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

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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 0.35λ×0.33λ×0.2λ 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.

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1. 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 10×10×10 cm^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 2.11GHz (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 90º. This parameter is denoted as (BW)_Δψ. The proposed polarizer features a 3 dB ARBW of 34.73% with a lowest of AR of 0.28dB, 〖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 φ=45˚ relative to the $x-$ axis, as shown in Figure 1. and travels towards –*z*-direction. E_x^i and E_y^i are two orthogonal linearly polarized components of E^{i}, along the x and y axis, respectively, both having equal magnitude and phases [5, 10, 18, 19]. The ratio between the magnitudes of two transmitted field components, E_x^t and E_y^t, is defined as [10, 19-21]:

$$q = \frac{|E_x^t|}{|E_y^t|} = \frac{|\mathrm{E_x^i}|\,|\mathrm{T_x}|}{|\mathrm{E_y^i}\,||\mathrm{T_y}|} \tag{1}$$

where T_x and T_y are the transmission coefficients for E_x^i and E_y^i [10, 19]. The value of q ranges from 0 to 1. For pure CP, $q = 1$, and the phase is given by [20];

$$\left[\Phi_{\mathrm{E_x^i}} + \Phi_{\mathrm{T_x}}\right] - \left[\Phi_{\mathrm{E_y^i}} + \Phi_{\mathrm{T_y}}\right] = \pm \mathrm{n}\frac{\pi}{2} \tag{2}$$

where $n = 1,2,3$. As E_x^i and E_y^i are equal in magnitude and phase, for pure CP, (1) and (2) takes the form of

$$|T_x| = |T_y| \tag{3}$$

$$\Phi_{T_x} - \Phi_{T_y} = 90^0 \tag{4}$$

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:

$$\eta_{conv} = \frac{(abs(C_-)^2 - abs(C_+)^2)}{(abs(C_-)^2 + abs(C_+)^2)} * 100 \qquad (5).$$

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];

$$C_+ = E_x^i T_x - j\,E_y^i T_y \tag{6}$$

$$C_- = E_x^i T_x + j\,E_y^i T_y \tag{7}$$

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_{min} as input port and Z_{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 45º 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^i component, whereas the gap between the two unit cells cancel out the initial inductance from the E_x^i component and adds capacitance effect on this component. As a result, the full structure has an inductive E_y^i and capacitive E_x^i. This results in a phase difference between Φ_{T_x} and Φ_{T_x}.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.

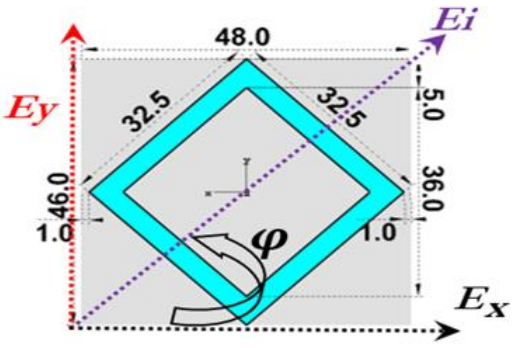


Figure 1. Unit cell front view

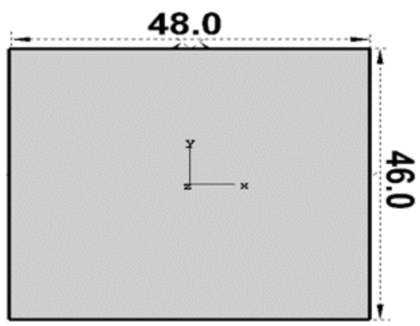


Figure 2. Unit cell back view

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(Tx)=ABS(Ty)* criterion has to be met. As presented in Figure 3, both *Tx* and *Ty* 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 $\eta_{conversion}$ of the proposed polarizer within the uplink and downlink based on [17, 23] is summarized in Table 1.

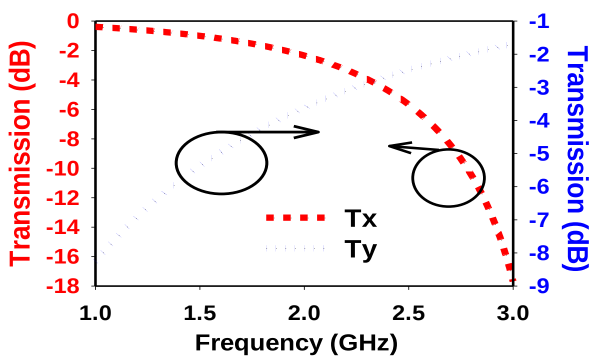


Figure 3. Transmission of *Tx* and *Ty* magnitude converging at 2.2 GHz

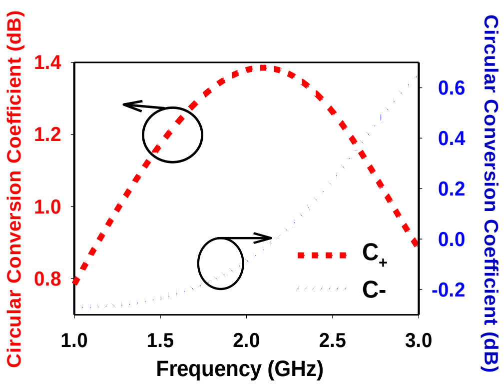


Figure 4. Circular conversion coefficient

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 %.

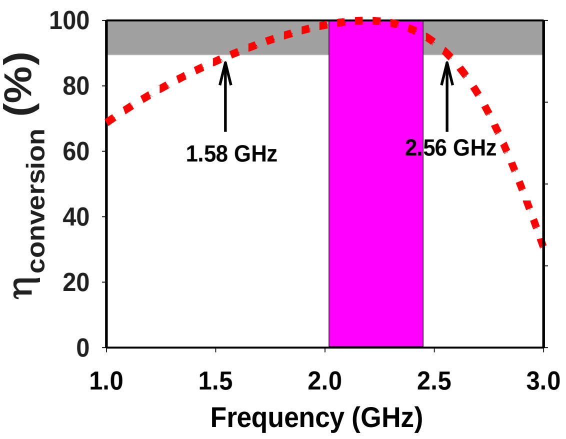


Figure 5. Conversion efficiency

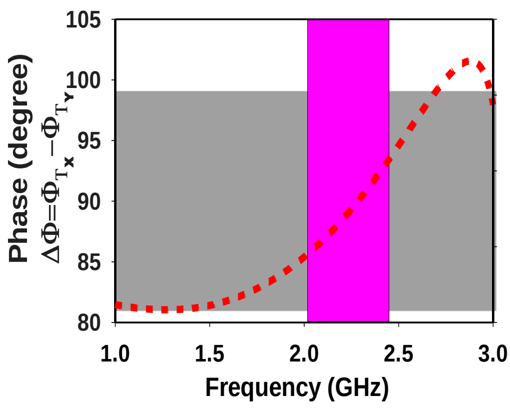


Figure 6. Phase difference between the phase of *Tx* and phase of *Ty*

Table 1. Conversion efficiency at different frequencies

No	Frequency (GHz)	$\eta_{conversion}$ (%) (min)
1	2.025-2.11	98.93
2	2.2-2.29	99.38
3	2.39	97.48
4	2.45	95.51

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.

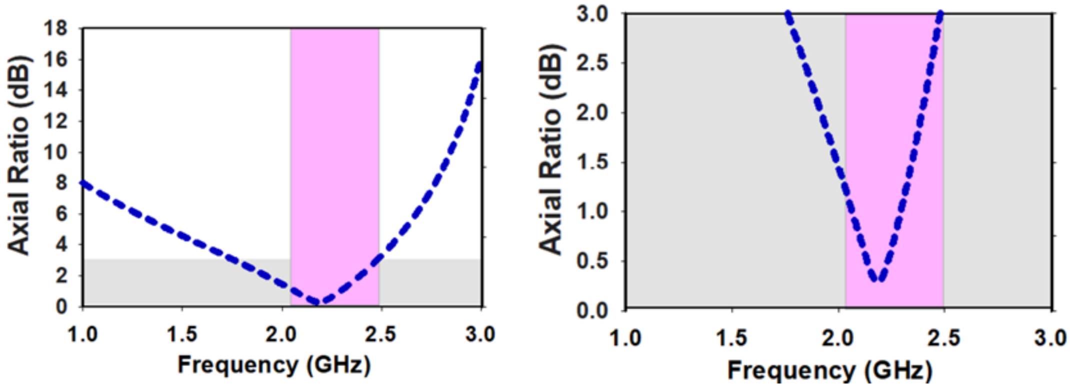


Figure 7. Axial ratio (in dB)

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 $\epsilon_r = 1.44$ 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.

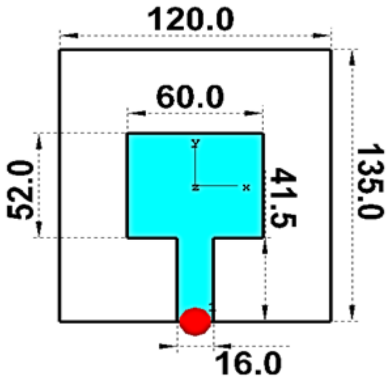


Figure 8. Front view of the antenna

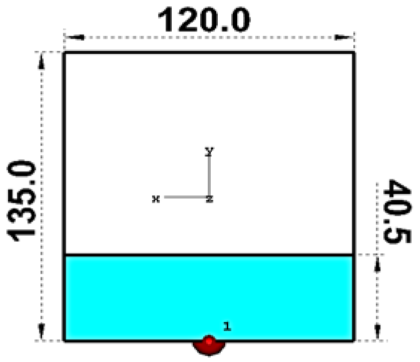


Figure 9. Back view of the antenna

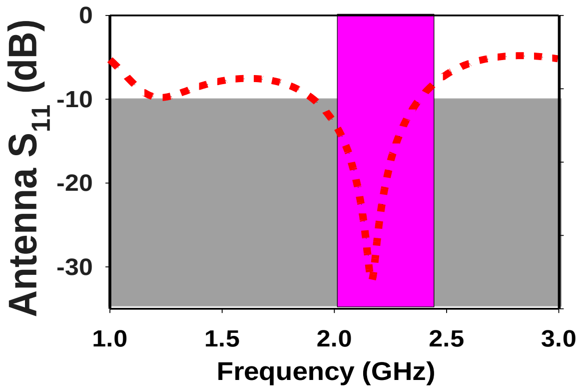
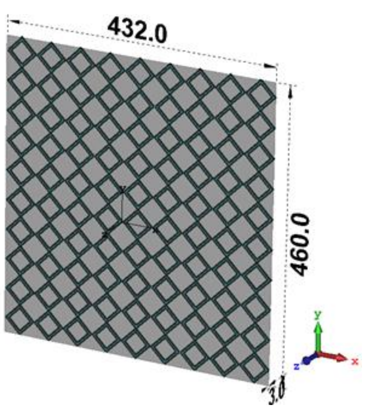
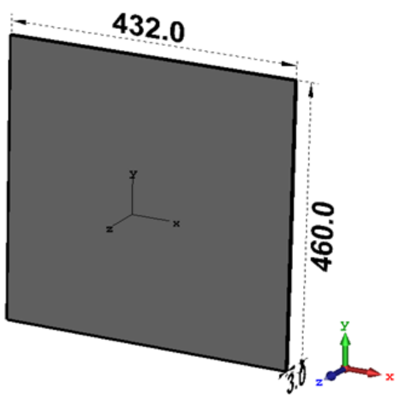


Figure 10. Reflection coefficient of the proposed antenna

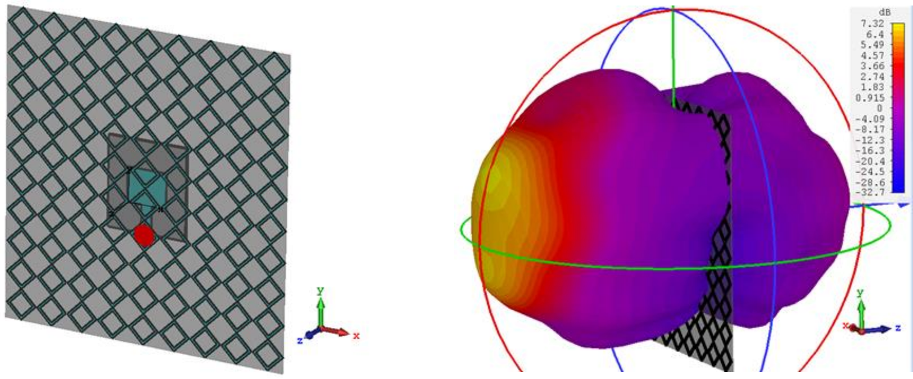
Figure 11(a) and (b). represents polarizer 9 by 9 matrix of unit cells front view and back view of the polarizer. As the polarizer is single sided so, there is no structure on the reverse side of the polarizer. Figure 11(c). shows the simulation setupof electromagnetic waves on the grid. The grid enhances 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.



(a)



(b)



(c) (d)

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

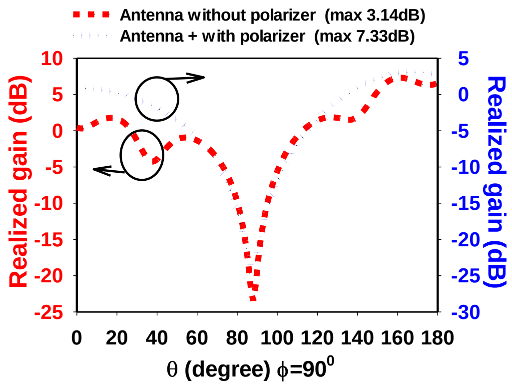


Figure 12. Realized gain of an antenna with and without polarizer cells

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.

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REFERENCES

[1] B. Y. Toh, R. Cahill and V. F. Fusco, "Understanding and measuring circular polarization," in *IEEE Transactions on Education*, vol. 46, no. 3, pp. 313-318, Aug. 2003.

[2] M. J. Rycroft, Understanding GPS. Principles and applications. 1997.

[3] H. Mirza and M. F. Elahi, "A UHF-RFID tag antenna for commercial applications," *2008 International Conference on Electrical and Computer Engineering*, Dhaka, 2008, pp. 764-767.

[4] H. Mirza, M. I. Ahmed and M. F. Elahi, "Circularly polarized compact passive RFID tag antenna," *2008 International Conference on Electrical and Computer Engineering*, Dhaka, 2008, pp. 760-763.

[5] A. H. Lokman et al., “A Review of Antennas for Picosatellite Applications,” *Int. J. Antennas Propag.*, vol. 2017, 2017.

[6] A. Babuscia, B. Corbin, M. Knapp, R. Jensen-Clem, M. Van De Loo, and S. Seager, “Inflatable antenna for cubesats: Motivation for development and antenna design,” *Acta Astronaut*., vol. 91, pp. 322–332, 2013.
[7] N. Chahat, R. E. Hodges, J. Sauder, M. Thomson and Y. Rahmat-Samii, "The Deep-Space Network Telecommunication CubeSat Antenna: Using the deployable Ka-band mesh reflector antenna.," in *IEEE Antennas and Propagation Magazine*, vol. 59, no. 2, pp. 31-38, April 2017.
[8] C. J. Vourch and T. D. Drysdale, "Inter-CubeSat communication with V-band “Bull's eye” antenna," *The 8th European Conference on Antennas and Propagation (EuCAP 2014)*, The Hague, 2014, pp. 3545-3549.
[9] W. Zhang, J. Li, and L. Wang, “Broadband circular polarizer based on multilayer gradual frequency selective surfaces,” *Int. J. Antennas Propag*., vol. 2016, 2016.
[10] L. Martinez-Lopez, J. Rodriguez-Cuevas, J. I. Martinez-Lopez and A. E. Martynyuk, "A Multilayer Circular Polarizer Based on Bisected Split-Ring Frequency Selective Surfaces," in *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 153-156, 2014.
[11] M. Mutlu, A. E. Akosman, G. Kurt, M. Gokkavas, and E. Ozbay, “Experimental realization of a high-contrast grating based broadband quarter-wave plate,” *Opt. Express*, vol. 20, no. 25, p. 27966, 2012.
[12] J. Wang, Z. Shen, W. Wu, and K. Feng, “Wideband circular polarizer based on dielectric gratings with periodic parallel strips,” *Opt. Express*, vol. 23, no. 10, p. 12533, 2015.
[13] H. Zhu, K. L. Chung, X. L. Sun, S. W. Cheung and T. I. Yuk, "CP metasurfaced antennas excited by LP sources," *Proceedings of the 2012 IEEE International Symposium on Antennas and Propagation*, Chicago, IL, 2012, pp. 1-2.
[14] M. Fartookzadeh and S. H. Mohseni Armaki, "Dual-Band Reflection-Type Circular Polarizers Based on Anisotropic Impedance Surfaces," in *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 2, pp. 826-830, Feb. 2016.
[15] H. Mirza et al., “A crossed dodecagonal deployable polarizer on textile and polydimethylsiloxane (PDMS) substrates,” *Appl. Phys. A*, vol. 124, no. 2, p. 178, 2018.
[16] Federal Communications Commision (FCC), “Guidance On Obtaining Licenses For Small Satellites”.
[17] Mcmc, “Spectrum Allocations in Malaysia,” p. 1, 2009.
[18] P. Lau, K. K. Yung and E. K. Yung, "A Low-Cost Printed CP Patch Antenna for RFID Smart Bookshelf in Library," in *IEEE Transactions on Industrial Electronics*, vol. 57, no. 5, pp. 1583-1589, May 2010.
[19] W. Zhang, J. Li, and L. Wang, “Broadband Circular Polarizer Based on Multilayer Gradual Frequency Selective Surfaces,” vol. 2016, 2016.
[20] I. Sohail, Y. Ranga, K. P. Esselle, and S. G. Hay, “*A linear to circular polarization converter based on Jerusalem-Cross frequency selective surface*,” in Antennas and Propagation (EuCAP), 2013 7th European Conference on, 2013, pp. 2141–2143.
[21] S. Yan and G. A. E. Vandenbosch, “*Compact circular polarizer based on chiral twisted double split-ring resonato*r,” Appl. Phys. Lett., vol. 102, no. 10, p. 103503, 2013.
[22] J. Wang, Z. Shen, W. Wu, and K. Feng, “Wideband circular polarizer based on dielectric gratings with periodic parallel strips,” *Opt. Express*, vol. 23, no. 10, pp. 12533–12543, 2015.
[23] F. C. Commission, “Guidance on Obtaining Licenses for Small Satellites,” in Fcc Public Notice, 2013, pp. 5.

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