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RESEARCH ARTICLE

Tailored EM Materials for Millimeter-Wave Direct Ink Write Printed Antennas

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ABSTRACT This paper presents the development of dielectric materials with tailored dielectric properties (electric permittivity and loss tangent) at Gigahertz frequencies for their use in low-cost millimeter-wave flexible Direct Ink Write (DIW) printed antennas. The materials can be created to exhibit specific mechanical properties (liquid, semi-solids, temperature-sensitivity, ink adhesion, flexibility, or stretchability) to cover different application needs. Electromagnetic performance of microstrip antennas manufactured through DIW technique on two crafted custom semi-solid materials will be presented for millimeter-wave applications. The antennas exhibit remarkable characteristics for 6G systems, particularly in terms of cost-effectiveness, owing to the low-cost fabrication process employed.

INDEX TERMS Custom-made materials, direct ink writing, flexible antennas, millimeter-wave antennas.

I. INTRODUCTION

The way in which the 5G networks will evolve towards 6G just started being defined [1]. Among many other concepts that are being considered to specify what 6G has to be in the future, it is clear that new frequency bands will be used above 6 GHz, in particular the 26 GHz band, and the millimeter-wave band (30-300 GHz) [2], [3]. At these frequencies, novel functionalities at the radio interface are being envisioned such as Integrated Sensing and Communications (ISAC) [4], or the implementation of intelligent surfaces (RIS, IRS…) for improving coverage or optimizing capacity [5], [6]. In addition, it is expected that 6G communications encompasses applications ranging from personal and body communications [7] to machine communications [8], including vehicular [9], or robotics [10].

Regardless the application, the development of novel wireless devices, particularly in the millimeter-wave band, requires the utilization of materials tailored to the specific envisioned uses [11]. Consequently, the ongoing research and development of materials that allow customization of their complex permittivity (real and imaginary part) are poised to play a key role in advancing future 6G devices and applications. Currently, there is a continuous stream of research in the realm of novel materials for both emerging and existing communications applications, aiming to introduce new capabilities and enhance overall performance [12], [13], [14], [15].

This paper is focused on the creation and development of materials tailored to exhibit specific electric permittivity values at Gigahertz frequencies and with different mechanical properties (liquid, semi-solids, temperature-sensitivity and flexibility, among others) to cater to various application needs. As a direct application, the paper further entails the design and production of flexible printed antennas for the millimeter-wave band, utilizing these custom-made semi-solid and flexible materials through the Direct Ink Write (DIW) technique [16]. DIW is a low-cost innovative printing method that constructs complex geometries layer by layer [17]. This procedure entails the precise extrusion of material through a dynamic dispenser nozzle, which is then carefully deposited onto the substrate [16].

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The objective of this paper is to demonstrate the feasibility of manufacturing custom low-permittivity substrates and show the viability of producing antennas through direct ink printing on these specialized substrates, particularly for millimeter-wave applications.

To achieve high antenna efficiency, it is essential to develop substrates characterized by both low permittivity and low losses [18]. Additionally, these substrates should exhibit small thickness to confer flexibility to the antenna. In [15], a thorough examination of flexible antennas at different frequency bands, the commercially available materials employed in their fabrication, and the manufacturing processes involved [19], along with an exploration of the properties that impact antenna performance is provided. In the current paper, the novelty lies in showing the production process for tailored low-permittivity substrates, showcasing the feasibility of printing antennas on these substrates for millimeter-wave applications.

The paper is organized as follows: In Section II, the development of custom electromagnetic materials with tailored dielectric properties from 20 to 67 GHz is addressed. In this section, the manufacturing process of custom-made substrates is explained and the materials characterization method is presented. In Section III, the specific preparation of the material for a printing process and the material characterization is presented, along with the characteristics of the Direct Ink Writing (DIW) technology. In Section IV, a microstrip antenna printed on two manufactured custom semisolid materials will be presented for millimeter-wave applications. The antenna geometry will be presented and the measured results for the manufactured prototypes will be shown. Finally, Section V exposes the conclusions of the paper.

II. ELABORATION OF FLEXIBLE SEMISOLID MATERIALS WITH CUSTOM DIELECTRIC PROPERTIES

A. MATERIALS AND METHODS

The candidate polymers for the substrates were wihtin the family of acrylates due to their features. These include flexibility, transparency, UV resistance, adhesive properties, chemical resistance, temperature stability, customizability, lightweight nature, electrical insulation capabilities, and potential for biocompatibility. The polymers considered for the substrate creation were:

- PMDS: Polydimethylsiloxane.
- PHEA: Poly(2-hydroxyethyl acrylate).
- PEA: Poly(ethyl acrylate).
- PMA: Poly(methyl acrylate).
- PBA: Poly(butyl acrylate).

The initial phase of the substrate fabrication process involves creating the polymer from the liquid monomer (polymer precursor), in a chain reaction, in accordance with the requirements of the intended application. The molecular structure is controlled with reactive agents like cross-linkers, which define the linear or three-dimensional structure of the polymers, and the final shape and thickness are controlled by the selected mold in which the substrate is produced.

TABLE 1. Summary of performed tests and description.

	Description
Dielectric characterisation	Relative permittivity is measured by means of the open-ended coaxial method.
Mechanical characterisation	The process involves subjecting samples of each material to stretching and analyzing the energy required for deformation. This analysis yields two significant material properties: the elastic modulus, which corresponds to the initial force needed to stretch the material, and the ultimate strength, which correlates with the maximum force the material can withstand before fracturing.
Temperature degradation	The ability of the material to endure elevated temperatures before undergoing degradation is assessed by examining weight changes during temperature elevation. A significant drop in mass indicates the occurrence of degradation.
Surface energy (adhesion)	The measurement involves determining the angle formed by a liquid drop on the surface of the material or substrate, which is indicative of its adhesion properties. This system comprises a camera equipped with software capable of calculating angles and distances through visual pattern analysis.

Fig. 1 provides an overview of the proposed manufacturing process of the substrates, which is similar to that explained in [20]. The polymers were molded into square shapes using glass molds to achieve the desired final thickness (see Fig. 2). These were sealed using plastic film and a separator to prevent any liquid leakage. Inside the molds, the monomers were placed along with the initiator molecules, which are the reagents that start the reaction. Initially, the synthesis started under UV light (hence requiring transparent molds), and then they were cured at 90 °C in a thermal oven. After the polymers completed their curing process, they were washed in boiling ethanol to eliminate any potential residual monomers. Acrylates can be tailored to meet specific requirements, offering a broad spectrum of properties while maintaining their elasticity across diverse temperature ranges.

PDMS was included in the analysis for comparison, since it is commonly used for printing antennas [21]. The preparation method for PDMS differed from that of the other polymers. It involved combining two separate components in the specified ratio, stirring them together, and subsequently pouring the mixture into glass molds. Afterwards, the PDMS was subjected to a curing process in an oven at 80 °C for an hour. PDMS is a commercially available material commonly found in the literature for different applications, making it suitable for comparative purposes.

B. CHARACTERIZATION OF MATERIALS

The conducted material tests are elaborated as described in Table 1.

Certain tests could not be conducted on all materials due to limitations in material preparation. For example,

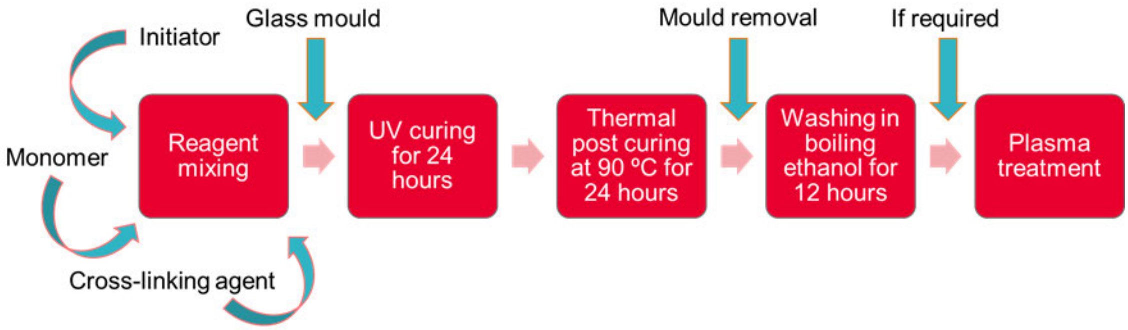


FIGURE 1. Manufacturing process of the different substrates for direct ink printing.

FIGURE 2. Glass mould for polymer substrate synthesis.

dielectric characterization of these materials necessitates specific bulk dimensions, as explained in the following section. Additionally, certain materials like PBA display exothermic behavior that results in the formation of bubbles. Under such circumstances, it becomes challenging to ensure accurate material characterization, rendering the obtained results unsuitable.

1) DIELECTRIC PROPERTIES

The most critical property of substrates in antenna design is their relative permittivity. Relative permittivity determines the electromagnetic properties of the substrate and significantly influences the radiation characteristics of antennas. It affects parameters such as the wavelength, propagation velocity, and phase velocity of electromagnetic waves within the substrate material. High relative permittivity can lead to shorter wavelengths and slower wave propagation, potentially impacting the antenna's resonant frequency and radiation pattern. The experimental results of relative permittivity presented in this paper were obtained using the open-ended coaxial method [22]. In this setup, a vector network analyzer and an open-ended coaxial probe are employed to evaluate the reflection coefficient (S_{11}) at the end of the circuit (probe tip), where the material under test (MUT) is placed. The open-ended coaxial probe for the dielectric measurement is shown in Fig. 3: Keysight PNA N5227A with the SPEAG DAK 1.2E probe (5-67 GHz).

FIGURE 3. Coaxial probe for measuring dielectric properties of the custom-synthesized materials.

The system requires to be calibrated prior to any measurement in order to remove the effect of the cables and other elements of the setup. This calibration is carried out with materials with well-known dielectric properties, which are used as references (also known as calibration standards). Calibrators are open-circuit (air), short-circuit (copper) and water. To obtain the accurate permittivity values, the sample must have dimensions of at least 5 cm × 5 cm × 5 cm [23].

Fig. 4 shows the relative dielectric constant (ε_r) and loss tangent ($\tan\delta$) of the different synthesized materials, from 5 to 40 GHz. As observed, PDMS, PBA, PEA, and PMA exhibited dielectric properties within a comparable range of values. However, PHEA, in contrast, displayed a significantly higher dielectric constant and loss tangent. A mention of

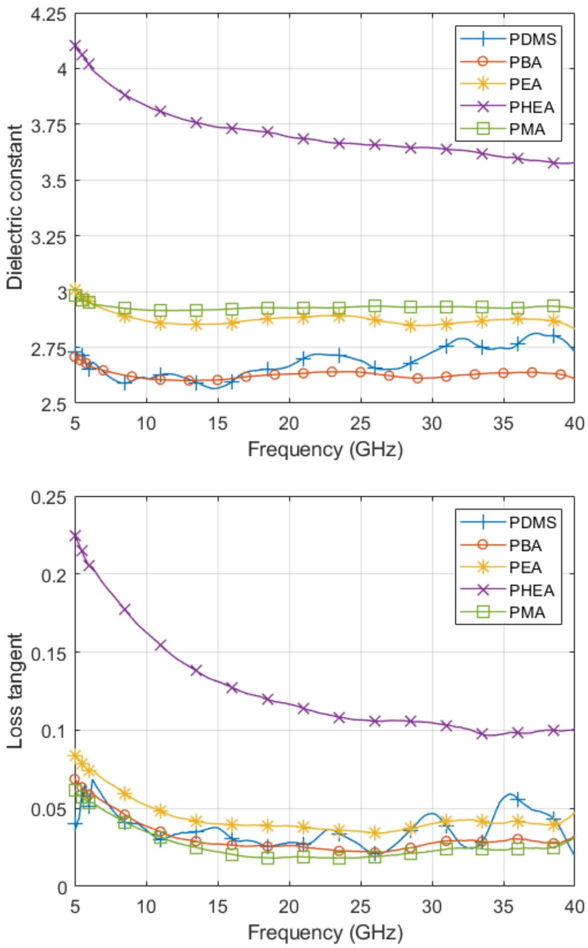


FIGURE 4. Relative permittivity of the custom-synthesized materials. Dielectric constant (top) and loss tangent (bottom).

interest is the observation that among these materials, PMA exhibited the lowest loss tangent values. These findings are particularly significant in the context of antenna design and efficiency, as the loss tangent plays a crucial role in determining the overall performance and energy dissipation characteristics of the antenna system. Hence, our results highlight the potential of PMA as a promising dielectric material for optimizing the antenna efficiency. Since the center frequency of the antennas will be around 30 GHz, Table 2 collects the dielectric values of the materials at this frequency.

TABLE 2. Dielectric properties of the different materials at 30 GHz.

Material	PBA	PEA	PHEA	PMA	PDMS
Dielectric constant	2.63	2.87	3.66	2.93	2.68
Loss tangent	0.022	0.034	0.106	0.019	0.037

The relative permittivity of substrates may be finely adjusted by incorporating porogenic agents into the material. These agents, chosen for their ability to create air gaps within the substrate, can be either soluble or insoluble. They are blended into the substrate during fabrication, and the subsequent processing causes the porogenic agents to dissolve, evaporate, or change form, leaving behind air holes. These air gaps significantly reduce the overall permittivity of the material, making it possible to precisely tailor both the real and imaginary parts to meet specific design requirements. This control over the relative permittivity through porogenic agents is a valuable tool for optimizing antenna and electromagnetic device performance. This can be considered if necessary to meet specific dielectric properties.

2) MECHANICAL PROPERTIES

The mechanical properties are essential for ensuring a proper performance of the materials under operational conditions. These materials are intended for use as substrates in elastic or stretchable circuits. Hence, the elasticity and maximum stress that these materials withstand will be key factors in the candidate selection process. In this sense, the materials studied here were analysed by means of a tensile test, which is a mechanical test that stretches a material to measure its strength and deformation properties. It involves applying a controlled pulling force to a material sample until it breaks or deforms significantly, helping to assess its mechanical behavior.

Thus, the elastic modulus was obtained from the measurement of 5 samples of each material due to the variability of this kind of measurements. The obtained values are represented in Fig. 5 in a box and whiskers plot to observe the deviation and extreme values as well as the average.

All the materials are stretchable but there is a difference on the required force to stretch, being the PMA the one that requires the most energy. In contrast, the PBA is the easiest material to stretch, being quite similar to PDMS. The PEA, PHEA and PMA are similar in stretching conditions. It should be taken into account that having a lower elastic modulus is not necessarily better, since it could lead to undesired deformations of the circuit that leads to alterations of their performance. Regarding the ultimate strength, which is the highest strength the material is capable of withstand, there were just two materials which broke at certain point. The other ones resisted the maximum force of the equipment (10 N).

III. INK PRINTING ON CUSTOM SEMISOLID MATERIALS

A. PRINTING TECHNOLOGY

Direct Ink Write (DIW) is a technology enabling the precise deposition of a wide range of materials or material combinations, as long as they exist in a highly viscous liquid state, referred to as "ink," and can maintain their shape once deposited [24]. This 3D-printing technology is low-cost and extremely versatile since a great variety of materials can be deposited [25], [26]. The type of material, viscosity and density of the ink, as well as the particle size within, dictate the type of dispenser to be used. The nozzle size and other specific requirements should be adjusted to obtain optimal deposition. Moreover, a post-fabrication process may be necessary to harden the resulting object and improve its mechanical properties via steps of drying, heating, or sintering.

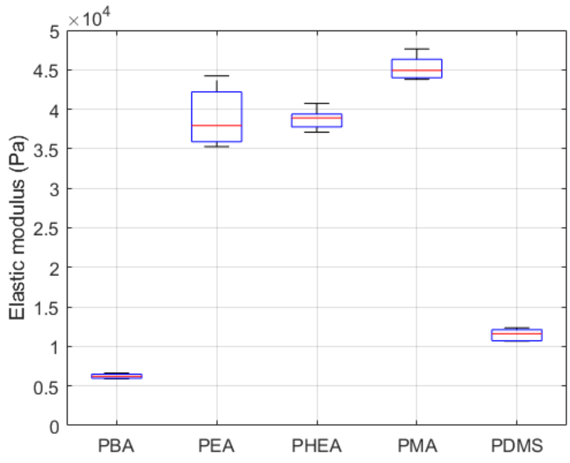


FIGURE 5. Comparison between the elastic modulus of the different polymers analysed as substrates.

The antenna prototypes proposed in this paper are printed using a conductive ink and Voltera V-One PCB printer (see Fig. 6), which is an affordable desktop-sized prototyping tool.

In this printer, the ink is supplied in 2 ml cartridges, which are equipped with a Luer taper, facilitating the connection of interchangeable nozzles with varying diameters: 100 μm, 150 μm and 225 μm. Since the software of the printer lacks the capability to specify the required nozzle diameter for printing, a preprocessing step has been developed to enhance precise control over the actual dimensions of the prototypes.

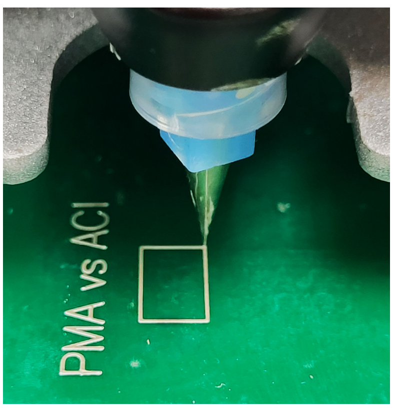


FIGURE 6. V-One printing on custom-made PMA substrate.

To attain the best printing results, specifically ensuring the printed traces have the appropriate width for the nozzle in use, the software offers various parameters that require fine adjustment, with the most critical ones being the dispense height, feedrate, kick and rheological setpoint.

Two additional parameters, external to both the software and the machine, also impact the printing process: ambient temperature and humidity. These variables can only be regulated if the equipment is situated within a dedicated environment.

B. CONDITIONING OF SUBSTRATES FOR ANTENNA PRINTING

Once the material has been designed, it is optimized to be used for flexible circuits through the DIW printing method. Consequently, the synthesis and characterization of these materials have been tailored to meet the demands of the printing process. Flexible printed antennas require low-loss substrate materials capable of enduring the bending and flexing of the antenna without compromising its performance.

Alongside the analysis of dielectric properties, we have explored other factors such as surface compatibility for optimal adhesion of the conductive ink of the final circuit, and the ability of the substrate to withstand the ink curing process thermally. One of the most critical challenges involved addressing the degradation temperature of the substrate material, as the ink should be cured at high temperature after the printing process. This hurdle was effectively resolved by incorporating a cross-linking agent into the polymer used for the substrate, enabling it to endure higher temperatures without deteriorating.

Additionally, surface roughness was a key concern, as it was essential for achieving uniform conductive ink layer printing. This was successfully improved by reducing the ultraviolet (UV) curing time to just 5 hours, resulting in a smoother printing surface. Finally, to enhance solvent resistance, the polymer of the substrate underwent a high-temperature curing process for 2 hours, resulting in a substrate material better suited for printing conductive ink in the context of flexible printed antennas. The substrate manufacturing process demonstrates sufficient repeatability for antennas operating around 30 GHz, ensuring that surface roughness does not significantly impact antenna performance at these frequencies.

1) DEGRADATION TEMPERATURE

After printing the circuit or antenna with the conductive on the substrate, a curing process at 160 °C needs to be performed. Because of that, the custom-made materials for inkjet printing were assessed in terms of the degradation temperature. The chosen method for this analysis was the thermal gravimetric analysis (TGA) [27], and the description is shown in Table 1. Since this experiment does not present a great variability between samples, one measurement per material was enough to obtain these results. The TGA was performed for the different materials in order to clarify the maximum temperature that these can stand without degradation. The results of these assays are shown in Fig. 7, all of them fulfilling the requirements of the thermal curation of the ink (160 °C maximum). Thus, one can conclude that all materials considered will be fine for thermal curing.

2) ADHESION CHARACTERIZATION

In addition to the key issues mentioned earlier, some substrates require special treatment to improve their surface adhesion capabilities for conductive ink. The adhesion

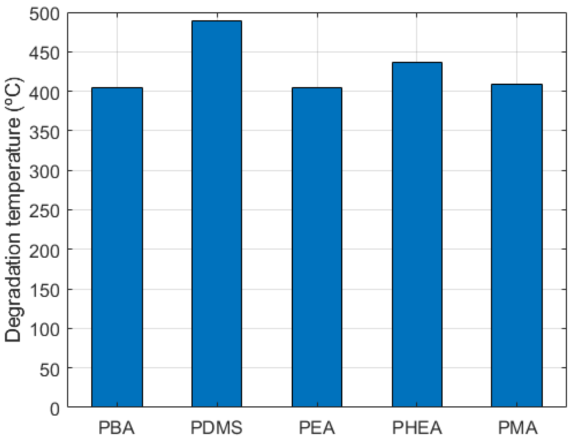


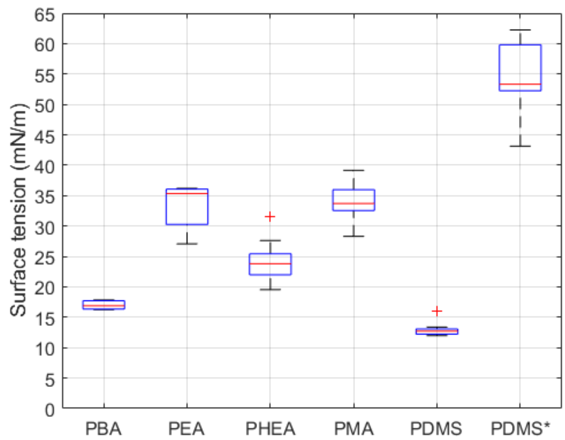
FIGURE 7. Degradation temperature of the different polymers analysed as substrates.

capabilities of a substrate can be assessed using contact angle analysis, which is a commonly used technique in surface science. This analysis involves measuring the angle formed between a liquid droplet and the surface of the substrate. The contact angle serves as an indicator of surface wettability, where lower contact angles indicates higher surface energy and better adhesion properties. In the case of flexible printed antennas, contact angle analysis can be used to evaluate the adhesion capabilities of the substrate for conductive ink. The analysis can provide valuable insights into the surface properties of the substrate, allowing researchers to optimize the surface treatment and design to improve adhesion and ultimately enhance the performance of the antenna. Overall, contact angle analysis is a valuable tool in evaluating substrate adhesion capabilities, and its use in conjunction with other testing methods can help to ensure the successful development of reliable and efficient flexible printed antennas.

The surface energy of the materials is directly related with its adhesion properties to other substances [28]. This will have a significant impact on the compatibility of the conductive inks that will be deposited on the substrate surface. A good adhesion will ensure a proper electromagnetic behaviour of the circuit or antenna. The surface energy was evaluated as described in Table 1. It was measured with 5 samples for each material, since this is a sensitive parameter that depends on the environment factors such as humidity and temperature. Thus, it requires constant environmental conditions to perform the assay.

By incorporating plasma treatment into the substrate creation, the adhesion capabilities of the substrate can be significantly improved [29], resulting in more reliable and efficient flexible printed antennas. PDMS (silicone) is one such substrate that typically requires a plasma treatment to enhance adhesion [30]. Plasma treatment involves exposing the substrate to a high-energy gas plasma, which causes the surface molecules to react and form new chemical bonds, resulting in a surface that is more receptive to conductive ink. The plasma treatment also helps to remove any residual contaminants on the surface, ensuring a clean and uniform surface for printing.

Fig. 8 shows the results of the performed material analysis. The higher the surface tension, the higher the expected adhesion for the conductive ink on the substrate. Consequently, based on the findings, it can be concluded that PDMS with plasma treatment exhibits the most robust adhesion, followed by PMA and PEA. Next in line is PHEA, while PBA and untreated PDMS display the least favorable adhesion behavior.



*PDMS with plasma treatment

FIGURE 8. Surface tension of the different polymers analysed as substrates.

It should be highlighted that PDMS underwent two distinct analyses, as deduced from Fig. 8. Initially, its surface exhibited relatively low surface tension, resulting in poor adhesion of the ink. To address this issue, a plasma treatment was applied to the material, altering its surface properties and rendering it more adhesive overall. The PDMS treated with plasma displayed a significant increase in surface energy, making it the most adhesive material in this study. It is worth noting that this treatment could potentially be applied to other materials as well to enhance their adhesive properties.

These enhancements in substrate creation have yielded more dependable and efficient flexible printed antennas suitable for a broad spectrum of applications, ranging from wearable devices to Internet of Things (IoT) sensors.

As a summary of the achieved features for each material, Table 3 collect the results of the different tests and the strengths and weaknesses for each property. Moreover, several printing tests have been conducted for the different custom-made materials with Voltera Flex 2 silver-filled flexible conductive ink [31]. In Figure 9, SEM images depict the ink printing on three distinct substrates (PDMS, PDMS with plasma treatment, and PMA) after substrate bending. Except for the PDMS, conductivity and adhesion in all the other substrates is satisfactory after bending.

TABLE 3. Summary of the features of each substrate material.

Material	PBA	PEA	PHEA	PMA	PDMS	PDMS*
Dielectric properties	-	✓	✗	✓	✓	✓
Elastic modulus	✗	✓	✓	✓	✓	✓
Ultimate strength	✗	✗	✓	✓	-	-
Degradation temperature	✓	✓	✓	✓	✓	✓
Surface energy	✗	✓	✓	✓	✗	✓

✓means it passes the test ✗ means it does not pass the test
*PDMS with plasma treatment

FIGURE 9. SEM images (100 times magnification) of the ink printed in PDMS (left), PDMS with plasma treatment (center) and PMA (right).

IV. PRINTED ANTENNAS ON CUSTOM SEMISOLID MATERIALS FOR MM-WAVE APPLICATIONS

A. ANTENNA GEOMETRY

A millimeter-wave microstrip antenna has been specifically designed for evaluating DIW printing capabilities on various custom semi-solid materials.

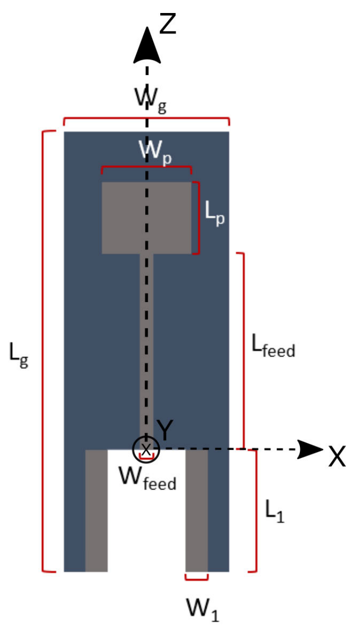


FIGURE 10. Geometry and parameters of the printed antenna, with metal (gray) and dielectric substrate (dark blue). Ground plane with dimensions $L_g \times W_g$ is at the back side of the antenna.

The general geometry is shown in Fig. 10. As it can be observed, the antenna consists of a rectangular patch fed by a microstrip line, printed on a tailored substrate of thickness t, along with a ground plane located at the back side of the antenna. A transition from GCPW to microstrip line has been designed for better attachment of the connector. The dimensions of the antenna are provided in Table 4. The antenna is aimed to operate around 30 GHz for $S_{11} < -10$ dB and will be narrowband.

The antenna has been manufactured using DIW printing technology on both PMA and PMDS custom-designed substrates.

TABLE 4. Dimensions of the proposed antenna (unit: *mm*).

W_g	L_g	W_p	L_p	W_{feed}	L_{feed}	W_1	L_1
6.7	17.98	3.64	2.92	0.52	5	0.9	5

B. DIW PRINTED ANTENNA ON PMA CUSTOM-MADE SUBSTRATE

The proposed antenna has been firstly printed on PMA substrate, with $\varepsilon_r = 2.93$, $\tan \delta = 0.019$ and thickness $t = 0.5$ mm.

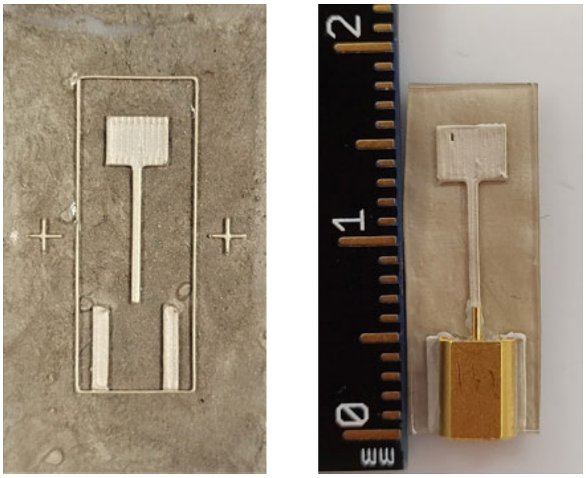


FIGURE 11. Antenna DIW-printed on custom-made PMA substrate of thickness 0.5 mm: Patch and ground plane printed with Flex 2 silver-filled flexible conductive ink from Voltera. Cured (left) and final antenna with mini-SMP connector (right).

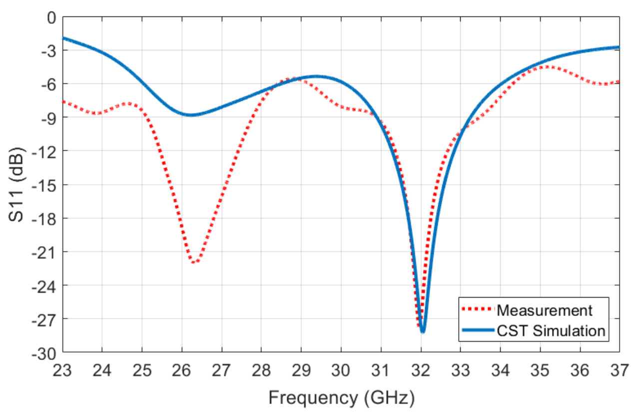


FIGURE 12. Measured and simulated S_{11} parameter (dB) for the antenna printed on PMA.

The fabricated antenna prototype is shown in Fig. 11. It has been printed using Flex 2 silver-filled flexible conductive ink from Voltera [31], and silver-filled, conductive solvent-based adhesive ME902 from Dupont [32] to attach a Rosenberger 18S203-40ML5 mini-SMP connector [33] to the antenna.

The comparison between the simulated and measured reflection coefficient (in dB) is shown in Fig. 12. As observed, the antenna presents two measured operating bands, centered at 26.3 GHz and 32 GHz for $S_{11} < -10$ dB. Please note that, for simulation purposes, $S_{11} < -8$ dB was deemed sufficient for the first band. As seen, simulated and measured results agree rather well, although impedance matching in the lower frequency band is better in the measurement. This may be due to the tolerances in the manufacturing process of the antenna and the conductive adhesive used to attach the connector.

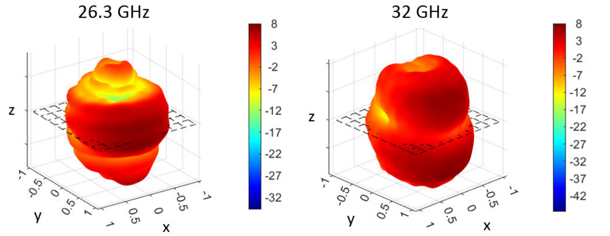


FIGURE 13. 3D measured radiation patterns at the central frequency of the two operating bands, for the antenna printed on PMA custom-made substrate. Antenna is located in the XZ plane.

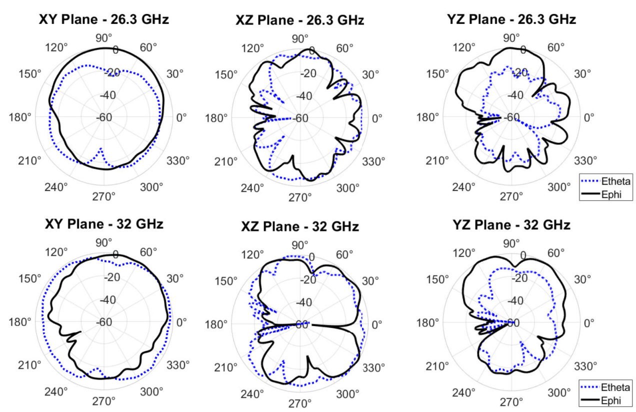


FIGURE 14. 2D cuts of the measured radiation pattern parameter for the antenna printed on PMA. Antenna is located in the XZ plane.

TABLE 5. Radiation parameters based on measurements for the antenna printed on PMA.

f (GHz)	D (dB)	G (dBi)	Rad. efficiency (%)	Total efficiency (%)
26.3	8.18	2.63	27.84	27.51
32	7.85	1.27	22	21.9

Radiation patterns of the antenna at different frequencies within the operating range are shown in Fig. 13 and the main 2D cuts planes are shown in Fig. 14. In this case, the results are as expected in the simulation, as the antenna concentrates the radiated electric field in the broadside direction. Due to the finite ground plane, some backward radiation is observed.

Finally, directivity, gain, radiation efficiency and total efficiency at the central frequencies of the two operating bands are shown in Table 5. As shown, total efficiency is around 27% in the lower band and 22% in the upper band, due to the resistivity of the ink and the losses in the custom-made material. However, the cost-effectiveness of the fabrication process and the versatility of the tailored materials make the efficiency of the antenna enough for high-sensitivity devices.

C. DIW PRINTED ANTENNA ON PDMS SUBSTRATE

To demonstrate the feasibility of printing on different custom-made substrates, the antenna has also been printed on PDMS substrate [21]. This susbstrate presents a relative electric permittivity of $\varepsilon_r = 2.68$, tan $\delta = 0.037$ and thickness $t = 0.5$ mm.

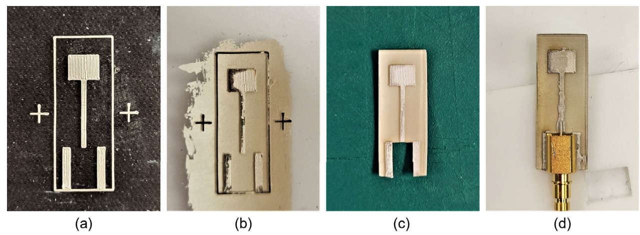


FIGURE 15. DIW-printed antenna on PDMS custom-made substrate at different phases of the manufacturing process: (a) Printed antenna before ink curing; (b) Printed antenna oxidated after second plasma treatment; (c) Cut and sanded printed antenna; (d) Final antenna connectorized and with microcracks repaired.

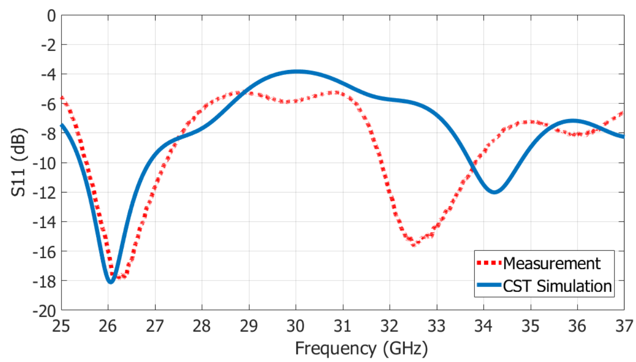


FIGURE 16. Measured and simulated S_{11} parameter for the antenna printed on PDMS.

TABLE 6. Radiation parameters based on measurements for the antenna printed on PDMS.

f (GHz)	D (dB)	G (dBi)	Rad. efficiency (%)	Total efficiency (%)
26	7.76	1.5	23.7	23.3
33.8	5.68	1.4	37.3	33.6

The manufacturing process of the antenna is similar to the one used for the PMA antenna, but in order to achieve good adhesion of the ink to the PDMS material, the substrate must

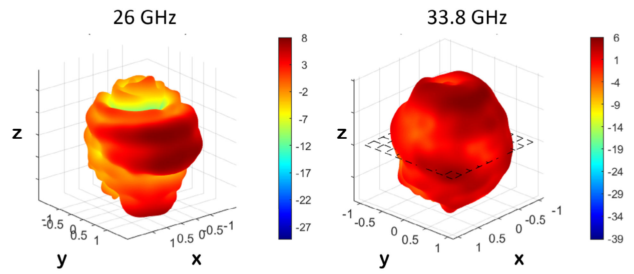


FIGURE 17. 3D measured radiation pattern parameter for the antenna printed on PDMS. Antenna is located in the XZ plane.

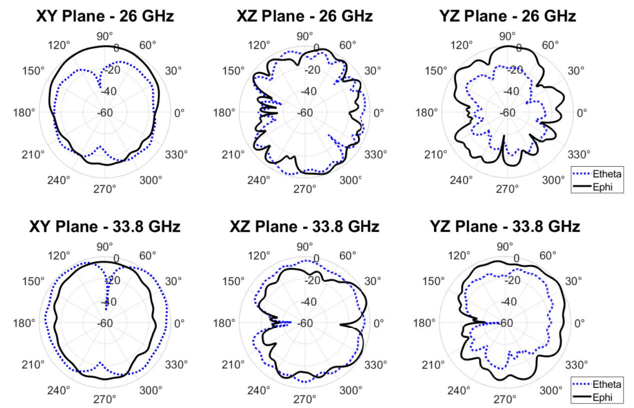


FIGURE 18. 2D cuts of the measured radiation pattern at 26 GHz and 33.8 GHz, for the antenna printed on PDMS substrate. Antenna is located in the XZ plane.

first be treated by plasma activation. The antenna prototype at different phases of the manufacturing process is shown in Fig. 15. In this case, the conductive ink, the adhesive and the connector were the same as in the PMA antenna.

Fig. 16 shows the comparison between CST Microwave Studio simulation and the measured reflection coefficient (in dB). As observed, measured and simulated results exhibit good agreement, although the measured upper band is shifted down in frequency. Again, this may be due to the tolerances in the manufacturing process of the antenna, the connector and the conductive adhesive used to attach the connector. As seen in Fig. 16, the antenna presents two narrow operating bands, centered at 26 GHz and 32.5 GHz for $S_{11} < -10$ dB.

Radiation patterns of the antenna at different frequencies within the operating range are shown in Fig. 17 and the main 2D cuts planes are shown in Fig. 18. In this case, the results are as expected in the simulation, as the antenna concentrates again the radiation in the broadside direction. Due to the finite ground plane, some backward radiation is observed.

Finally, directivity, gain, radiation efficiency and total efficiency at the central frequencies of the two operating bands are shown in Table 6. As shown, in this case total efficiency is around 23% in the lower band and 33% in the upper band, due to the resistivity of the ink and the losses in the PDMS substrate.

V. CONCLUSION

This work has been mainly focused on the development of low-permittivity custom materials for their use as substrates in millimeter-wave flexible printed antennas. In this sense, a wide set of low-permittivity materials have been fabricated and characterized considering different aspects: dielectric permittivity (real and imaginary part), mechanical behaviour (elastic modulus and ultimate strength), degradation temperature, and surface tension (adhesion suitability).

These materials are designed to address the requirements of a broad range of applications, with a particular focus on meeting the demands of 6G wireless technology.

Results demonstrated that it is possible to customize the dielectric constant of the specially crafted materials through various polymers and agents, while their mechanical properties can be enhanced through a suitable fabrication process. Furthermore, the substrates should be conditioned to align with the requirements of cost-effective printing methods, such as direct ink writing, thereby indicating the potential for producing cost-effective 6G antennas. Two microstrip antennas have been fabricated on two custom-made substrates (PMA and PDMS) for millimeter-wave applications. The presented measured results for both designs illustrate favorable antenna performance, thereby affirming the feasibility of utilizing these custom substrates in 6G antennas through cost-effective printing technologies.

In summary, our study innovatively develops and characterizes low-permittivity custom materials, uniquely combining tailored dielectric properties, mechanical robustness, and adhesion suitability. This approach positions these materials as crucial for cost-effective, high-performance DIY 6G antennas.

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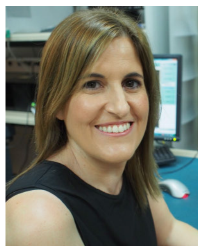

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