance Pro characterization setup for gain estimation.

typically $p_0 \approx -22/-23$ dBm [43].

C. Environmental stability

Based on the hygroscopic properties of the PS film discussed in Section IV, the sensitivity of the antenna response to ambient humidity was evaluated through a two-level characterization aimed at separating impedance-related effects from overall radiation-performance variations. The antenna was first placed inside a climatic chamber enforcing a step-wise humidity cycle ($RH = 20\% \rightarrow 80\% \rightarrow 20\%$), with 20% increments every 25 minutes. Throughout the test, the RFID tag was wirelessly interrogated to record the Sensor Code provided by the Magnus S3 IC, which was used as an indirect indicator of RH-induced variations in the antenna susceptance [37]. Moisture absorbed by the PS-LIG structure may alter the electrical response of the antenna, potentially causing a mismatch with the microchip and activating the IC self-tuning mechanism.

In addition, the realized gain of the antenna was measured under the two extreme humidity conditions, namely $RH = 20\%$ and $RH = 80\%$, to evaluate the overall impact of moisture on the wireless performance. Unlike the SC, which mainly reflects susceptance variation, the realized gain also accounts for possible humidity-induced changes in losses.

Fig. 12a shows the relationship between the relative antenna susceptance variation, $\Delta B_{ant}/B_{ant,0}$, and relative humidity, whereas Fig. 12b compares the realized gain G_r under low- and high-humidity conditions. The susceptance variation remains limited to about -1.5% and shows no relevant hysteresis, indicating negligible humidity-induced impedance detuning. The realized gain variation is approximately 1 dB, which is comparable with the intra-sample dispersion. Accordingly, although the substrate has been proved to be extremely sensitive to moisture absorption and release, the PS-LIG antenna maintains stable electromagnetic performance even for significant RH variations.

D. Mechanical robustness

To assess the mechanical robustness of the PS-LIG composite, the device was mounted on a dielectric hinge connected to

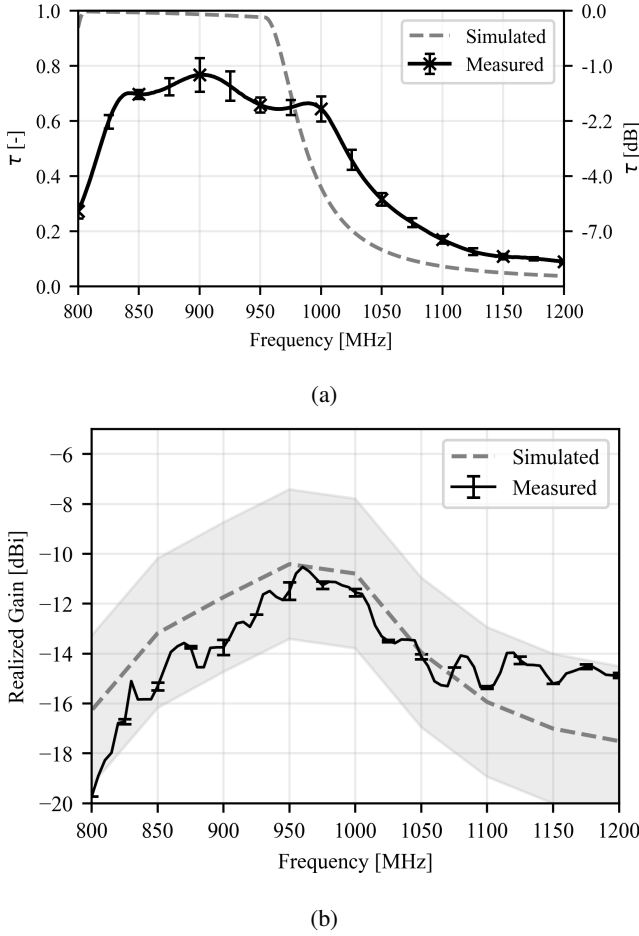


Fig. 11: Simulated (dashed) and measured (solid) (a) Power transfer coefficient along with inter-sample variability, and (b) realized gain averaged over three samples. The gray shaded area indicates the ± 3 dB uncertainty area due to manufacturing.

a stepper motor controlled by a microcontroller (Fig. 13a). The setup enforced a periodic $\pm 45^\circ$ bending, with a mechanical frequency of $f_B = 30$ bending/min.

Simultaneously, the device was wirelessly interrogated by an RFID reader and the Received Signal Strength Indicator (RSSI) was collected as a proof of the correct establishment of the RFID link. The test was carried on until the loss of communication with the tag due to film breakage.

Fig. 13b reports the RSSI as a function of the number of bending cycles. The antenna returns a stable response for more than 1000 cycles, indicating that both the PS substrate and the embedded LIG trace can withstand repeated mechanical stress without significant degradation of the wireless link. Beyond this threshold, a sudden drop of the RSSI is observed, corresponding to the formation of cracks in the PS film and in the conductive pattern. This behavior is attributed to the progressive loss of residual moisture in the PS matrix, which increases its stiffness and reduces its fracture tolerance. As a result, the material becomes more brittle under cyclic deformation, ultimately leading to mechanical failure of the conductive path.

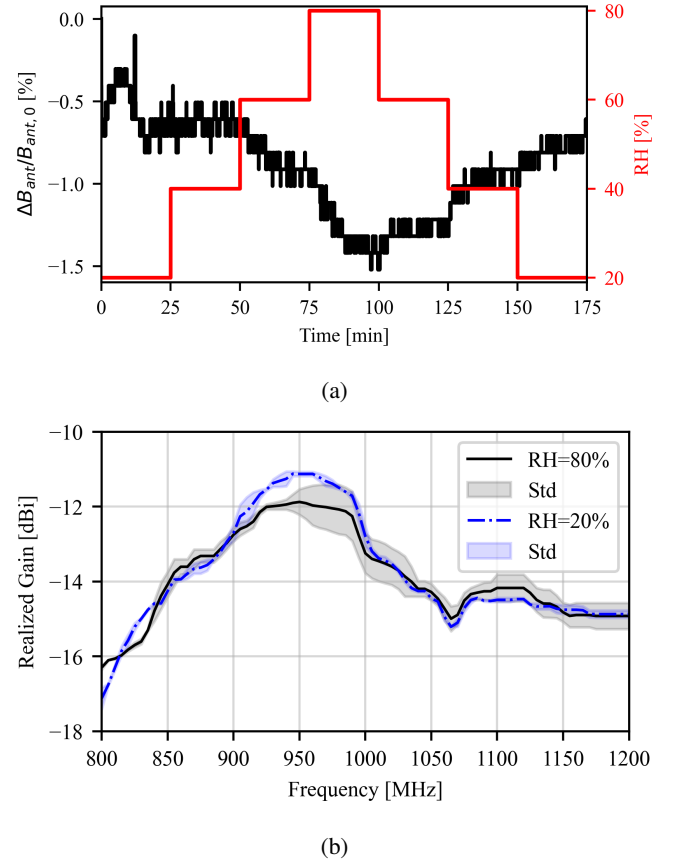


Fig. 12: Environmental stability: (a) Relative variation of the antenna susceptance (black) with the relative humidity (red), and (b) measured realized gain after low-RH (20%) and high-RH (80%) exposure.

E. Example of Application to Smart Packaging

Finally, the proposed antenna was integrated into a smart packaging mock-up. The device was attached to a polyethylene film and wrapped around three packagings containing dry bread (Fig. 14a), some fruits (Fig. 14b), and pork veil loins (c). These configurations were selected to emulate realistic food packaging scenarios, where the antenna operates in close proximity to low-, medium-, and high-lossy media, respectively.

Fig. 14d reports the measured realized gain of the prototype in the filled-package configurations. As expected, the meat and fruit cases are the most detrimental configurations due to the high water content and dielectric losses of the media. The maximum realized gain, $\approx -22/-24$ dBi across the RFID band, ensures a read range of 45/60 cm, which is still compatible with short-range monitoring scenarios, such as on-shelf supermarket reading and smart-fridge applications. Conversely, the dry bread case is the most favorable configuration, since, due to the absence of water, the measured realized gain approaches that of the free-space case.

VI. CONCLUSIONS

This work demonstrates an RF-optimized transfer process enabling the integration of Laser-Induced Graphene into plas-

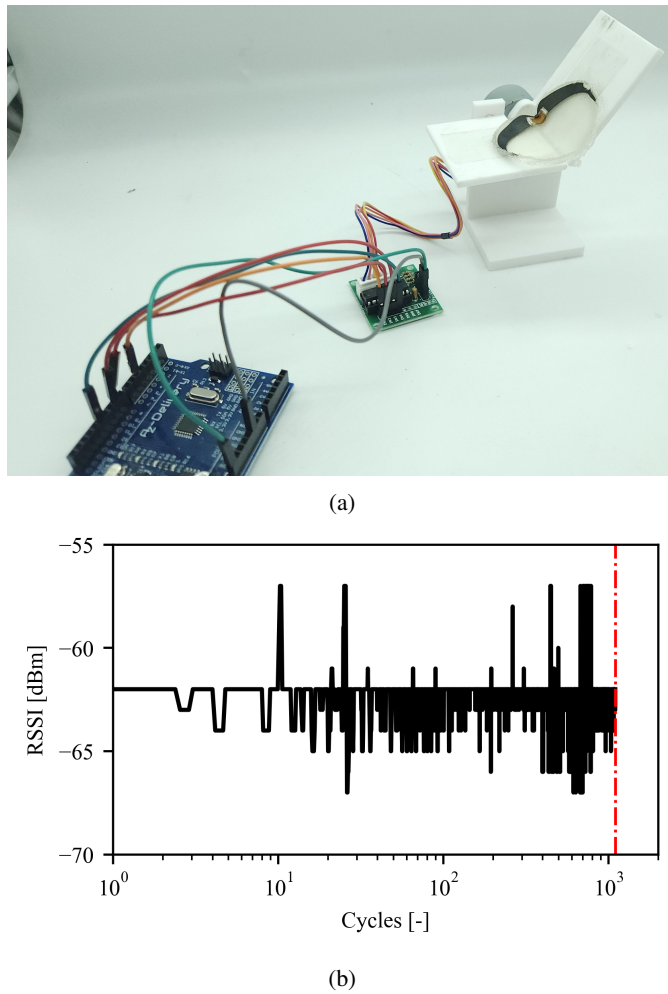


Fig. 13: (a) Cyclical bending test bed and sample installation. (b) Variation of RSSI as a function of the number of cycles.

tized starch films while nearly preserving the sheet resistance of the original conductive pattern.

The fabricated PS-LIG antennas can provide stable RFID operation with limited sensitivity to humidity variations and good robustness under repeated mechanical deformation.

Since the platform combines a bio-derived PS substrate with a metal-free carbon-based conductor, the complexity of end-of-life management is potentially reduced, as no separation of metallic traces from the biodegradable support is required. It can be regarded as a potentially compostable wireless device, where the starch-based substrate may undergo environmental degradation while the carbon-based conductive layer remains as a chemically inert residue.

Future work will focus on improving the PS formulation to reduce brittleness after water loss, investigating end-of-life reuse of PS-LIG composites for new devices, and integrating sensing functionalities directly into the wireless platform. Additionally, different transferring methods will be investigated; for instance, surface solubilization [26], [44] of already formed PS substrates could potentially speed-up the LIG integration and make the process compatible with industrial manufacturing.

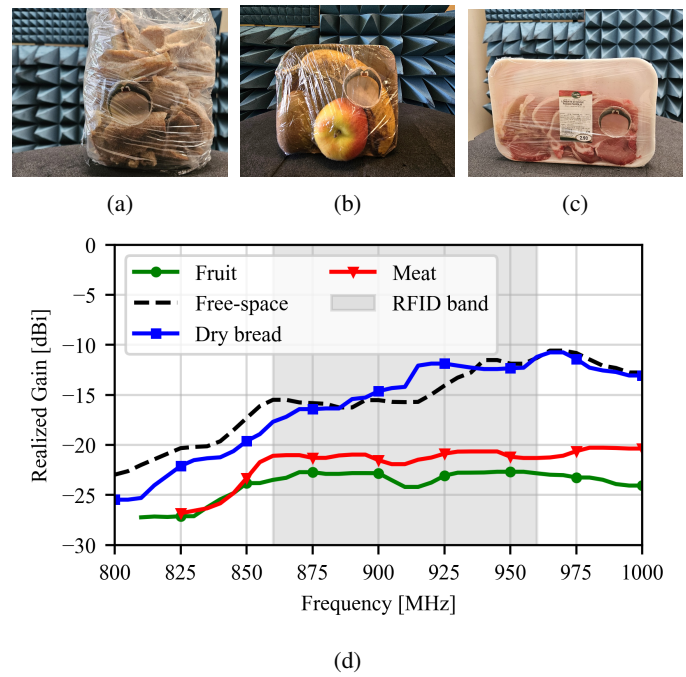


Fig. 14: Proposed PS sensor embedded in a commercial food packaging containing (a) dry bread, (b) some fruit, and (c) pork veil loins. (d) Measured realized gain in the case of filled packaging with dry bread (solid blue), fruit (solid green), pork veil loins (solid red), and free space (dash).

ACKNOWLEDGMENT

Work supported by Project ECS 0000024 Rome Technopole, - CUP B83C22002820006, NRP Mission 4 Component 2 Investment 1.5, Funded by the European Union-NextGenerationEU. Spoke: 2. Flagship Project 7.

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