Design of a Reflectarray Fed by a Planar Leaky-Wave Antenna for 3U CubeSats

Daniel R. Prado*, Miguel Poveda-García†, George Goussetis‡ and Lei Wang*
*School of Engineering, Lancaster University, U.K. Email: {d.rodriguezprado, lei.wang}@lancaster.ac.uk
†Department of Information and Communications Technologies, Technical University of Cartagena, Spain.
Email: miguel.poveda@upct.es
‡Institute of Sensors, Signals and Systems, Heriot-Watt University, Edinburgh, U.K. Email: g.goussetis@hw.ac.uk

***Abstract*—This work presents the design of a reflectarray fed by a planar leaky-wave antenna (LWA) for use in a 3U CubeSat. The LWA is based on substrate-integrated waveguide (SIW) technology and radiates in single-linear polarization. A full-wave simulation is carried out to obtain the near field radiated by the SIW LWA on a surface corresponding to the reflectarray, whose size is set to fit three sides of the CubeSat for stowage and deployment. A single-layered reflectarray unit cell consisting of three parallel dipoles has been chosen for simplicity and low profile. It provides a phase-shift range of more than 360° for layout design. In addition, the angle of incidence of the impinging near field is calculated by means of the Poynting vector. Simulation results at 24 GHz show the suitability of the design procedure for point-to-point communications, achieving an estimated gain of more than 30 dBi, taking into account substrate losses, and illumination and spillover efficiencies.**

***Index Terms*—Reflectarray, leaky wave antenna, 3U CubeSat, Poynting vector, point-to-point communications**

I. Introduction

Reflectarray antennas are a low profile, low volume and low cost alternative to parabolic reflectors for applications that require high gain [1]. In the case of CubeSats [2], reflectarrays are also very attractive since they can be easily stowed folded on one or three sides of the CubeSat [3]. Furthermore, they have already been tested in space, as demonstrated by NASA's ISARA and MarCo missions [4]. ISARA employs a feed consisting of a thin microstrip patch while MarCo uses a 4×2 element microstrip patch array. Both of them are automatically deployed by means of a hinge after the main reflectarray panels are deployed.

This work proposes an alternative feeding mechanism, employing a planar leaky-wave antenna (LWA) based on substrate-integrated waveguide (SIW) technology [5], [6] that is easy to feed by means of a coaxial cable and does not need deployment. Although some works have already employed an LWA to feed a reflectarray [7], it consists of an integrated LWA placed on top of the reflectarray with a bulky feeding system, making it unsuitable for use in CubeSats. Here, the SIW LWA is placed on the CubeSat to feed the reflectarray, as shown in Figure 1, and since the SIW LWA can be designed to radiated at a certain angle, it does not need to be deployed as the patches in the case of the ISARA and MarCo missions [4]. The SIW LWA is comprised of a number of rectangular slots along the long dimension of the LWA, providing single-linear polarization in the transversal direction ($\hat{y}$ polarization of the reflectarray). Then, the reflectarray is designed employing as a unit cell a set of three parallel dipoles appropriately oriented and tuned to provide the required phase-shift to collimate the beam in the desired direction. For the analysis and design of the reflectarray layout, the near field of the SIW LWA is simulated using Ansys HFSS [8]. The angles of incidence at each reflectarray unit cell are calculated from the near field using the Poyting vector. Simulation results show that an estimated gain of more than 30 dBi is achieved.

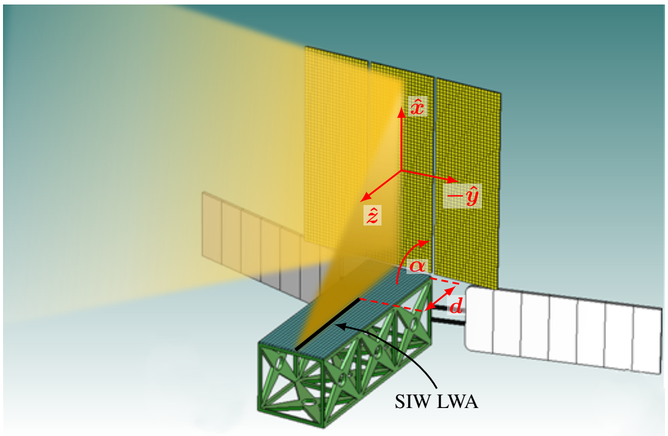


Figure 1. Illustration of a deployed reflectarray in a CubeSat fed by a planar SIW LWA. The reflectarray is tilted an angle α with respect to the CubeSat, and the SIW LWA is placed at a distance d from the reflectarray. The input port of the SIW LWA is the one closest to the reflectarray (see Figure 2).

II. Antenna Design

A. Definition of the Antenna Geometry

The goal is the design of an antenna system comprised of a deployable reflectarray and a planar SIW LWA for a 3U CubeSat, as illustrated in Figure 1. To that end, the deployed reflectarray is placed at one end of the CubeSat, with a tilt angle α and at distance d from the closer end of the SIW LWA (see Figure 1). The size of the reflectarray is 300 mm × 300 mm, and it is comprised of 2 500 elements in a regular grid of 50×50 with a periodicity of 6 mm in both directions, corresponding to $0.48\lambda_0$ at the working frequency of $f_0 = 24$ GHz. On the other hand, the size of the SIW LWA,

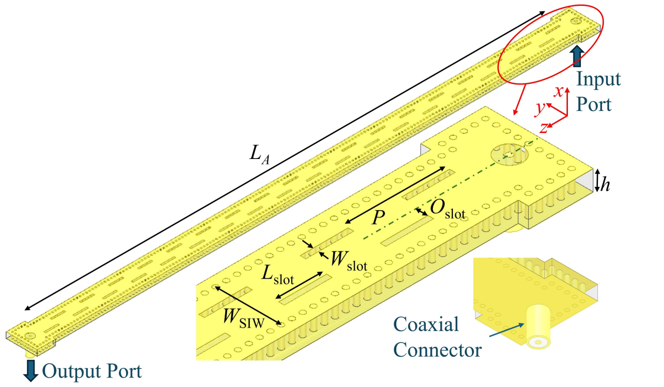


Figure 2. Designed SIW LWA feeding antenna. Dimensions: L_A = 144.5 mm, W_{SIW} = 5.18 mm, P = 8 mm, W_{slot} = 0.446 mm, L_{slot} = 3.78 mm, O_{slot} = 1.15 mm.

including the feeding ports, is 154.7 mm × 8.5 mm. This gives a potential range for d of $[0, 145.3]$ mm.

For this work, an angle $\alpha = 85°$ and a distance $d = 140$ mm have been chosen. Since the direction of radiation will go parallel to the CubeSat, the pointing angle in the reflectarray coordinate system will be 5°.

B. SIW LWA Design

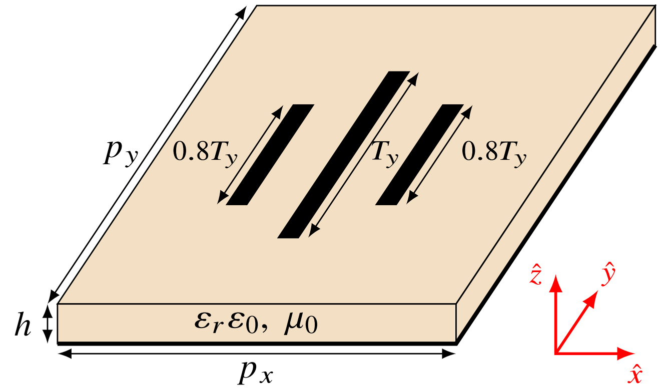
The feeding antenna consists of a SIW LWA, designed in a substrate with $\varepsilon_r = 2.2$, $\tan\delta = 0.0009$ and thickness h = 1.575 mm with longitudinal slots etched on its top layer [5], as depicted in Figure 2. In this structure, the SIW width W_{SIW} is set so the propagating TE_{10} mode is above cutoff. On the other hand, the periodicity P controls the far-field radiation angle θ_R and follows the expression [9]:

$$\theta_R = \sin^{-1}\left(\frac{\beta_0 - 2\pi/P}{k_0}\right), \quad (1)$$

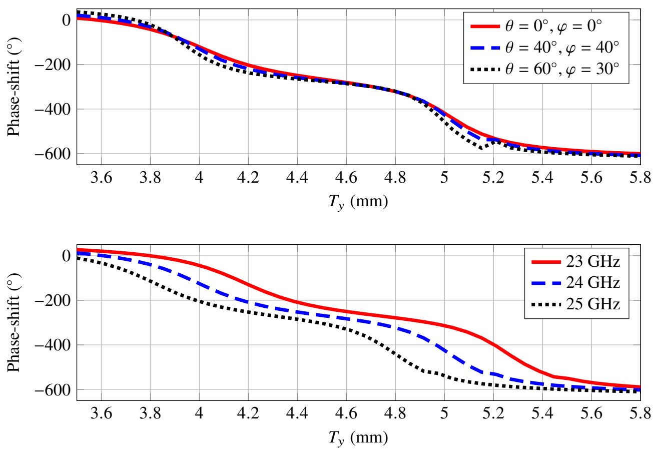
where β_0 is the phase constant of the fundamental TE_{10} mode and k_0 is the free-space wavenumber. Finally, the slots dimensions (W_{slot}, L_{slot} and O_{slot}) control the radiation (leakage) rate and are optimized so that less than 10% of the input power reaches the output port. This is a normal trade-off in leaky-wave antennas to ensure a proper aperture efficiency [9]. With these parameters, the SIW LWA efficiency is up to η_{LWA} = 85% and the far-field radiation angle is $\theta_R = -40°$ w.r.t. the x-axis of the SIW LWA (see Figure 2) at 24 GHz. Thus, the radiation is mostly directed towards the reflectarray, as illustrated in Figure 1.

C. Reflectarray Design

The chosen unit cell is comprised of three parallel dipoles in one layer of metallization backed by a ground plane, as shown in Figure 3(a). An efficient and flexible in-house method of moments in the spectral domain (MoM-SD) employing basis functions with edge singularities [10] has been developed to analyse this unit cell. The lateral dipoles have the same length as the central dipole, but scaled by a factor of 0.8, and the distance centre-to-centre between the central



(a)



(b)

Figure 3. (a) Unit cell consisting of three parallel dipoles in one layer of metallization backed by a ground plane. (b) Electromagnetic response of the unit cell for various angles of incidence at 24 GHz (top) and various frequencies for ($\theta = 20°$, $\varphi = 20°$) (bottom).

and lateral dipoles is 1.5 mm. The width of the dipoles is 0.5 mm. A Diclad 880 substrate is employed in the simulations, with measured parameters $\varepsilon_r = 2.3$, $\tan\delta = 0.005$ and $h = 0.762$ mm. Figure 3(b) shows the electromagnetic response of this unit cell for various angles of incidence at 24 GHz and various frequencies for ($\theta = 20°, \varphi = 20°$). The unit cell offers a phase-shift range of more than 360°, as well as a good angular stability. It is worth mentioning that there is a resonance for sizes of dipoles greater than 5 mm and large angles of incidence. However, these sizes can be avoided during the layout design process.

The analysis of the reflectarray requires knowledge of the impinging incident field on its surface. To that end, the SIW LWA was simulated using Ansys HFSS [8] and the near field obtained at the centre of each unit cell. Figure 4 represents the magnitude of the $\hat{y}$ component of the near field on the reflectarray surface, showing the fan-shaped radiation typical of an LWA. This causes a high magnitude field at the edges of the reflectarray.

The MoM-SD requires, among other parameters, the local angle of incidence in order to obtain the electromagnetic

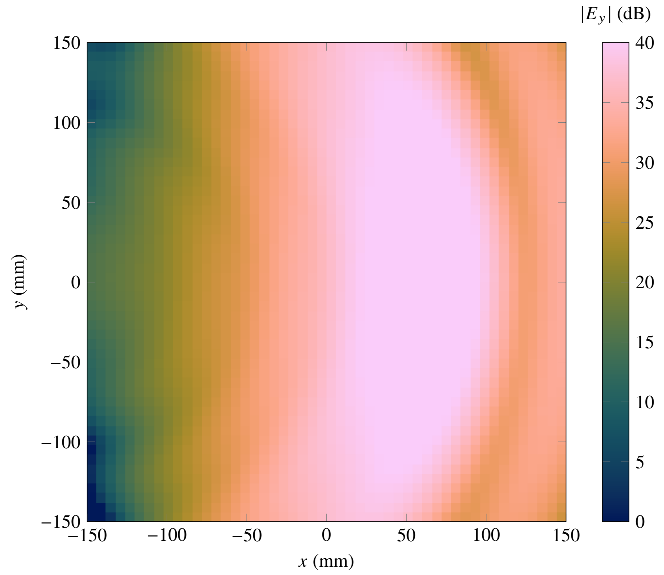


Figure 4. Magnitude of the $\hat{y}$ component of the near field radiated by the SIW LWA on the reflectarray surface.

response of the unit cell. The calculation of the angle of incidence is based on the Poynting vector, which gives the direction of the power flow of the electromagnetic wave. The complex Poynting vector is defined as:

$$\vec{S} = \frac{1}{2}\vec{E} \times \vec{H}^*, \tag{2}$$

where the asterisk (*) denotes the complex conjugate. Both the electric and magnetic fields are the ones simulated at the surface of the reflectarray and radiated by the SIW LWA. The real part of the Poynting vector represents the power density, and the imaginary part represents the reactive power [11]. Thus, the direction of the locally incident wave at the ith reflectarray element is given by:

$$\hat{s}_i = \frac{\mathrm{Re}\left\{\vec{S}_i\right\}}{\left\|\mathrm{Re}\left\{\vec{S}_i\right\}\right\|} = \frac{\mathrm{Re}\left\{\vec{E}_i \times \vec{H}_i^*\right\}}{\left\|\mathrm{Re}\left\{\vec{E}_i \times \vec{H}_i^*\right\}\right\|} = s_{x,i}\hat{x} + s_{y,i}\hat{y} + s_{z,i}\hat{z}, \tag{3}$$

where $\|\cdot\|$ is the Euclidean norm. From the components of $\hat{s}_i$ the angles of incidence can be readily obtained.

The layout is obtained by employing a root-finding routine that iteratively calls the MoM-SD tool to adjust the phase-shift of each unit cell. A complete description of this process can be found elsewhere [12]. Finally, the far field is calculated from the tangential reflected field using Love's principle of equivalence. The gain is then estimated, and substrate losses, illumination efficiency and spillover are taking into account in the calculations [1].

D. Far Field Simulation

Figure 5 shows the main cut of the far field of the simulated reflectarray layout fed by the SIW LWA. Both the copolar and crosspolar components are plotted. The designed reflectarray layout is able to collimate the incoming incident field from

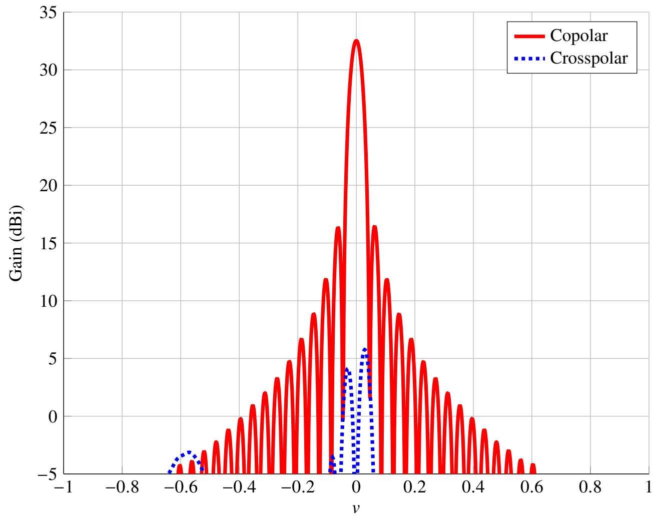


Figure 5. Main cut in v ($u = 0.087$) of the far field of the simulated reflectarray fed by a SIW LWA for linear polarization Y.

the feed in the desired direction ($\theta = 5°$, corresponding to $u = \sin 5°$). The estimated gain is 32.5 dBi, taking into account substrate losses, illumination efficiency and spillover [1].

Acknowledgment

M. Poveda-García has been partially funded by the Post-doctoral Program Margarita Salas–Spanish Ministry of Universities through the European Union–NextGenerationEU; D. R. Prado and L. Wang are supported by the EPSRC grant EP/Y003144/1.

References

[1] J. Huang and J. A. Encinar, *Reflectarray Antennas*. Hoboken, NJ, USA: John Wiley & Sons, 2008.

[2] S. Abulgasem, F. Tubbal, R. Raad, P. I. Theoharis, S. Lu, and S. Iranmanesh, "Antenna designs for CubeSats: A review," *IEEE Access*, vol. 9, pp. 45 289–45 324, 2021.

[3] R. E. Hodges, D. J. Hoppe, M. J. Radway, and N. E. Chahat, "Novel deployable reflectarray antennas for CubeSat communications," in *IEEE MTT-S International Microwave Symposium*, Phoenix, Arizona, USA, May 17–22, 2015, pp. 1–4.

[4] S. Gao, Y. Rahmat-Samii, R. E. Hodges, and X.-X. Yang, "Advanced antennas for small satellites," *Proc. IEEE*, vol. 106, no. 3, pp. 391–403, Mar. 2018.

[5] L. Yan, W. Hong, G. Hua, J. Chen, K. Wu, and T. J. Cui, "Simulation and experiment on SIW slot array antennas," *IEEE Microw. Wireless Compon. Lett.*, vol. 14, no. 9, pp. 446–448, Sep. 2004.

[6] S. Han, M. Poveda-García, Y. Ding, G. Goussetis, and L. Wang, "A mmWave leaky-wave antenna for efficiency enhanced near-field wireless power transfer and communication," in *18th European Conference on Antennas and Propagation (EuCAP)*, Glasgow, United Kingdom, Mar. 17–22, 2024, pp. 1–5.

[7] Q. Zhang, M. Zhang, X. Shi, S. Gao, Q. Luo, L. Chen, J. Wan, and X. Wang, "A low-profile beam-steering reflectarray with integrated leaky-wave feed and 2-bit phase resolution for Ka-band SatCom," *IEEE Trans. Antennas Propag.*, vol. 70, no. 3, pp. 1884–1894, Mar. 2022.

[8] "HFSS," Ansys Inc., Pittsburgh, Pennsylvania, USA.

[9] A. A. Oliner and D. R. Jackson, "Leaky-wave antennas," in *Antenna Engineering Handbook*. New York, NY, USA: McGraw-Hill, 2007, ch. 11.

[10] R. Florencio, R. R. Boix, E. Carrasco, J. A. Encinar, and V. Losada, "Efficient numerical tool for the analysis and design of reflectarrays based on cells with three parallel dipoles," *Microw. Opt. Technol. Lett.*, vol. 55, no. 6, pp. 1212–1216, Jun. 2013.

[11] C. A. Balanis, *Advanced engineering electromagnetics*, 2nd ed. Hoboken, NJ, USA: John Wiley & Sons, 2012.

[12] D. R. Prado, J. A. López-Fernández, M. Arrebola, M. R. Pino, and G. Goussetis, "General framework for the efficient optimization of reflectarray antennas for contoured beam space applications," *IEEE Access*, vol. 6, pp. 72 295–72 310, 2018.