A Curved 3D-Printed S-Band Patch Antenna for Plastic CubeSat

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ABSTRACT The new space economy paradigm demands for cost-effective systems for its development. Plastic CubeSats are appealing candidates. To enable the use of this new generation of space systems, the challenge of designing suitable communication sub-systems must be faced. In this work, a 3D-printed ABS antenna easily embeddable in a plastic CubeSat is proposed. The 3D-printed material has been characterized in terms of dielectric, mechanical and thermal properties, and the compliance with space requirements has been assessed. In particular, thermogravimetric and calorimetric tests have been carried out. Static and dynamic mechanical analysis were performed. To comply with the stringent weight and space requirements, the unique antenna design of a curved stacked patch has been proposed. The patch covers the uplink (2.025–2.11 GHz) and downlink (2.2–2.29 GHz) bands for Telemetry Tracking and Command (TT&C) applications, with an overall bandwidth of about 300 MHz (14%). Additionally, taking advantage of the curved shape, the proposed antenna shows a size reduction of the resonant length of about 34%. The size of the antenna is 71.5 x 71.5 x 13 mm3 and is characterized by a weight of only 51 g. Also, in silico tests, by relying on the measured physical properties and a non-linear numerical model, have been carried out to assess the performances of the final antenna layout during a typical CubeSat mission. The proposed design strategy could be used to develop plastic CubeSats embedding performing antennas.

INDEX TERMS 3D printing, antennas, ABS, CubeSats, new space economy.

I. INTRODUCTION

CONVENTIONAL satellites, largely employed in space missions over the past decades are characterized by a large mass, which can easily reach 1000 kg, and by a high power consumption [1], [2]. The advent of a brand new compelling space economy, however, calls for a careful choice of cost-effective technologies for future space developments [3]. This trend explains the popularity of...
the CubeSat standard. CubeSats are compact modular nano-satellites (1–10 kg) that can be realized with commercial off-the-shelf (COTS) components, qualified for spaceflights [2], [4], and whose elementary unit (1U) consists of a cubic module of $10 \times 10 \times 10$ cm$^3$ size [1], [3]. They are born for educational purposes and soon they came under the spotlight of the space industry for their low cost, lightweight, and low power consumption [5], [6]. These CubeSats features perfectly fit the new space economy paradigm of democratizing the space sector so that innovative systems with short development times (12–18 months) and capable of ensuring a high economic return are needed [7]. In this framework, the cost and weight of these satellites can be further reduced through unconventional development approaches, such as emerging fast-prototyping technologies like 3D printing, if suitable materials are employed. This is why plastic CubeSats have been proposed and investigated [8].

In this respect, few 3D printable plastic filaments have proven to fully comply with the stringent requirements of the CubeSat design specifications, hence can be regarded as available materials for space applications. In particular, one of the main specifications is the low outgassing criterion, according to which CubeSat materials shall have a Total Mass Loss (TML) $\leq$ 1.0 % and a Collected Volatile Condensable Material (CVCM) $\leq$ 0.1 % [9]. The Acrylonitrile Butadiene Sterylene (ABS) is a promising material for plastic CubeSats, further lowering their overall cost and mass, being lighter in weight and less expensive than aluminum [8], [10]. It can be proficiently used in vacuum or even high-vacuum environments (e.g., space applications), as shown in [11], where scientists from the National Institute of Standard and Technologies (NIST) reported the outgassing rate of 3D printed ABS in vacuum. The conclusion states that the main gas absorbed by the material from the atmosphere is water and that it can be easily degassed in a relatively short time (3 days at 100 °C). The 3D-printed ABS has been also added by NASA to the list of approved low-outgassing materials, scoring a TML of 0.94 % and a CVCM of 0.04 % [12].

Furthermore, during the 4-year Polymer Erosion and Contamination Experiment (PEACE), wherein 41 different polymers were exposed to the Low Earth Orbit (LEO) environment on the exterior of the International Space Station (ISS) in order to evaluate the atomic oxygen erosion, the ABS stood out for one of the lowest mass losses [13]. Nonetheless, to better understand if the space’s harsh environment affects the characteristics of the material, a rigorous thermal and mechanical analysis should be performed. The temperature variation in LEO ranges from $-65$ °C to 125 °C with thermal cycling depending on the orbit height [14]. However, to mitigate the temperature excursion, satellites employ cooling/heating systems and/or thermal blankets, in such a way that the considered temperature range can be narrowed between $-20$ °C and 80 °C for most external components (except for solar panels) [10], [14].

In this paper, a thorough analysis of a commercial, transparent 3D plastic filament ABS for CubeSat application is presented. The chosen ABS filament (SUNLU, China) has the peculiar characteristic of being transparent, which opens up the possibility of integrating directly their subsystems, without covering solar panels. The thermal and mechanical properties of 3D printed ABS are retrieved to assess its suitability for a plastic CubeSat. The thermal analysis is particularly useful to evaluate possible changes in the material dielectric permittivity, since the ABS can be used as a substrate for the antennas within the CubeSat communication system, in a convenient integrated system. Indeed, the free-form factor of 3D printing can be exploited to obtain complex shapes, suitable for the CubeSat applications.

As a proof of concept, an S-band curved microstrip patch made of ABS is presented. S-band patch antennas for CubeSat applications are very popular among researchers. Pittella and Nascetti propose a layout based on four rectangular patches on the four sides of a square annular ring, in [15] and [16]. These prototypes are reconfigurable thanks to the changeable phase of the feeding lines. Meshed antennas are proposed in [17] and [18], showing a fully solar-panel integrated circularly polarized patch for CubeSat ground/intersatellite communication [17] and three proximity coupled patches that achieve large bandwidth thanks to the slight difference in size. A dual-band stacked circularly polarized patch antenna is proposed in [19]. Veljovic and Skrivelj design a low-profile antenna, achieving wideband behavior through aperture coupled feeding [20]. A fractal geometry is chosen instead in [21], to obtain a compact, lightweight, and wideband deployable patch antenna. Finally, a dual-fed, dual-circularly polarized antenna fed by 3-dB coupler is presented in [22]. Some of the key parameters of these antennas are reported in Table 1.

The proposed antenna is based on the layout of the curved patch proposed in [23], wherein the curvature radius has a notable effect on both fractional bandwidth (which is a product of the increase of the average substrate thickness) and efficiency. In particular, decreasing the curvature radius leads to an increase in bandwidth and efficiency (please refer to [23, Table 2] for more details). A smaller curvature radius leads also to a gain enhancement, which is contrasted by a reduction of the directivity. This is explained by the reduction of the distance between the radiating edges of the patch, as the curvature radius decreases.

The original layout has been enhanced with a stacked configuration and an additional small air gap within the lower substrate for a further bandwidth and efficiency increment. Furthermore, the curved shape allows for a reduction of the resonant length of the antenna of about 34% w.r.t. its planar counterpart, a desirable feature for CubeSat applications in order to save space for the solar panels [24] and/or other components. The operating bandwidth of the antenna covers both the uplink and downlink bands of the S-band communications frequencies for satellite applications (2.025–2.110 GHz and 2.20–2.29 GHz, respectively). It is
TABLE 1. S-band patch antenna comparison table.

| Ref | Size [mm²] | f [GHz] | BW [%] | Gain [dBi] | Efficiency [%] | Polarization | 3D-printed |
|-----|------------|---------|--------|------------|----------------|--------------|------------|
| [15] | 96x96x2.1 | 2.45 | 0.04 (1.63) | 3.7 | 44.7 | LP/CP | No |
| [16] | 96x96x2.1 | 2.45 | 0.77 (31.4) | 7.3 | n/a | CP | No |
| [17] | 40.2x39.5 | 2.45 | 0.1 (4) | 4.8 | n/a | CP | No |
| [18] | 98.8x98.8 | 2.43 | 0.064(2.6) | 3 | 72 | 70 | LP | No |
| [19] | 100x100x11 | 2.2 | 0.212 (9.66) | 5.4 | n/a | CP | No |
| [20] | 100x100x12 | 2.45 | 0.808 (33) | 8 | 76-90 | CP | No |
| [21] | 35x45 | 2.3 | 0.66 (28.7) | 4.39 | n/a | LP | No |
| [22] | 100x100x14.7 | 2.5 | 0.28 (11.2) | 8.2 | n/a | CP | No |

This work 71.5x71.5x13 2.16 0.3 (14) 6.7 96 LP Yes

characterized by a fractional bandwidth of about 14%, a gain of about 6.7 dBi, high efficiency of 96%, and an overall weight of about 50 g. The size reduction, bandwidth coverage, and lightweight make this antenna particularly appealing for S-band CubeSat applications. With respect to other antennas presented in the literature, the proposed patch is characterized by a novel approach in the prototyping process, relying on the 3D printing, a rather large operating bandwidth, an extremely reduced weight and a very high efficiency. The patch has been designed to fit 1U CubeSats, as shown in Fig. 1, wherein a detailed representation of the antenna integrated in the ABS chassis is reported. However, if needed, the antenna could be also used in a conventional metallic CubeSat, with the printed ABS acting exclusively as substrate for the patch.

It has to be clarified, to avoid any type of confusion that the proposed antenna is not meant to be transparent. One of the authors’ intent is to present to the scientific community a suitable 3D printed material for CubeSat applications that has also a degree of transparency, and as such could be employed to design transparent antennas (using meshed configurations or, for example, ITO materials).

II. ANTENNA DESIGN AND FABRICATION

The presented antenna is composed of two main parts: the bottom layer and the top layer. Fig. 2 shows a dimensional sketch of the bottom layer from the top, front, and side perspectives. This part of the antenna exhibits a layout similar to the rectangular curved patch proposed in [23]. The major differences reside in the substrate material, made, in this case, of Acrylonitrile Butadiene Styrene (ABS, \( \varepsilon_r = 2.3, \tan\delta = 0.01 \) at 2.15 GHz) and in the presence of an air gap encased in the substrate. The latter is an \( S \times S \times H_S \) box (with \( S = 71.5 \) mm and \( H_S = 2.5 \) mm) topped by a cylindrical protrusion, made also of ABS, with a bending radius \( R_H = 12 \) mm. The footprint of the cylindrical protrusion on the \( x-y \) plane (see Fig. 2a) has length \( W = 50.6 \) mm along the \( x \)-direction and \( L = 23.81 \) mm along the \( y \)-direction. The bent bottom aluminum patch is placed over the cylindrical protrusion and has a thickness equal to \( t_P = 0.050 \) mm.

The height of the cylinder above the flat substrate can be simply calculated from the geometrical relationship as \( H_B = R_H \left[ 1 - \cos(\arcsin (L/(2R_H))) \right] \) which in this case is equal to 10.5 mm. The feeding is provided through a commercial coaxial connector, placed at distance \( y_f = 11.25 \) mm from the center of the substrate (see Fig. 2a and 2c), to guarantee the 50 \( \Omega \) matching. A rectangular \( W \times L_1 \times H_A \) air gap has been placed inside the bottom substrate, in direct contact with the ground plane, wherein \( L_1 = 45 \) mm, and \( H_A = 1 \) mm (see Fig. 2). The ground plane is an aluminum plate \((\sigma = 3.5 \cdot 10^7 \text{ S/m})\) with thickness \( t_M = 0.9 \) mm. The four holes with diameter \( D_H = 5 \) mm, placed at the corners of the structure allow a practical sealing through nylon screws and nuts. The holes are surrounded by hollow pillars with diameter \( D_P = 7.1 \) mm that act as spacers between the two layers, keeping a gap equal to \( H_G = 1 \) mm. To help the reader, a 3D view of the structure is displayed in Fig. 3a.

In the same fashion, a 3D sketch of the top layer (with a transparent bottom layer) is reported in Fig. 3b. To better understand the overall structure, a cut view of the whole antenna is reported in Fig. 3c as well. With reference to Fig. 3, the top layer substrate has the same thickness as its bottom counterpart. The parasitic aluminum patch (having...
the same thickness $t_P$ of the bottom one) is also placed over a cylindrical surface characterized by a different bending radius ($R_{H2} = 15.5$ mm) from the same center and by a planar footprint equal to $W_2 \times L_2$ (with $W_2 = 60.6$ mm and $L_2 = 29.33$ mm).

This second cylindrical shape has a height from the top flat substrate equal to $H_{B2} = 10.5$ mm. This means that the overall height of the antenna is 17.4 mm. In order to maintain the chosen gap $H_G$, the curvature radius of the lower profile of the top layer must be equal to $R_{H3} = R_H + H_G = 13$ mm. A summary of the geometrical parameters of the antenna is reported in the caption of Figs. 2 and 3. It is worth noting that the values of $H_A$ and $H_G$ have been simulated to obtain the best performance in terms of efficiency and to properly cover the S-band uplink and downlink bands.

The substrate of the antenna has been manufactured employing the commercial 3D printer Raise 3D N2 Plus. The details of the printing procedure are summarized in Table 2. The height of each extruded layer has been set to 0.1 mm. The thermoplastic filament is a commercial ABS (Sunlu Company). The metallization is provided through aluminum tape for the patches whereas an aluminum plate has been used for the ground. A photo of the realized antenna is shown in Fig. 4. The total weight of the prototype antenna is 51 g, meaning that this element is extremely lightweight and, thus, well suited for CubeSat applications.

### III. ANTENNA SIMULATIONS AND MEASUREMENTS

The antenna has been designed using CST Studio Suite. After the fabrication, its frequency response, radiation pattern, and gain have been measured in an anechoic chamber using the setup depicted in Fig. 5, which includes the Anritsu MS46322B two-port vector network analyzer (VNA), and a test calibrated antenna (model HyperLOG 7060 by AARONIA AG). The test antenna has been connected to a broadband Low Noise Amplifier (LNA) (model ZX60-83LN- S+ by Minicircuits) to improve the sensitivity of the measurement. The LNA gain has been accurately measured using the VNA to obtain a reliable estimation of the antennas under test gain.

The comparison between simulated and measured $|S_{11}|$ is reported in Fig. 6. It can be noticed the good agreement between the two curves. Concerning the measured $S_{11}$,
the antenna bandwidth is about 300 MHz (14% fractional bandwidth) covering both the S-band TT&C uplink and downlink bandwidths for CubeSat applications. From the CST simulations, it appears that the radiation efficiency of the patch is around 96% over the entire operating bandwidth. The comparison between the measured and simulated gain at room temperature is reported in Fig. 7. The measured gain is about 6.7 dBi in the target bandwidths. Given the measured antenna gain, considering the typical link budget analysis for CubeSat missions [25], the proposed ABS stacked antenna can achieve a signal-to-noise ratio (SNR) of ~11 dB, satisfying the requirement of a $10^{-5}$ bit error rate for the most common modulations and less than 0.1 dB link margin [26].

Finally, the comparison between measured and simulated radiation patterns is reported in Fig. 8, for E-plane and H-plane cuts at 2.16 GHz, showing a good agreement also in this case. The measured radiation patterns are provided only at a central frequency (2.16 GHz) and not at initial (2.025 GHz) of final frequency (2.29 GHz) within the whole operating bandwidth, since there is no substantial difference between the patterns. It is worth noting that the simulated E-plane cross-polar component is not shown because lower than $-50$ dB. The measured cross-polarization level is around $-20$ dB, whereas the simulated Front-to-Back (F/B) ratio is about 16. We were not able to measure the back radiation due to the interferences of the test coaxial cable connected to the VNA.

IV. MATERIALS AND METHODS

A. DIELECTRIC CHARACTERIZATION OF THE ABS AT DIFFERENT TEMPERATURES

To take into account the temperature influence on the dielectric response of the ABS, a 3 cm cubic sample has been
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FIGURE 8. Comparison between simulated and measured normalized radiation pattern for E-plane and H-plane cuts at 2.16 GHz (center band). The simulated cross-polar component for E-plane is not shown because <−50 dB.

B. THERMO-MECHANICAL, OPTICAL AND SURFACE ROUGHNESS CHARACTERIZATIONS

The thermal degradation of ABS samples was investigated through thermogravimetric analysis (TGA) using a Q500 analyzer from TA instruments. All measurements were carried out on 3 mg samples in an aluminum pan at a heating rate of 10 °C/min, from 30 to 800 °C in nitrogen atmosphere. The weight loss (TG curve) and its first derivative (DTG curve) were recorded simultaneously as a function of time and temperature.

Differential scanning calorimetry (DSC) thermograms were acquired with a Diamond DSC (Perkin Elmer) from −90 to 250°C for ABS samples under a dry nitrogen flow (50 mL/min) at 10°C/min. A heating-cooling-heating cycle was performed. For this analysis, small pieces (~5 mg) were cut from the films and loaded in hermetic aluminum pans before running the DSC experiment. The melting ($T_m$) and the glass transition ($T_g$) temperature were obtained from the second heating cycle.

The mechanical properties of the films were measured by uniaxial tensile test on a dual column Instron 3365 universal testing machine equipped with a 2 kN load cell. Dog-bone-shaped samples (25 mm length, 4 mm width, 2.2 mm thick) were stretched at a rate of 2 mm min$^{-1}$. All the stress-strain curves were recorded at 25 °C and 44% RH. The tensile measurements were conducted according to ISO 572-2. Seven measurements were carried out for each sample and the results were averaged to obtain a mean value. The Young’s modulus, the stress, and the elongation at break values were extracted from the stress-strain curves.

Dynamic mechanical thermal analysis (DMTA) was performed using a TA Instruments DMA Q800 with a dual cantilever clamp. Samples were tested in temperature sweeps from −140 to 160°C with a heating rate of 10°C-min$^{-1}$. Experiments were performed in a single frequency oscillation mode with a frequency of 10 Hz and a displacement amplitude of 15 μm. The glass transition temperature ($T_g$) was determined from the loss modulus ($E''$) peak.

Since the employed printed ABS has transparent characteristics, the authors decided to include an optical characterization as a useful information for the scientific community. This characterization is for dissemination purposes only, as the authors deny any claims for the proposed antenna to be transparent (feature clearly invalidated by the presence of a thick ground plane). The total transmission ($\%T$), reflection ($\%R$), and absorption (Abs) coefficients were derived via a Cary 5000 UV/VIS/NIR spectrophotometer, equipped with an integrating sphere accessory, on a sample with dimension 2 cm x 2 cm x 1 mm. The wavelength range extends from the ultraviolet (300 nm) to the near-infrared (1000 nm) at normal incidence.

Surface roughness was quantified on a Zeta optical profilometer (Zeta Instruments, San Jose, CA, USA); a 20× camera lens was applied.

printed using the commercial 3D printer Raise 3D N2 Plus and the dielectric permittivity has been measured using the resonant cavity method [27]. The measurements have been taken with the sample at room temperature, at −20 °C (using cold storage), and at 80 °C (using an oven). The sample temperature has been registered by using a Fluke TiS45 thermographic camera (Fluke Sys., 2% precision, frame rate of 30 Hz).
V. MATERIAL CHARACTERIZATION

Within the temperature range provided in Section IV-A, the permittivity of the ABS sample fluctuated between 2.285 and 2.330. Therefore, we have simulated the designed antenna using the minimum and maximum of this range, founding no variation in the antenna behavior, thus confirming its robustness to space-like thermal excursion, which is a stringent requirement for CubeSat antennas.

The thermal characterization of 3D printed ABS was carried out by thermogravimetric analysis (TGA), shown in Fig. 9a, and differential scanning calorimetry (DSC), displayed in Fig. 9b. From the TGA measurements, ABS resin exhibited a single weight loss at \(\sim 400^\circ C\) corresponding with the structural decomposition of the polymer. A final residue of \(\sim 0\%\) was achieved indicating the total combustion of the residual char. The thermal properties of the samples were also characterized by DSC (Fig. 9b). A typical DSC curve for ABS resin was obtained with two major thermal events [28]. The first modest event appears in the range of \(-50^\circ C\) to \(-25^\circ C\) indicating the rubber-phase glass transition region. The second thermal event takes place from 100°C to 120°C and it is representative of the styrene-acrylonitrile glass transition.

Tensile test and dynamic mechanical analysis (DMA) were used to evaluate the mechanical properties of 3D printed ABS with different percentages of filling (from 20% to 100%). Fig. 9c shows the typical tensile stress-strain curves, while the measured mechanical parameters (i.e., Young’s modulus, stress, and strain at break) are reported in Table 3. It could be observed how the mechanical properties are linearly proportional to the percentage of printing filling. ABS sample with 100% infill interlaced pattern is the sample with the maximum Young’s modulus of \(\sim 715\) MPa, stress at break around \(\sim 33\) MPa, and good elasticity with \(\sim 11\%\) of strain at break. On the contrary, ABS samples with 20% infill interlaced pattern showed a general decrease in the mechanical properties (Young’s modulus: \(\sim 300\) MPa, stress at break: \(\sim 14\) MPa, strain at break: \(\sim 8\%\)). This change can be directly attributed to the different printing fillings which can make the printed sample stronger or weaker when subjected to traction forces. Interestingly, the different infill pattern of ABS filaments from the interlaced to the linear affects the mechanical behavior showing a decrease in the strain at break of \(\sim 60\%\) (Fig. 9c). Thermo-mechanical properties were confirmed by DMA (Fig. 9d). In particular, there are no significant differences according to the infill percentage of ABS resin, and two main events can be observed.

### Table 3. Mechanical parameters.

| Samples | Young’s Modulus (MPa) | Stress at break (MPa) | Strain at break (MPa) |
|---------|-----------------------|----------------------|----------------------|
| 100% lin| 714 ± 50              | 26 ± 2               | 4.6 ± 0.2            |
| 100%    | 736 ± 5               | 32 ± 0.6             | 11 ± 1               |
| 80%     | 578 ± 17              | 22 ± 0.3             | 9 ± 0.6              |
| 60%     | 422 ± 17              | 18 ± 0.1             | 8.6 ± 1.6            |
| 40%     | 362 ± 15              | 16 ± 0.2             | 9.8 ± 1.4            |
| 20%     | 296 ± 22              | 14 ± 0.3             | 8.5 ± 0.65           |
| 100%    | 736 ± 5               | 32 ± 0.6             | 11 ± 1               |
also from this analysis. The first event is a small peak in the \(\tan(\delta_m)\) around \(-60^\circ\)C corresponding to the glass transition temperature of the rubbery phase, while the second event in the range of 100 – 130°C is connected to the main glass transition temperature detected also by DSC.

The total transmission \((%T)\), reflection \((%R)\), and absorption \((\text{Abs})\) coefficients were derived. The results are shown in Fig. 10 below. It can be noticed that, as the filling factor increases, the transmission decreases to a maximum of about 20%, while decreasing as the wavelength increases. On the other hand, the reflection increases for increasing filling factor, the absorption is higher for higher filling factor, while the difference in the coefficient vanishes above 500 nm. These results highlight that the 100% printed ABS material could be reliably used on CubeSat and does not represent a limiting factor for the solar panels. Indeed, the optical transparency is similar to other materials used found in the literature for similar applications [29], [30]. From the surface roughness analysis, whose results are reported in Fig. 11, we derived that the arithmetical mean height is 0.31 \(\mu\)m, whilst the root mean square height is 0.38 \(\mu\)m. The maximum peak height is 1.35 \(\mu\)m and the deepest pit is 1.19 \(\mu\)m. Considering the working frequency band around 2.1–2.3 GHz, the free-space wavelength is \(\lambda_0 \sim 15\) cm and, hence, the roughness of the ABS substrate cannot affect the current distribution on the adhesive copper tape.

### VI. IN SILICO EVALUATION

Given the harsh LEO environment, a coupled mechanical-thermal numerical analysis has been performed to investigate if temperature gradients faced during the orbital cycles can induce mechanical stresses that could potentially lead to antenna damage or failure. Indeed, during the orbit, three main heat sources may drastically affect the operation of the communication device, as shown in Fig. 12a, i.e., the direct sun radiation \((Q_s)\), the albedo radiation \((Q_a)\), and, finally, the infrared energy directly emitted from Earth’s atmosphere or surface \((Q_e)\). Considering a LEO mission which consists of a sun-synchronous circular orbit, having an orbital height of 300 km and an orbit inclination angle \(\beta = 90^\circ\), the total power fluxes directed on the CubeSat surfaces were computed [31], [32], [33], and are reported in Fig. 12b. By relying on the multiphysics numerical model reported in [6], we performed simulation by solving the unsteady heat transfer balance for study the dynamics of the temperature.
FIGURE 12. a) Schematic description of the thermal conditions in a typical CubeSat mission. b) Power fluxes on the six CubeSat faces (in W/m²) for the case of a typical low earth orbit mission.

\( T(T(x, y, z, t)) \) in the case of a 1U CubeSat, on which the proposed stacked patch antenna is deployed (Fig. 1), and derive the deformation and Von Mises stresses \((\sigma_{VM})\) distributions using the finite element method (FEM) commercial software Comsol Multiphysics 5.5 (Comsol Inc., MA, USA). Homogeneous temperature distribution was assumed as the initial condition, i.e., \( T(x, y, z, t = 0) = T_0 \). As boundary conditions for the thermal problem, thermal insulation and surface-to-ambient radiation are considered. The external temperature was set to 4 K. The materials properties are reported in Table 4. The thermal and mechanical properties of solar cells were taken from [6]. The thermal and mechanical properties of ABS were derived from the experimental characterization. Five orbits, with a 1 min time step, were simulated. The maximum temperature is of \( \sim 50^\circ\text{C} \) and it is reached in the top layer of the stacked curved patch antenna (Fig. 13a). On the other hand, the lower antenna layer is colder and can reach a minimum temperature of \( \sim -100^\circ\text{C} \), as shown in Fig. 13a.

As a matter of fact, the average antenna temperature ranges from \( \sim -50^\circ\text{C} \) to \( -100^\circ\text{C} \) and hence the temperature gradients are relatively high (\( \sim 6 \text{ C/cm} \)), as can be seen from Fig. 13a-13c. The thermal stresses induced during the orbits present a narrow range of variation between 6–12 MPa, reaching a maximum of \( \sim 100 \text{ MPa} \) on the antenna edges in the top layer. Probably this is due to the holes presence. The analyzed Von Mises stresses deserve to be analyzed to assess if the antenna performances can be degraded.

By analyzing Fig. 13d, it is possible to notice that, after a small transient, the maximum antenna deformation is of \( \sim 0.38 \text{ mm} \), occurring at the maximum point of cooling (Fig. 13a), and presenting a narrow range of variation (\( \pm 0.1 \text{ mm/h} \)). We focused on this worst case scenario. On average, the displacement level ranges from 0.1 mm to 0.18 mm. By observing the displacement patterns shown in Fig. 13e and Fig. 13f, a very low retraction around the holes is found (\( \sim 0.35 \% \)), whilst, on the bottom and top layer, the curved patch surfaces, given the air gap below, tends to bend. By simulating the deformed antenna configuration, a difference of \( \sim 5 \text{ dB} \) at the peak of the \( |S_{11}| \) response is found. Hence, the antenna performances, i.e., matching and the other radiation properties, are poorly affected by the thermo-mechanical deformation induced by the harsh environment encountered during the orbital periods. It is worth noting that in CubeSat system it is possible to use a temperature control systems and potentially prevent any malfunctioning of plastic antennas [34].

VII. CONCLUSION

The paradigm and trend of the new space economy are engaging private stakeholders who demand innovative systems with short development times (12–18 months) and are capable of ensuring a high economic return. In this regard, plastic CubeSat could play a pivotal role in boosting the availability of cost-effective spacecrafts for innovative space missions. Therefore, in this work, a commercial, transparent ABS filament was characterized in terms of dielectric, thermal, and mechanical properties to assess its compliance with space requirements and to retrieve information useful for the design and analysis of a 3D-printed, integrated S-band curved patch antenna. Indeed, some of the most desirable features for a CubeSat antenna include low weight, low cost, wide band, and reduced size to have more space dedicated to the solar panels. In this paper, a curved 3D printed patch antenna capable of meeting all these requirements is presented. The substrate of the antenna is made of ABS, which has proven to be a reliable material for space applications. The proposed antenna covers both the uplink

| Material properties used in the simulations. |
| --- |
| Property | Definition | 3D-printed ABS | Aluminum |
| --- | --- | --- | --- |
| \( \rho \) (kg/m³) | Density | 1110 | 26 ± 2 |
| \( C_p \) (J/kg·K⁻¹) | Specific heat | 1650 | 32 ± 0.6 |
| \( k \) (W/m·K⁻¹) | Thermal conductivity | 0.17 | 238 |
| \( \alpha_{ex} \) (°C⁻¹) | Thermal expansion coeff. | 8.46·10⁻⁵ | 23·10⁻⁶ |
| \( E \) (MPa) | Young’s modulus | 736 | 70·10¹ |
| \( \nu \) | Poisson’s ration | 0.36 | 0.10 |
| \( \eta \) | Emissivtity | 0.90 | 0.10 |
(2.025–2.110 GHz) and downlink (2.2–2.29 GHz) bands of the S-band communications frequencies for satellite applications. It is characterized by a gain of about 6.7 dBi, an efficiency of 96%, a size reduction along the resonant length of about 34% w.r.t. a planar antenna, and most importantly by a total weight of about 50 g, providing a less significant contribution to the total mass of the satellite. Compared with other S-band patch antennas found in the scientific literature, the proposed antenna relies on a fast prototyping process, founded on the 3D printing. Based on the presented study, the viability of plastic CubeSats would enable the possibility to fabricate both the CubeSat chassis and the antenna in a single, convenient, and cost-effective process.

Future works will deal with the re-design and engineering of the proposed antenna layout to develop a fully transparent device, investigating solutions such as meshed patch and ground plane or ITO as conductive material. Moreover, given the innovative character of the proposed antenna concept, its characterization methodology and numerical analysis, this work could be the starting point for studying 3D-printed plastic antennas for large CubeSat units and further advance the flourishing of the new space economy.

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MUNTONI et al.: CURVED 3D-PRINTED S-BAND PATCH ANTENNA FOR PLASTIC CubeSat

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