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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

Yuepei Li¹,², Jiayu Rao³, Lei Wang¹, Yuan Ding¹, and Symon K. Podilchak¹,²

¹Institute of Sensors, Signals and Systems (ISSS), Heriot-Watt University, Edinburgh, UK.
²Institute of Digital Communications, School of Engineering, University of Edinburgh, Edinburgh, UK.
³School of Electrical and Information Engineering, Jiangsu University of Technology, Changzhou, China.

This letter presents a three-dimensional (3-D) printed metallic antenna array that combines folded-shorted patches (FSPs) and meandering for structure compactness. The proposed antenna operates 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 $0.4 \times 0.4 \times 0.056\lambda_0$ (where $\lambda_0$ is the free space wavelength at 1.2 GHz), making the design suitable for CubeSats and other space constraint applications. The measured right-handed circular polarised realised gains are 2.32 dBi and 1.84 dBi 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 aluminium), 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 compactness. The design provides dual-band functionality, which is compact and broadband providing functionality from 1.1 to 2.6 GHz.

Multi-radiation modes, stacked patches were employed and the design was supported by characteristic mode analysis (CMA). However, the structure was challenging to fabricate and ensure that all four antenna elements resonated at the same frequency. In another work [18], a miniaturised CP slot helix antenna was designed for satellite applications by using a spiral microstrip feed line. Also in [19], a miniaturised microstrip CP antenna was reported using T-shaped coupled feedlines. Some of the above works, including those in [20], [21] which realised CP antenna radiation by an array of 2 by 2 folded-shorted patches (FSPs) for CubeSats and Picosats, respectively, offered narrow and single-band operation. This is not supportive of the requirement for multiband or wideband antenna systems for satellites. To improve upon these earlier contributions, we introduce a new 3-D printed metallic array consisting of a 2 by 2 arrangement of FSPs (see Fig. 1). These elements exhibit excellent fabrication consistency and this is needed for well defined and controlled radiation of the TM$_{010}$ and the TM$_{030}$ modes of the FSPs, and additionally, which were optimised and newly exploited for dual-frequency operation at 1.2 and 2.4 GHz. Also, with the developed and integrated feed, which is wideband, the antenna provides CP functionality at both these L-band and S-band frequencies.

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
aluminum powder \(3.56 \times 10^7\) and to ensure consistent fabrication quality, we adopt herein 3-D metal this required re-fabrication and assembly of the individual elements to CNC technologies and metal work machining). Basically it was difficult the metallic FSP elements (which were fabricated by more conventional the top patch) for a single FSP antenna. They were optimised to 16.7 mm and 1.5 mm, respectively, in our final design.

Fig. 2: Parametric study of \(L_s\) and \(W_s\) (length and width of the slots on the top patch) for a single FSP antenna. They were optimised to 16.7 mm and 1.5 mm, respectively, in our final design.

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 powder \((3.56 \times 10^7 \text{ S/m})\) was used in the 3-D printing of the FSP elements.

In Fig. 1, the perspective view is illustrated for the proposed 2 by 2 FSP antenna array. The physical dimension of the entire array is \(10 \times 10 \times 1.4 \text{ cm}^3\), and this corresponds to \(0.4 \times 0.4 \times 0.096 \lambda_0^3\), where \(\lambda_0\) 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 Fig. 1. The antenna feeding ports 2 to 5 can be set to provide suitable phase \(\pm 1.2^\circ\) to the input port matching is about \(-10\ \text{dB}\) for both bands, and the average transmission coefficients are about \(-6.9\ \text{dB}\) at 1.2 GHz and \(-7.4\ \text{dB}\) at 2.45 GHz. Also, in the worst case, measured magnitude imbalances approach 0.8 dB while the output phase differences are \(-88^\circ\) to \(-86^\circ\), \(-162^\circ\) to \(-177^\circ\), and \(-249^\circ\) to \(-266^\circ\) at 1.2 and 2.4 GHz, respectively. In addition, similar imbalances are observed from 1.2 GHz to 2.6 GHz. The bandwidth of the feeding network is defined by the average transmission coefficients of \(S_{21}\), \(S_{31}\), \(S_{41}\) and \(S_{51}\), which is around 74%. We set the bandwidth threshold at when operation at both L-band and S-band frequencies. These desirable dual-band antenna features can simultaneously support S-band downlinks [24] and communications and/or data links between conventional satellites (which typically operate at the L-band). Furthermore, this antenna functionality can also support communications between a network of CubeSats (enabling satellite-to-satellite connectivity), for example, while also, not consuming excessive area on the satellite structure itself. This is because the proposed 2 by 2 array can support these multiple functions whilst using a single antenna array only. As a result, space is made available on the satellite itself for other communication equipment, additional sensor technologies, more solar cells, etc. and this approach to the satellite design can foster more advanced mission capabilities.

**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 Fig. 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_{001} modes of the FSPs. Also, the simulated surface currents on the upper layer of the antenna is displayed in Fig. 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 Fig. 4(a) and (b)). 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 which are vertical. Also, the strength of the surface currents for both modes is observed to be the same. These two modes are formed as mode pairs at 1.2 GHz which can support CP radiation. In contrast, Mode 3 is illustrated in Fig. 4(c) at 2.4 GHz which is defined by modal currents generated on all the four FSP elements with uniform amplitude. This current and field configuration can also be exploited for CP radiation. This analysis approach follows [17], [25–27]. Moreover, a similar CMA study was reported in [17] for a CP antenna which was defined by four elements in a sequential rotation arrangement.

A five-port feeding network was designed to offer the required phase shifts and equal power splitting at 1.2 GHz and 2.4 GHz. This feeding system was optimised in CST and the circuit structure is composed of two 90° couplers and one 180° coupler, as outlined in Fig. 1. The designed 90° couplers adopt a cascaded branch-line approach as in [28], while the 180° network is defined by a Lange coupling structure by following [29]. Also, as shown in Fig. 1(a) and (b), 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, tanδ of 0.0027, and a thickness of 0.51 mm. 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 Fig. 5(a) and configured in a 2 by 2 arrangement for CP. The fabricated feeding network, seen in Fig. 5(b), was attached to the backside of the structure and this setup defined a shared ground plane for the antenna array and feeding circuit.

Fig. 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 about 1.18 GHz while measurements demonstrated reduced reflections at 1.20 GHz (for all the fabricated elements). Similarly, the upper band showed best and consistent matching at about 2.45 GHz.

The simulated and measured S-parameters of the wideband planar feeding network are summarised in Table 1 and Fig. 7. From these results, it can be observed that the input port matching is about \(-10\ dB\) for both bands, and the average transmission coefficients are about \(-6.9\ dB\) at 1.2 GHz and \(-7.4\ dB\) at 2.45 GHz. Also, in the worst case, measured magnitude imbalances approach 0.8 dB while the output phase differences are \(-88^\circ\) to \(-86^\circ\), \(-162^\circ\) to \(-177^\circ\), and \(-249^\circ\) to \(-266^\circ\) at 1.2 and 2.4 GHz, respectively. In addition, similar imbalances are observed from 1.2 GHz to 2.6 GHz. The bandwidth of the feeding network is defined by the average transmission coefficients of \(S_{21}\), \(S_{31}\), \(S_{41}\) and \(S_{51}\), which is around 74%. We set the bandwidth threshold at when...
respectively. Given these measurements, the 3-dB axial ratio beamwidth gain was found to be structure (see Fig. 8 from [20]). Also, at 2.45 GHz, the RHCP realised and similar challenges were reported in [20] for such a compact antenna squint can be attributed to the practicalities of the measurement setup connected cable during the measurements. Moreover, this minor beam maximum at broadside. It should be mentioned that there is (i.e. LHCP) is relatively low, with values more than 20 dB below the coefficient higher than network, the bandwidth is thus defined as the average transmission loss, since this is a 1-to-4 feeding system 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°, −180°, and −270° 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 Fig. 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°), and this may be attributed to some interference from the antenna positioner and a minor reduction for the RHCP gain. Moreover, this minor beam squint can be attributed to the practicalities of the measurement setup and similar challenges were reported in [20] for such a compact antenna structure (see Fig. 8 from [20]). 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 Fig. 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 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 antenna design.
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$_{001}$ modes, and, at the desired frequencies of 1.2 and 2.4 GHz, respectively. In particular, a 2 by 2 array was prototyped and the maximum realised gain was measured to be 2.32 dBic and 1.84 dBic at 1.2 GHz and 2.45 GHz, respectively. This is made possible by a wideband feeding circuit, which is more than 80%, and this provides the needed 90º phase feeding for the sequentially rotated elements. The proposed dual-band CP antenna structure can be suitable for CubeSats and other size-constraint wireless platforms. Furthermore, the elements can also be arranged in different array configurations, providing flexibility and versatility for other scenarios, and in particular, where compact and dual-band arrays are required.

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Table 2: Comparisons with Similar Antenna Designs in the Literature

<table>
<thead>
<tr>
<th>Refs.</th>
<th>Fabrication</th>
<th>Liquid Crystal Frequency (GHz)</th>
<th>Liquid Crystal Gain (dBi)</th>
<th>Total Efficiency</th>
<th>Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>3-D Dielectric Printing</td>
<td>9x0x1.95</td>
<td>30</td>
<td>N.A</td>
<td>CP</td>
</tr>
<tr>
<td>[10]</td>
<td>3-D Metal Printing</td>
<td>2.56x2.56 x6.3</td>
<td>12.0 &amp; 14.0</td>
<td>−20</td>
<td>2 &amp; 3.0</td>
</tr>
<tr>
<td>[16]</td>
<td>PCB</td>
<td>1.93x1.93 x0.31</td>
<td>5.6 to 6.0</td>
<td>&gt; −18</td>
<td>13.5</td>
</tr>
<tr>
<td>[17]</td>
<td>Metal Sheet Welding</td>
<td>1.16x1.16 x0.24</td>
<td>3.3 to 7.3</td>
<td>&gt; −18</td>
<td>9.4 &amp; 12.4</td>
</tr>
<tr>
<td>[18]</td>
<td>PCB</td>
<td>0.16x0.16 x0.18</td>
<td>1.5 to 1.7</td>
<td>&gt; −35</td>
<td>5.13</td>
</tr>
<tr>
<td>[19]</td>
<td>PCB</td>
<td>0.29x0.29 x0.04</td>
<td>1.56 to 1.61</td>
<td>&gt; −26</td>
<td>3.13</td>
</tr>
<tr>
<td>[22]</td>
<td>Metal Sheet Welding</td>
<td>N.A ground plane size</td>
<td>1.53 to 3.27</td>
<td>−17 &amp; −12</td>
<td>0.4 &amp; 1.9</td>
</tr>
<tr>
<td>[23]</td>
<td>Metal Sheet Welding</td>
<td>0.3x0.3x0.05</td>
<td>2.4 &amp; 5</td>
<td>−27 &amp; −30</td>
<td>3.3 &amp; 5.5</td>
</tr>
<tr>
<td>Our work</td>
<td>3-D Metal Printing</td>
<td>0.4x0.4 x0.056</td>
<td>1.2&amp;2.45</td>
<td>−22 &amp; −28</td>
<td>2.32 &amp; 1.84</td>
</tr>
</tbody>
</table>

Note: where \( \lambda_0 \) is the freespace wavelength at the lowest frequency.

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