Textile-based flexible linear-to-circular polarizing surface for s-band pico-satellites

Hidayath Mirza\textsuperscript{1}, Ping Jack Soh\textsuperscript{2}, Azremi Abdullah Al-Hadi\textsuperscript{3}, Toufiq Md Hossain\textsuperscript{4}, Rais Ahmad Sheikh\textsuperscript{5}, Mohd Faizal Jamlos\textsuperscript{6}

\textsuperscript{1,2,3,4,6} Advance Communication Engineering (ACE) CoE, School of Computer and Communication Engineering, Universiti Malaysia Perlis (UniMAP), Pauh Putra, 02600 Arau, Perlis, Malaysia

\textsuperscript{1,5} Department of Electrical Engineering, College of Engineering, Jazan University, P. O. Box 706, Jazan 45142, Kingdom of Saudi Arabia

\textbf{ABSTRACT}

This paper presents a single layered textile-based flexible linear-to-circular polarizing surface. The proposed structure is designed based on a rectangular ring structure for CubeSat application in the S-band. Each unit cell is sized at $0.35\lambda \times 0.33\lambda \times 0.2\lambda$ for operation centered at 2.2 GHz. This unit cell is then multiplied into a 9x10 array to form the polarizing surface. It features a 3 dB axial ratio bandwidth (ARBW) of 34.73\%, with a minimum AR of 0.28 dB. Besides that, it also offers a 90\% conversion efficiency bandwidth of up to 47.34\%. The proposed structure’s performance is validated by placing it in front of a patch antenna operating at 2.2 GHz. The antenna performance indicated an increase in terms of gain from 3.14 dBi to 7.33 dBi when integrated with the polarizing surface, besides successfully converting linearly-polarized waves to circularly-polarized.

\textbf{Keywords:}

Flexible surfaces
Metamaterials
Pico satellites
Polarizer

\textbf{Corresponding Author:}

Ping Jack Soh,
Advance Communication Engineering (ACE) CoE,
School of Computer and Communication Engineering,
Universiti Malaysia Perlis (UniMAP), Pauh Putra, 02600 Arau, Perlis, Malaysia.
Email: pjsoh@unimap.edu.my

1. \textbf{INTRODUCTION}

The polarization in electromagnetic waves can be either: a) linear, b) circular or c) elliptical [1, 2]. Circular polarized (CP) wave is used in many applications to reduce multipath, and applications such as Radio Frequency Identification (RFID) for convenience in retail, payment and purchasing [3, 4]. Besides these applications, CP waves is also prominently used in satellite communication and remote sensing. Examples of them include location and tracking, global positioning system, imaging and etc. Traditional satellites are designed to be large, heavy, and capable of performing multiple tasks. Due to the advancements in components’ miniaturization and their cost efficiency, pico-satellites become the pragmatic alternative to conventional satellites [5, 6]. However, pico-satellites such as the Cube Satellite (CubeSat) are limited in terms of size, typically to $10\times10\times10$ cm\textsuperscript{3}. Moreover, in comparison to traditional satellites, CubeSats operates with limited lifespan and serves limited functionality, for instance, imaging, deep space network communications between satellites and etc. [7, 8].

For CubeSat to communicate, CP antennas are preferred, and can be implemented using two approaches; a) directly designing CP antennas; or b) designing a polarizer for use with linearly polarized (LP) antenna. The second approach is investigated in this work. A polarizer can convert LP wave into CP coming from the LP antenna. Option a) is mostly opted by the designers, but the drawback of using CP antennas is the potentially limited gain and bandwidth. On the contrary, the gain of the antenna can be enhanced using a polarizer, besides capable of converting linear to circular polarized waves. Recent available polarizers are
either: a) built using multiple layers, b) require large gaps between the layers, and c) are designed on rigid materials and are unsuited to be implemented on CubeSats in a deployable form [9–14].

In this work, a single layered textile based flexible polarizer is proposed. The polarizer operates throughout the recommended CubeSat frequency spectrum, from 2.025 GHz to 2.11 GHz (in the uplink) and from 2.2 GHz to 2.29 GHz (in the downlink), besides the proposed band by Federal Communications Commission (FCC) from 2.39 GHz to 2.45 GHz [16, 17]. It is designed based on a square ring unit cell sized at 48×46×3.34 mm3 (0.35λ×0.33λ×0.2λ) for operation centered at 2.2 GHz. Next, the polarizer is formed by arranging the proposed unit cells in a 9 x 10 array. Several important parameters to validate the functionality of the polarizer are first described. Its operation is validated using these parameters, which includes the fractional bandwidth covering 90 % of the conversion efficiency, denoted as (BW)_CE [15]. Another parameter is the fractional bandwidth for the phase difference between the x- and y- transmitted components (Tx and Ty), aimed to be within ±10˚ % of 90˚. This parameter is denoted as (BW)_Δψ. The proposed polarizer features a 3 dB ARBW of 34.73 % with a lowest of AR of 0.28 dB, (BW)_CE of 47.34 % and a conversion efficiency of 99.93 % at 2.2 GHz. Besides that, the polarizer increased the realized gain by more than two-fold of the LP antenna used with it.

2. OPERATING PRINCIPLE

2.1. Condition of Circular Polarization (CP)

A linearly polarized wave is assumed to be incident on the polarizer whose electric field vector \( E^i \) is directed towards an angle of \( \varphi=45^\circ \) relative to the x-axis, as shown in Figure 1, and travels towards –z-direction. \( E'_x \) and \( E'_y \) are two orthogonal linearly polarized components of \( E^i \), along the x and y axis, respectively, both having equal magnitude and phases. The ratio between the magnitudes of two transmitted field components, \( E'_x \) and \( E'_y \), is defined as [10, 19–21]:

\[
q = \frac{|E'_x|}{|E'_y|} = \frac{|T_x|}{|T_y|}
\]

(1)

where \( T_x \) and \( T_y \) are the transmission coefficients for \( E'_x \) and \( E'_y \) [10, 19]. The value of \( q \) ranges from 0 to 1. For pure CP, \( q = 1 \), and the phase is given by [20]:

\[
\left[ \Phi_{E'_x} + \Phi_{T_x} \right] - \left[ \Phi_{E'_y} + \Phi_{T_y} \right] = \pm n \frac{\pi}{2}
\]

(2)

where \( n = 1,2,3 \). As \( E'_x \) and \( E'_y \) are equal in magnitude and phase, for pure CP, (1) and (2) takes the form of

\[
|T'_x| = |T'_y|
\]

(3)

\[
\Phi_{T_x} - \Phi_{T_y} = 90^\circ
\]

(4)

2.2. Conversion coefficients and conversion efficiency

To evaluate the effectiveness of the linear-to-circular conversion, two parameters are used: 1) conversion coefficient, as shown in Figure 4 and 2) conversion efficiency as shown in Figure 5. They are defined based on the following equations:

\[
\eta_{conv} = \frac{(abs(C_+)^2 - abs(C_-)^2)}{(abs(C_+)^2 + abs(C_-)^2)} \times 100
\]

(5)

where, \( C_+ \) and \( C_- \) are the circular conversion coefficient (CCC) for right-handed circular polarization (RHCP) wave and left-handed circular polarization (LHCP) wave respectively [21, 22]. They can be simplified as [11, 19, 21]:

\[
C_+ = E'_x T_x - j E'_y T_y
\]

(6)

\[
C_- = E'_x T_x + j E'_y T_y
\]

(7)
2.3. Unit cell and polarizer design

The proposed unit cell of the polarizer is modeled and simulated using the frequency domain solver in CST Microwave Studio, as shown in Figure 1 and 2. The unit cell boundaries were defined in both the x- and y-directions in CST, while Floquet port was used to excite the structure; port $Z_{\text{min}}$ as input port and $Z_{\text{max}}$ as output port. The thickness of the felt substrate is 3 mm, whereas its conductor used is 0.17 mm thick ShieldIt. Calculation of $T_x$ and $T_y$ were performed using template-based processing available in CST. A 45° rotated rectangular square loop is chosen as the unit cell of the polarizer, without any metallic backing, as shown in Figures 1 and 2. The rectangular structure strip causes a primarily inductive effect in the $E_y$ component, whereas the gap between the two unit cells cancel out the initial inductance from the $E_x$ component and adds capacitance effect on this component. As a result, the full structure has an inductive $E_y$ and capacitive $E_x$. This results in a phase difference between $\Phi_T$ and $\Phi_F$. This is proven when the polarizer is simulated in two different conditions: 1) with a 1 mm gap between cells; and 2) with a 3 mm gap between cells.

![Figure 1. Unit cell front view](image1)

![Figure 2. Unit cell back view](image2)

The simulated 3dB ARBW using case 1) is improved to 34.17 %, with the lowest AR value of 0.3 dB at 2.2 GHz. Meanwhile, in case (2), the 3dB ARBW is 22 %, with a minimum AR of 2.8 dB at 2.2 GHz. As the distance between the unit cell increases, the capacitance decreases, resulting in a decline in the 3dBARBW.

To extract the CP wave, the $ABS(T_x)=ABS(T_y)$ criterion has to be met. As presented in Figure 3, both $T_x$ and $T_y$ are converging at 2.2 GHz. Figure 4 shows circular conversion coefficient. This indicates that the proposed polarizer will have highest conversion efficiency and near zero axial ratio at this frequency point. Figure 5, represents the conversion efficiency, $BW_{CE}$ which starts from 1.58 GHz to 2.56 GHz, representing 47.34 % (with the 90% limit of conversion efficiency highlighted in Figure 5. The resulting $\eta_{\text{conversion}}$ of the proposed polarizer within the uplink and downlink based on [17, 23] is summarized in Table 1.

![Figure 3. Transmission of $T_x$ and $T_y$ magnitude converging at 2.2 GHz](image3)

![Figure 4. Circular conversion coefficient](image4)
Figure 6. depicts the phase difference between the Tx and Ty phases, which should be 90˚ to create the pure CP waves. The required working frequency band for this is highlighted in magenta, whereas, the ±10 % (81˚ to 99˚) limit of this 90˚ phase difference is highlighted in grey. The frequency range for the given ±10 % of 90˚ starts from 1 GHz to 2.69 GHz, enabling a (BW)_Δψ of 91.60 %.

Table 1. Conversion efficiency at different frequencies

<table>
<thead>
<tr>
<th>No</th>
<th>Frequency (GHz)</th>
<th>η_conversion (%)</th>
<th>(min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.025-2.11</td>
<td>98.93</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.2-2.29</td>
<td>99.38</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.39</td>
<td>97.48</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.45</td>
<td>95.51</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7. represents the axial ratio from 1 GHz to 3 GHz. The area marked in grey represents the band where axial ratio is below 3 dB. The 3 dB ARBW for the proposed structure is 34.73% with a minimum AR of 0.28 dB, as shown in Figure 7.

3. VALIDATION OF POLARIZER

To validate the functionality of the proposed polarizer unit, a patch antenna operating at 2.2 GHz is designed using the same materials. Its 3 mm thick substrate is made using felt with \( \varepsilon_r = 1.44 \) and \( \tan\delta = 0.044 \). Meanwhile, a 0.17 mm thick Shieldit Super is used as its conducting fabric. The antenna is designed based on a planar monopole fed using a microstrip line, as illustrated in Figure 8 and 9. Figure 10 illustrates the reflection coefficient of the antenna with the proposed antenna operational within the band of interest.
Figure 8. Front view of the antenna

Figure 9. Back view of the antenna

Figure 10. Reflection coefficient of the proposed antenna

Figure 11(a) and (b) represents polarizer 9 by 9 matrix of unit cells front view and back view of the polarizer. As the polarizer is single sided so, there is no structure on the reverse side of the polarizer. Figure 11(c). shows the simulation setup of electromagnetic waves on the grid. The grid enhances overall realized gain as shown in Figure 11(d). Realized gain for single the flexible antenna with the polarizer grid, the distance between them is 5 mm. The proposed antenna gain is 3.14 dB without the polarizer, whereas a gain of 7.33 dB is produced when combined with the grid LCP layer at 2.2 GHz, see Figure 12. It can be observed that there is a two-fold increment of realized gain of the antenna, at the expense of size.
Figure 11. (a) Front view of the polarizer, (b) Back view of the polarizer, (c) Polarizer placed in front of the monopole antenna and (d) Three-dimensional radiation pattern

Figure 12. Realized gain of an antenna with and without polarizer cells

4. CONCLUSION

The design of a new flexible linear to circular polarizing (LCP) surface is investigated. It is designed for operation on a pico-satellite in the S-band at 2.2 GHz. The proposed polarizing surface serves two main purposes; first is to convert linear to circular waves; and secondly, contributing to gain enhancement of the antenna. The overall structure is fully designed using textiles-ShieldIt Super as the conductive element and Felt as the substrate. Assessment of the metasurface indicated satisfactory simulated conversion efficiency of above 90% at 2.2 GHz in planar condition.

ACKNOWLEDGEMENTS

The author would like to acknowledge the support from the Science fund (Grant No: 01-01-015-SF0258) from the Ministry of Science, Technology & Innovation, and the funding by the Prototype Development Grant Scheme (PRGS) (Grant No: PRGS/2/2015/ICT06/UNIMAP/02/1) awarded by the Malaysian Ministry of Education.

REFERENCES


**BIOGRAPHIES OF AUTHORS**

Hidayath Mirza was born in Hyderabad, India, in 1981. He received bachelor’s in electronics & communication engineering from Jawaharlal Nehru Technological University (JNTU), Hyderabad, India and M.S. in Radio Engineering from Kyung Hee University (KHU), South Korea, in 2005 and 2008, respectively. He is currently working towards the PhD degree at School of Computer and Communication Engineering, Universiti Malaya Perlis (UnMAP), Malaysia. From 2006 to 2008, he was research assistant at Wireless Technology laboratory at Kyung Hee university and from 2009 to 2011 he was full time researcher at ESAT-TELEMIC Research Division, KU Leuven, Belgium. From 2012, he is working as a Lecturer at department of electrical engineering, Jazan University, Jazan, Kingdom of Saudi Arabia. His research interests include wearable antennas, RF energy scavenging using rectenna, RFID tag antenna design, Characterization of materials; extraction of permittivity, metamaterials and flexible linear-to-circular polarizers. Mr. Hidayath was a recipient of the Young Scientist Travel Grant (YSTG), 2007 International Symposium on Antennas and Propagation (ISAP) and from 2006 to 2008; for four consecutive semesters he was recipient of KHU President scholarship.

**Textile-based flexible linear-to-circular polarizing surface for s-band pico-satellites (Hidayath Mirza)**
Ping Jack Soh was born in Sabah, Malaysia. He received the B.Eng and M.Eng degrees from Universiti Teknologi Malaysia, and the PhD degree from KU Leuven, Belgium. He is currently an Associate Professor at the School of Computer and Communication Engineering, Universiti Malaysia Perlis (UniMAP), and a Research Affiliate at KU Leuven. From 2002 to 2004, he was a Test Engineer in Venture Corp., and worked in Motorola Solutions as an R&D Engineer in 2005. From 2006, he was a Lecturer in UniMAP before joining the ESAT-TELEMIC Research Division, KU Leuven as a Research Assistant (2009-2013) and a Postdoctoral Fellow (2013-2014). Dr. Soh was the recipient of the IEEE AP-S Doctoral Research Award in 2012, the IEEE MTT-S Graduate Fellowship in 2013 and the URSI Young Scientist Award in 2015. He is a Chartered Engineer; is a Senior Member of the IEEE; and Member of IET and URSI.

Azremi Abdullah Al-Hadi was born in Michigan, United States of America. He received the Master of Science degree in communication engineering from Birmingham University, United Kingdom in 2004 and the Doctor of Science in Technology degree from Aalto University, Finland in 2013. His current research interests include design and performance evaluation of multi-element antennas, mobile terminal antennas and their user interactions. He is currently working as an Associate Professor at the School of Computer and Communication Engineering, Universiti Malaysia Perlis (UniMAP). He is an active volunteer with IEEE Malaysia Section, acting as the Senior Member of IEEE, Vice-Chair of the IEEE Antenna Propagation/Microwave Theory & Techniques/Electromagnetic Compatibility (AP/MTT/EMC) Malaysia Chapter and also as Counselor for IEEE UniMAP Student Branch. He was the recipient of the Best Student Paper Award presented at the 5th Loughborough Antennas and Propagation Conference (LAPC 2009) and the CST University Publication Award in 2011.

Toufiq Md Hossain, a Bangladeshi national, was born in Al-Kharj, Kingdom of Saudi Arabia, in 1991. He has received his B.Sc. degree in Electrical and Electronic Engineering (EEE) from Khulna University of Engineering & Technology (KUET), Khulna, in 2014. His research interests include Metamaterials, flexible linear to circular polarizers for CubeSat applications and five port reflectometers and microwave imaging of brain injury diagnosis applications.

Rais Ahmad Sheikh was born in Jaunpur, India, in 1977. He received bachelor’s in electronics & communication engineering from Ajay Kumar Garg Engineering College (AKGE), Ghaziabad, India and Master of Technology (M.Tech.) in digital system from Motilal Nehru National Institute of Technology (MNNIT), Allahabad, India in 2002 and 2010, respectively. He is currently working towards the PhD degree at School of Computer and Communication Engineering, Universiti Malaysia Perlis (UniMAP), Malaysia. From 2011, he is working as a Lecturer at department of electrical engineering, Jazan University, Jazan, Kingdom of Saudi Arabia. His research interests include flexible wearable antennas, antenna design for Cospas Sarsat application, antenna design for GPS application and Impedance matching and Characterization of materials.

Mohd Faizal Jamlos received Ph.D. in 2010 from Universiti Teknologi Malaysia, Johor, Malaysia and M.Sc. in 2008 from University of Adelaide, South Australia, Australia. He is currently Associate Professor at Advanced Communication Engineering Centre (ACE), School of Computer and Communication Engineering, Universiti Malaysia Perlis. He has (co-)authored some 220 scientific publications in peer-reviewed journals and conferences. His research interest are wireless embedded system, remote sensing, on-platform antennas and microwave circuitry. He is a practice professional Engineer of Board of Engineers Malaysia (BEM), Senior Member of IEEE, a National Medical Researcher (NMRR) and Corporate Member of Institute Engineers Malaysia (MIEM).