

Additive Manufacturing of High-Frequency Radiating Devices on Flexible Substrates: From Conformal Electronics to Thermoformed 3D Structures

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Short abstract

Printed electronics by additive manufacturing enables the fabrication of high-frequency devices on flexible and complex substrates. This work experimentally demonstrates two complementary approaches. First, high-frequency lines are screen-printed on a planar polypropylene (PP) flexible substrate, showing that functional radiating structures can be produced for developable three-dimensional applications. Measurements on the flat substrate confirm the quality and repeatability of the printed lines.

Second, metasurface antenna patterns are printed and thermoformed onto developable three-dimensional surfaces, demonstrating that printed patterns can adapt to curved geometries while maintaining structural integrity. Although experimental characterization of the thermoformed devices is not yet available, the fabrication process validates the compatibility of screen printing with thermoforming for flexible substrates.

These results highlight the importance of choosing the appropriate substrate and fabrication method according to the target geometry, providing practical guidance for implementing printed high-frequency electronics in both non-developable and developable 3D applications.

Keywords: Screen printing, radiating devices, flexible electronics, 3D electronics.

1. Introduction and background

Traditionally, high-frequency lines and antennas are fabricated on rigid substrates using subtractive processes, which limits their geometric flexibility and adaptation to three-dimensional surfaces. Flexible substrates combined with printing technologies offer a solution to these constraints, enabling circuits and radiating structures to be patterned on planar substrates that can later be adapted to complex geometries.

The fabrication of high-frequency devices on flexible or three-dimensional substrates remains challenging. Mechanical constraints, adhesion and durability of conductive patterns, and the maintenance of electrical performance under bending or deformation all impose practical limitations. (Nicholson et al. 2021; Zadeh and Komjani 2023). In addition, the dielectric properties of commonly used polymers (PET, PI, PP, $\epsilon_r \approx 2.2-4.5$) are often suboptimal for high-frequency applications, restricting impedance control, miniaturization, and bandwidth.

Most practical applications involve developable surfaces, where flexible substrates must conform to the shape without significant stretching. Additive manufacturing of printed electronics is particularly suited for these cases, enabling the fabrication of flexible PCBs, sensors, and organic electronic devices (OPV, OLED, OTFT). Among radiating elements, RFID tags represent the most common application, while flexible antennas are actively studied in research but remain less developed at the industrial scale.

For non-developable surfaces, thermoforming offers a complementary strategy, allowing printed patterns to be reshaped through controlled plastic deformation of the substrate while preserving their electrical functionality. This distinction between planar fabrication for developable surfaces and thermoforming for non-developable surfaces highlights the importance of selecting substrates and fabrication methods according to the target geometry.

In this work, we present experimental demonstrations of high-frequency structures on flexible substrates through two approaches: (i) planar PP lines for developable 3D applications, representing the majority of practical cases, and (ii) thermoformed antennas for non-developable surfaces. These results illustrate the critical role of substrate choice and fabrication method in achieving functional high-frequency devices on complex geometries.

2. Materials and methods

2.1. Printing Techniques and Process

Screen Printing: The dielectric substrate was metallised using screen-printing, a versatile technique widely used in textiles and increasingly applied in printed electronics for depositing conductors, insulators, or semiconductors on various substrates to fabricate functional devices such as sensors or antennas (Selmi et al. 2025; Wane et al. 2025; Rogel et al. 2017; Herry et al. 2024.)

A consistent process was applied for all experiments to ensure reproducibility. The screen, a fine fabric mesh stretched over a rigid frame, was photolithographically treated so that open areas defined the ink deposition pattern. Printing was performed on a 1 mm polypropylene substrate using a silver-based conductive ink (Silver Electron Low Energy Curing, VFP Ink Technologies). A metallic floodbar spread the ink across the mesh, and a 75 Shore A squeegee transferred it onto the substrate at a 20° angle, 200 mm/s speed, and 0.2 mm off-contact distance.

The semi-automatic ATMAOE MF44 machine used a 120 mesh/cm screen, tensioned to 16 N/cm and angled at 22.5° relative to the frame, with a screen size of 850 × 750 mm balancing resolution and ink transfer efficiency. After printing, the ink was thermally cured at 60°C for 60 minutes to ensure conductivity and adhesion. A ground plane was subsequently printed on the opposite side using the same procedure.

All steps were performed under controlled ambient conditions (22°C, 50% RH) to stabilize ink rheology, which had a viscosity of 10,000 cP at 560 RPM. High-resolution imaging confirmed excellent agreement between the printed patterns and the original design, demonstrating the process accuracy.

Thermoforming: Direct three-dimensional fabrication technologies are essential to meet the demand for lightweight, compact, and multifunctional electronic systems. Unlike conventional planar fabrication followed by assembly, these approaches integrate electronic functions directly onto or within complex geometries, reducing assembly steps and improving structural integration.

Strategies include direct ink writing, aerosol jet printing on non-planar substrates, additive manufacturing of structural electronics, thermoforming-assisted processes, and Water Transfer Printing (WTP). WTP enables high-conformability transfer of pre-patterned conductive films onto complex 3D surfaces, though alignment precision and long-term reliability remain challenging.

In-Mold Electronics (IME) is one of the most mature and industrially scalable solutions. By combining printed electronics on thermoplastic films with thermoforming and injection molding, IME allows direct embedding of circuits into structural plastic components. It leverages existing injection molding infrastructure for high repeatability, mechanical robustness, and compatibility with high-volume production. Industrial players such as TactoTek have driven its technological maturation and commercialization.

Figure 1 illustrates the IME process, showing how flexible printed circuits can be transformed into fully integrated three-dimensional functional components.

In-Mold Electronics Process

Conductive ink and Functional ink Printing

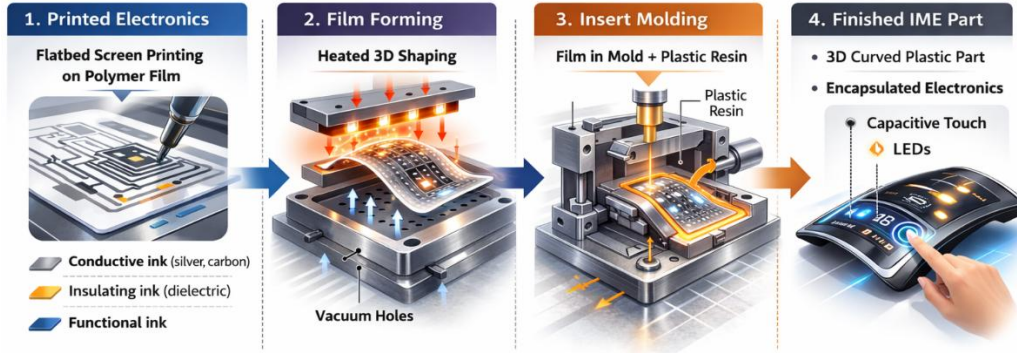


Figure 1: AI-generated schematic overview of the In-Mold Electronics (IME) process, illustrating the integration of printed flexible circuits into molded plastic components. The process includes four main steps: Printed Electronics on a flat polymer film, Film Forming via thermoforming, Insert Molding with plastic injection, and the Finished IME Part with fully embedded electronic functionalities. This approach demonstrates how the design flexibility and miniaturization capabilities of printed electronics can be combined with the mechanical robustness and surface quality of injection-molded plastics

The IME process starts with printed electronics, where a flat polymer film is patterned with conductive and insulating inks to define circuits and functional regions. The film is then reshaped into three-dimensional geometries via thermoforming, using heat and vacuum to ensure precise conformity while preserving circuit integrity.

During insert molding, the thermoformed film is placed into an injection mold, and molten plastic encapsulates the electronics, creating a robust three-dimensional part with integrated circuits. The finished component combines the flexibility and miniaturization of printed electronics with the mechanical durability and scalability of injection-molded plastics, enabling features such as touch-sensitive areas or embedded LEDs.

2.2 High-Frequency Design and Measurement Techniques

High-frequency microstrip lines were designed on a 1 mm thick polypropylene (PP) substrate, chosen for its favorable dielectric properties ($\epsilon_r = 2.2$, $\tan \delta \approx 0.002$) and flexibility. The lines were intended to operate in the K-band (18–26 GHz), commonly used for satellite communications and radar. Figure 2a shows the screen-printed transmission lines with varying lengths and critical dimensions at the line extremities, as well as the standard RF interface for connection to a Rohde & Schwarz ZVA67 two-port vector network analyzer (VNA).

Dimensional accuracy was carefully assessed. For example, the longest line measured 60.012 mm instead of 60 mm, and the spacing between two connector pins was 170 μm versus the nominal 250 μm (Figure 2a). Such deviations may limit high-frequency performance, as tolerances directly affect electrical behavior.

Simulations were performed using Ansys HFSS 2023 (ANSYS Inc. 2023), with devices placed in an air region bounded by perfectly matched layers (PML) to minimize boundary reflections. To reduce computational cost while accurately representing the 2.40 mm solderless edge-launch connectors (ref.1492-02A-6, Southwest Microwave), lumped port excitations were used (Figure 2b). For baseline simulations, the materials were idealized: metallic traces and ground plane were modeled as perfect electric conductors (PEC), and the PP substrate was treated as a lossless dielectric.

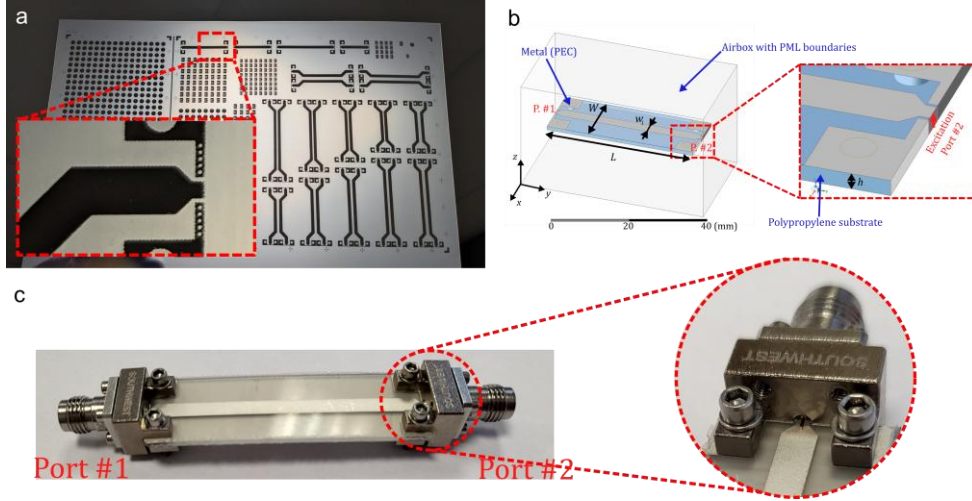


Figure 2: a) Photographs of the screen-printed devices on a PP substrate, highlighting one extremity where the connectors are installed. From a fabrication standpoint, the most critical features are the via holes, which have a diameter of $150\ \mu\text{m}$. b) Simulation model of the microstrip. The inset shows the excitation (lumped port), indicated by a red arrow, used to replicate the solderless end-launch. Dimensions: $W = 15\ \text{mm}$; $w_l = 3.1\ \text{mm}$; $h = 1\ \text{mm}$; $L \in [30, 40, 50, 60]\ \text{mm}$. The airbox is bounded by PML. c) Photograph of the fabricated microstrip line with end-launch connectors attached at Port #1 and Port #2. The inset shows a close-up of the connection point, highlighting the coaxial pin interface with the microstrip line.

To validate the design, four prototypes of different lengths were fabricated and mounted with connectors (Figure 2c). S-parameters were measured at room temperature using a vector network analyzer (VNA). A standard 2.40 millimeter calibration was performed prior to measurement.

The results in Section 3 demonstrate that conventional plastic substrates, particularly PP, which has been only marginally explored for high-frequency applications, can be effectively used in the microwave domain. Screen printing, being both robust and scalable, shows strong potential for industrial upscaling.

Although a one-millimeter-thick polypropylene substrate is required to achieve proper electromagnetic performance and device stability, the material remains mechanically flexible. As shown in Figure 3, the printed devices can be mounted on a cylindrical support with a diameter of ten centimeters, inducing strains well below the maximum elongation of silver inks of approximately ten percent. This confirms both the mechanical viability and technological relevance of printed electronics for flexible and rollable radiating components.

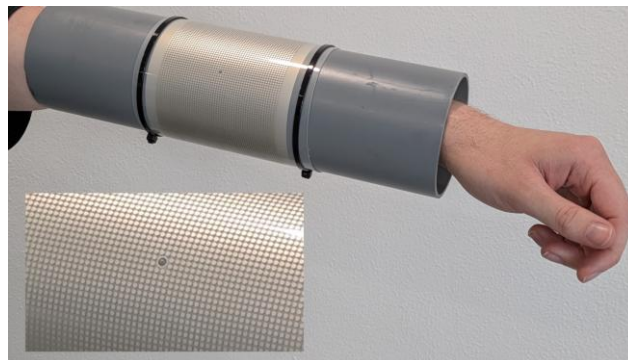


Figure 3: Optical image of screen-printed devices fabricated on a 1 mm-thick polypropylene (PP) substrate, mounted onto a cylindrical support with a diameter of 10 cm.

For applications requiring the integration of electronics onto complex three-dimensional non-developable surfaces, alternative fabrication strategies are necessary, as illustrated in Section 3.2.

3. Results and discussion

3.1. Flexible High-Frequency Devices for Developable 3D Surfaces

Figure 4a presents the magnitude of the input reflection coefficients (S_{11}) in dB for both simulated (solid curves) and measured (dashed curves) lines. The prototypes exhibit good impedance matching at the connector interfaces, with measured S_{11} generally below 10 dB, closely following the simulated performance. This indicates a high-quality contact between the coaxial pin and the printed line with minimal power reflection. The reflection at port 2 (S_{22}) shows similar behaviour. A slight frequency shift between simulated and measured resonances is observed. This deviation can be attributed to fabrication tolerances in line length, as standing waves are highly sensitive to the physical dimensions of the microstrip.

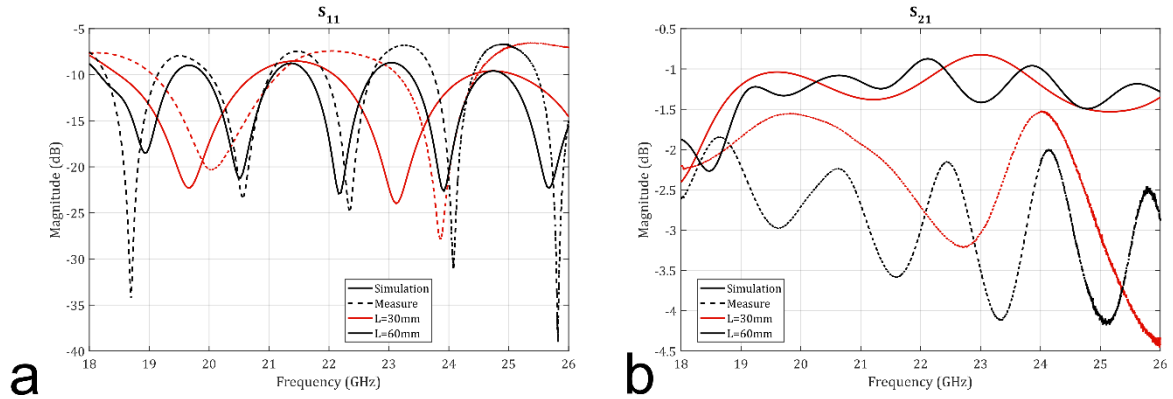


Figure 4: a) Comparison of the simulated (solid lines) and measured (dashed lines) reflection coefficient (S_{11}) for microstrip lines of varying lengths; b) Comparison of the simulated (solid lines) and measured (dashed lines) transmission parameters (S_{21}) for microstrip lines of varying lengths.

The transmission coefficients (S_{21}) for the same set of microstrip lines are shown in Figure 4b. The results demonstrate effective power transmission, confirming the potential of flexible polypropylene substrates for high-frequency applications, including conformal and developable three-dimensional surfaces. A discrepancy of approximately two decibels in insertion loss is observed between simulations and measurements. This difference is likely due to non-ideal material properties not included in the initial simulations. The printed silver ink has a finite electrical conductivity of $5.9 \times 10^5 \text{ S/m}$, resulting in Ohmic losses, while the PP substrate exhibits inherent dielectric losses. In addition, slight curvatures of the flexible lines may introduce additional radiation losses, to which microstrip lines are sensitive.

3.2. Thermoformed High-Frequency Devices for Non-Developable 3D Surfaces

Figures 5 illustrate the adaptation of IME technology to typical metasurface antenna patterns, specifically anchor-shaped resonant elements (Faenzi et al. 2019). The unit-cell motifs have diameters of approximately 1.8 millimeters and trace thicknesses around 200 micrometers, enabling radiation near 24 GHz on planar polypropylene substrates. These antennas exhibit enhanced radiation directivity, making them attractive for high-frequency applications (González-Ovejero et al. 2020, Nicholson et al. 2021).

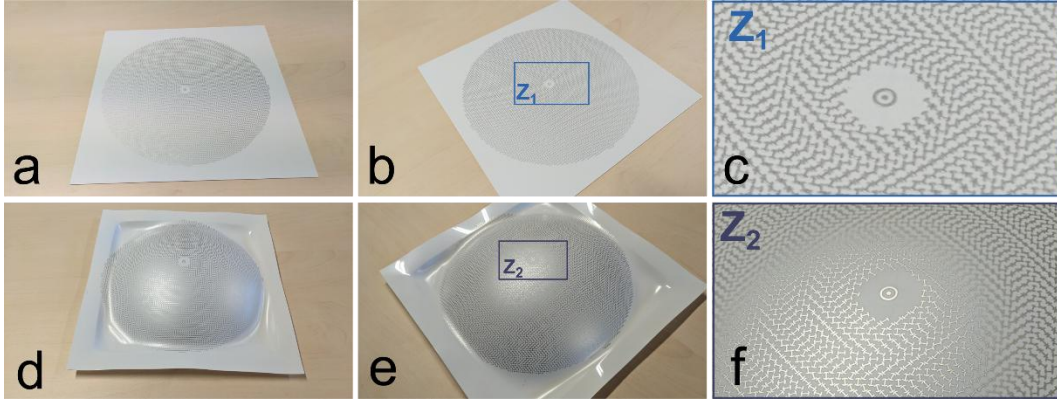


Figure 5: a-c) Optical images of screen-printed anchor-based metasurface antennas on a PVC substrate: a) front view, b) 45° tilted view, c) close-up inset showing the periodic arrangement of the anchors and the circular excitation launcher. d-f) Optical images of anchor-based metasurfaces after thermoforming onto a hand-sized hemispherical substrate: d) front view, e) 45° tilted view, f) close-up inset highlighting the anchors and the circular excitation launcher.

The results demonstrate that thermoforming can successfully transfer patterned structures onto spherical, non-developable surfaces, overcoming the limitations of planar or flexible 2D substrates, which conform only to developable geometries such as cylinders. IME enables functional RF patterns on fully three-dimensional geometries, expanding the design space for conformal antenna systems.

Challenges remain, including thermoforming thicker substrates without excessive mechanical deformation and accurately simulating and optimizing antenna geometries for non-planar surfaces. The simulation and design of 3D antennas are significantly more complex than those of 2D antennas. Work is in progress to improve the reliability of such simulations, starting with developable geometries (curved planes), with encouraging results (Mikulić et al. 2026). Non-developable 3D surfaces remain even more challenging to model and simulate. The proof of concept used a 200 micrometer PVC substrate, which is too thin to ensure efficient radiation at 24 gigahertz, where thicker substrates are needed to achieve the desired surface impedance. Further work is required to balance mechanical formability, substrate thickness, and RF performance for fully functional three-dimensional metasurface antennas. Reliable RF characterisation of the thermoformed antennas will become possible once accurate simulation for 3D non-developable geometries and thermoforming of RF-compatible (thicker) substrates are achieved.

4. Conclusions

This work demonstrates the feasibility of fabricating high-frequency devices using additive manufacturing on flexible polymer substrates, focusing on polypropylene. Screen-printed microstrip lines on one millimeter thick PP operate effectively within the 18 to 26 gigahertz range, with simulations and measurements in good agreement. Minor frequency shifts and additional insertion losses arise from fabrication tolerances and non-ideal material properties, yet the overall performance validates PP as a viable microwave substrate.

Thick PP substrates, needed for K-band operation, remain flexible enough for conformal integration onto developable three-dimensional surfaces. Mechanical strains under moderate bending stay well below the elongation limits of printed silver inks, confirming the robustness of screen-printed RF components for flexible systems.

Extending beyond planar and developable geometries, In-Mold Electronics enables three-dimensional non-developable metasurface antennas. Thermoforming anchor-based patterns onto hemispherical substrates shows that printed electronics combined with thermoforming and molding can expand the design space of conformal antennas. Challenges remain for thicker

substrates required for efficient 24 GHz radiation and for accurate electromagnetic modeling on complex shapes.

This study highlights the interplay between substrate properties, printing accuracy, mechanical formability, and electromagnetic performance. By bridging planar printed RF technology with three-dimensional structural integration, these approaches open new perspectives for lightweight, compact, and industrially scalable conformal antenna systems for communications, sensing, and smart devices.

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