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A 3-D metal printed folded-shorted patch array with an integrated feeding circuit offering dual-band circularly polarised radiation for cubesat applications

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This letter presents a three-dimensional (3-D) printed metallic antenna array that combines folded-shorted patches (FSPs) and meandering for structure compactness. The design provides dual-band functionality, operating in the L-band and the S-band. The compact and broadband feeding network, which is also integrated onto the backside of the antenna ground plane, enables circularly polarised radiation over an operational bandwidth of more than 80%. The dimensions of the array are 0.4 × 0.4 × 0.056 λ0 (where λ0 is the free space wavelength at 1.2 GHz), making the design suitable for CubeSats and other space constraint applications. The measured right-handed circularly polarised realised gains are 2.32 dBiC and 1.84 dBiC at 1.2 GHz and 2.45 GHz, respectively. In addition, the 3-D metallic printed FSP elements can be flexibly arranged for different link requirements and other applications like beam steering.

Introduction: The application of three-dimensional (3-D) printing technology has proven to be increasingly useful in microwave engineering, including 3-D printed antennas [1–5], radio frequency (RF) filters [6, 7], and lenses [8]. This modern technology can offer reasonable accuracy in fabricating prototypes and commercial products. Its efficiency and precision are comparable to, or even superior than, most conventional fabrication techniques and metallic machining approaches, particularly for designs with intricate features. In addition, powders with negligible to high electrical conductivity (i.e. similar to dielectrics and copper or aluminum), can be used to print dielectric [1, 2] and metallic-based antenna structures [3–5], respectively.

Following this trend, there have been a number of 3-D printed satellite antennas reported [9, 10] constituted mainly by dielectric resins, and this research is important as such antennas are needed to support current and future 5G/6G wireless communications and satellite systems [11, 12]. Also, as compared to conventional large satellites, the development of small satellites such as CubeSats and Picosats, offers a relatively inexpensive access to space and can support the aforementioned communication systems [13, 14]. CubeSats, for instance, are typically sized in multiples of one cubic unit 10 × 10 × 10 cm3 (i.e. 1U). Thus, it is essential that the electronics, especially the antennas, are as small as possible to meet these volume constraints.

These satellite systems, on the other hand, also strive to employ multiband or wideband antennas and some 3-D printed designs have been reported [9–12]. Also, low-profile planar structures such as conventional patch antennas are particularly attractive due to their low-cost and simple fabrication. Typical sizes are around half a wavelength, however, and when employed within CubeSat platforms, designers can face challenges to meet volume and gain requirements. One solution is to use substrates with a high relative permittivity for compactness. However, this can bring some practical uncertainty. For example, such dielectrics can be susceptible to changes in the ambient temperature and environment that, unfortunately, are severe in space and can cause unwanted shifts in the patch operational frequency [15].

In recent work, a C-band stacked Yagi-Uda antenna array was proposed for CubeSats with a self-deployment mechanism enabled by 3-D printing technology [16]. Its volume was 1.15 λ0 × 10 cm3 (i.e. 1 U). Thus, it is seen that this can bring some practical uncertainty. For example, such dielectrics can be susceptible to changes in the ambient temperature and environment that, unfortunately, are severe in space and can cause unwanted shifts in the patch operational frequency [15].

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The rest of the letter is organised as follows. The next section describes the structure and operation of the proposed dual-band FSP antenna array as well as details for the wideband feeding network. Following that, results of the integrated feed and complete antenna system measurements are presented and discussed. The work is then summarised. To the best knowledge of the authors, no similar FSP array...
and integrated feeding circuit (with similar performance metrics), has been reported previously.

**Dual-band FSP antenna array design:** We employ 3-D metal printing technology to fabricate the miniaturised FSP antenna array for dual-band operation. In our earlier works [20, 21], designed for single-frequency operation, it was found challenging to ensure consistency of the metallic FSP elements (which were fabricated by more conventional CNC technologies and metal work machining). Basically it was difficult to achieve suitable impedance matching at the same frequency. At times this required re-fabrication and assembly of the individual elements to achieve the desired operation. To overcome these practical challenges and to ensure consistent fabrication quality, we adopt herein 3-D metal printing technology. It is also worth mentioning that high conductivity aluminum metal (3.56 × 10^8 S/m) was used in the 3-D printing of the FSP elements.

In Figure 1, the perspective view is illustrated for the proposed 2 by 2 FSP antenna array. The physical dimension of the entire array is 10 × 10 × 1.4 cm^3, and this corresponds to 0.4 × 0.4 × 0.056 λ_0, where λ_0 is the free space wavelength at 1.2 GHz. The wideband feeding network is positioned under the ground of the antenna array, see the inset in Figure 1. The antenna feeding ports 2 to 5, can be set to provide suitable impedance matched connectors [22, 23]. In Figure 1, the perspective view is illustrated for the proposed 2 by 2 FSP antenna array. The physical dimension of the entire array is 10 × 10 × 1.4 cm^3, and this corresponds to 0.4 × 0.4 × 0.056 λ_0, where λ_0 is the free space wavelength at 1.2 GHz. The wideband feeding network is positioned under the ground of the antenna array, see the inset in Figure 1. The antenna feeding ports 2 to 5, can be set to provide suitable impedance matched connectors [22, 23].

The simulated mode significance for the complete antenna array is studied using characteristic mode analysis (CMA). In particular, by using CST, the simulated mode significance (see Figure 3) shows three resonant modes in the frequency band of interest. The peaks for Mode 1 and Mode 2 are found identical at 1.2 GHz, and the peak for Mode 3 is around 2.4 GHz and these, respectively, correspond to the TM_{010} and the TM_{030} modes of the FSPs. Also, the simulated surface currents on the upper layer of the antenna is displayed in Figure 4. The main directions of the modal electric fields are also identified using black arrows. For these results, it should be mentioned that the 2 by 2 array was studied without any feeding considerations.

It can be observed that at 1.2 GHz, two adjacent LP modes are generated, namely Mode 1 and Mode 2 shown in Figures 4a and 4b. Mode 1 is an even mode, characterised by horizontally directed currents on the upper layer for two FSPs, while Mode 2 is an odd mode, with anti-phase currents generated on all the four FSP elements with uniform amplitude. Analysis of the radiating elements: In order to gain further insight into the radiation features of the proposed design, the FSP elements were studied using characteristic mode analysis (CMA). In particular, by using CST, the simulated mode significance (see Figure 3) shows three resonant modes in the frequency band of interest. The peaks for Mode 1 and Mode 2 are found identical at 1.2 GHz, and the peak for Mode 3 is around 2.4 GHz and these, respectively, correspond to the TM_{010} and the TM_{030} modes of the FSPs. Also, the simulated surface currents on the upper layer of the antenna is displayed in Figure 4. The main directions of the modal electric fields are also identified using black arrows. For these results, it should be mentioned that the 2 by 2 array was studied without any feeding considerations.

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following [29]. Also, as shown in Figures 1a and 5b, 50-Ω resistors were used to terminate the isolation ports of the couplers. The feeding network was constructed on a RT4003C substrate with a relative dielectric constant $\varepsilon_r$ of 3.38, tan$\delta$ of 0.0027, and a thickness of 0.51 mm. Also, the physical dimensions of the fabricated circuit were $90 \times 70$ mm$^2$.

Results & discussions: Four copies of the proposed FSP antenna element were fabricated using metal 3-D printing technology, as observed in Figure 5a and configured in a 2 by 2 arrangement for CP. The fabricated feeding network, seen in Figure 5b, was attached to the backside of the structure and this setup defined a shared ground plane for the antenna array and feeding circuit.

Figure 6 reports the simulated and measured reflection coefficients for the four individual FSP elements. It can be observed that the measured results closely match the simulated, however, there is a small frequency shift. For example, simulations for the lower band were optimised for 1.20 GHz (for all the fabricated elements). Similarly, the upper band resulted in 3 dB loss, since this is a 1-to-4 feeding network, the bandwidth of the feeding network is defined by

\[ \text{average transmission coefficients} = \frac{S_{11} + S_{21} + S_{31} + S_{41}}{4} \]

at 1.2 GHz. The bandwidth of the feeding network is defined by the average transmission coefficients of $S_{21}, S_{31}, S_{41}$ and $S_{11}$, which is around 74%. We set the bandwidth threshold at when the feeding network introduces 3 dB loss, since this is a 1-to-4 feeding network, the bandwidth is thus defined as the average transmission coefficient higher than −9 dB. It should be mentioned that ideally the output phase differences should be $-90^\circ$, $-180^\circ$ and $-270^\circ$ for RHCP, however, it was not trivial to achieve these exact values at both 1.2 GHz and 2.4 GHz during the design and optimisation. Regardless of these results, RHCP operation was made possible when this feeding circuit was affixed to the aforementioned 2 by 2 antenna design as described next.

Realised RHCP gain patterns reported in Figure 8 demonstrate a maximum value of 2.32 dBi at 1.2 GHz. The cross-polarisation level (i.e. LHCP) is relatively low, with values more than 20 dB below the main beam maximum at broadside. It should be mentioned that there is a minor reduction for the RHCP gain (between 310° to 350°), this may be attributed to some interference from the antenna positioner and connected cable during the measurements. Moreover, this minor beam squint can be attributed to the practicalities of the measurement setup and the wideband nature of the system. Also, at 2.45 GHz, the RHCP realised gain was found to be $-0.22$ dBi and 1.84 dBi at broadside and 312°, respectively. Given these measurements, the 3-dB axial ratio beamwidth was 125° and 74° at 1.2 GHz and 2.45 GHz, respectively, defining broad beam CP functionality.

The measured reflection coefficient and peak realised gain versus frequency for the complete antenna system (i.e. the integrated feed and the 2 by 2 array of FSPs) is shown in Figure 9. It is noted that the measurement was only conducted in the range from 1 to 1.3 GHz and from 2.2 to 2.6 GHz in the far-field. As it can be observed there is a general agreement between the simulations and the measurements. Overall, results suggest that the developed and fabricated 3-D printing antenna can offer good radiation performance, particularly in terms of realised CP gains and AR beamwidth which can be required for

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**Figure 5** 3-D metal printed prototype: (a) 2 by 2 array design; (b) fabricated five-port feeding circuit which was affixed to the antenna backside.

**Figure 6** Simulated and measured reflection coefficients for the FSPs. Here ‘i’ for $S_{ii}$ ($i = 1, 2, 3, 4$) refers to each FSP within the 2 by 2 array.

**Table 1.** Five-port feeding system simulated & measured comparison

<table>
<thead>
<tr>
<th>Simulated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq: 1.2 / 2.4 GHz</td>
<td>Freq: 1.2 / 2.4 GHz</td>
</tr>
<tr>
<td>$S_{11}$</td>
<td>Mag: $-12.4 / -9.4$ dB</td>
</tr>
<tr>
<td>$S_{21}$</td>
<td>Mag: $-6.6 / -7.8$ dB</td>
</tr>
<tr>
<td>$S_{31}$</td>
<td>Mag: $-6.7 / -7.4$ dB</td>
</tr>
<tr>
<td>$S_{41}$</td>
<td>Mag: $-6.7 / -7.5$ dB</td>
</tr>
<tr>
<td>$S_{51}$</td>
<td>Mag: $-6.8 / -7$ dB</td>
</tr>
<tr>
<td>$\delta S_{11}$</td>
<td>Phase: $-99^\circ / -91^\circ$</td>
</tr>
<tr>
<td>$\delta S_{21}$</td>
<td>Phase: $-186^\circ / -181^\circ$</td>
</tr>
<tr>
<td>$\delta S_{31}$</td>
<td>Phase: $-269^\circ / -275^\circ$</td>
</tr>
</tbody>
</table>
Table 2. Comparisons with similar antenna designs in the literature

<table>
<thead>
<tr>
<th>Refs.</th>
<th>Antenna fab.</th>
<th>Size ($\lambda$)</th>
<th>Frequency (GHz)</th>
<th>$S_{11}$ (dB)</th>
<th>Peak Gain (dBiC)</th>
<th>Total eff.</th>
<th>Polarisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>3-D Dielectric Printing</td>
<td>9×9×1.95</td>
<td>30</td>
<td>NA</td>
<td>26</td>
<td>NA</td>
<td>CP</td>
</tr>
<tr>
<td>[10]</td>
<td>3-D Metal Printing</td>
<td>2.56×2.56×6.3</td>
<td>12.0 &amp; 14.0</td>
<td>−20</td>
<td>2.0 &amp; 3.0</td>
<td>NA</td>
<td>CP</td>
</tr>
<tr>
<td>[16]</td>
<td>PCB</td>
<td>1.93×1.93×0.31</td>
<td>5.6 to 6.0</td>
<td>&gt; −18</td>
<td>13.5</td>
<td>NA</td>
<td>CP</td>
</tr>
<tr>
<td>[17]</td>
<td>Metal Sheet Welding</td>
<td>1.16×1.16×0.24</td>
<td>3.3 to 7.3</td>
<td>&gt; −18</td>
<td>9.4 &amp; 12.4</td>
<td>NA</td>
<td>CP</td>
</tr>
<tr>
<td>[18]</td>
<td>PCB</td>
<td>0.16×0.16×0.18</td>
<td>1.5 to 1.7</td>
<td>&gt; −35</td>
<td>5.13</td>
<td>NA</td>
<td>CP</td>
</tr>
<tr>
<td>[19]</td>
<td>PCB</td>
<td>0.29×0.29×0.04</td>
<td>1.56 to 1.61</td>
<td>&gt; −26</td>
<td>3.13</td>
<td>NA</td>
<td>CP</td>
</tr>
<tr>
<td>[25]</td>
<td>Metal Sheet Welding</td>
<td>NA</td>
<td>Ground plane size</td>
<td>1.53 to 3.27</td>
<td>−17 &amp; −12</td>
<td>0.4 &amp; 1.9</td>
<td>NA</td>
</tr>
<tr>
<td>[26]</td>
<td>Metal Sheet Welding</td>
<td>0.3×0.3×0.05</td>
<td>2.4 &amp; 5</td>
<td>−27 &amp; −30</td>
<td>3.3 &amp; 5.5</td>
<td>NA</td>
<td>LP</td>
</tr>
</tbody>
</table>

Our work 3-D Metal Printing 0.4×0.4×0.056 1.2 & 2.45 −22 & −28 2.32 & 1.84 84% & 95% CP

Fig. 7 S-parameters measurements for the five-port feeding system (see Figure 5b); (a) magnitudes in dB and (b) phases in degrees.

Fig. 8 Realised CP gain patterns for the 2 by 2 antenna array and integrated feeding circuit at (a) 1.2 GHz and (b) 2.45 GHz.

dual-band communications enabling data links for CubeSats and other small satellites.

Table 2 compares the proposed design to other related works found in the literature. As can be observed, benefits include structure size and dual-band functionality (in the L- and S-band). The existing works [1, 17] reported the CP antennas with high gains, but the physical dimensions of the antenna arrays are relatively high. There is a trade-off between the array profile and the gain. Moreover, the antenna designs in [18, 19] employed dielectric materials to achieve goals of compact size and high gain performance. However, these materials introduce susceptibility to variations in ambient temperature and environmental factors, especially for space applications.

To the best knowledge of the authors, no similar antenna design has been reported. Regardless of the compact size, the total antenna efficiency (which includes the feeding circuit) remains high, despite its miniaturisation using folding, shorting, and meandering techniques.

Conclusion: This letter presented an investigation into the use of 3-D metal printing technology for the fabrication of a miniaturised CP antenna using four FSP elements. The measured results indicate that this technology proves to offer suitable fabrication consistency for
the complex antenna structure, and this is needed for optimisation of the FSPs to operate at the TM$_{010}$ and the TM$_{030}$ modes, and, at the

![Fig. 9](image)

Fig. 9 Reflection coefficient (solid line) and maximum realised gain (dash line) versus frequency for the 2 by 2 array and integrated feeding system.

References


2 Lei, S., Wei, G., Han, K., Li, X., Qu, T.: A Wideband 3-D-Printed Multi-beam Circularly Polarized Ultrathin Dielectric Slab Waveguide Luneburg Lens Antenna. *IEEE Antennas Wireless Propag. Lett.* 21(8), 1582–1586 (2022)


