A Gain-Reconfigurable and Frequency-Beam-Steerable Additively Manufactured Antenna

Carlos R. Mejias-Morillo, Sam LeBlanc, and Eduardo A. Rojas-Nastrucci

Department of Electrical Engineering and Computer Science,
Embry-Riddle Aeronautical University, Daytona Beach, FL, 32114, USA.
Email: mejiasc1@my.erau.edu

***Abstract*— Due to the exponential growth of small satellite technology, novel shapes for antennas have been explored to make them low-cost, lightweight, compact, and easy to deploy. The use of frequency beam-scan antennas reduces the complexity of the small satellite front-end by avoiding the need to use phase shifters, especially when a reliable inter-satellite link (ISL) is required to keep up the communication and the formation accurately in a CubeSat swarm mission. This paper reports the design and a manufacturing process focused on in-space manufacturing (ISM) of a fully 3D-printed leaky-wave antenna, using ULTEM 9085 for aerospace applications. The antenna shows frequency beam steering capabilities from 4.4 GHz to 7.4 GHz, and a gain reconfigurable by angular rotation of the ground planes. The resulting antenna shows a measured peak gain of 10.07 dBi at 6.5 GHz, with a gain reconfigurability, as function of the elevation angle of the ground planes, in the range of 0 to 40°, providing an additional gain from 0 to 2 dBi, respectively.**

***Index Terms*— Additive Manufacturing, leaky-wave antenna, microstrip antenna, frequency beam scanning, tunable gain**

I. Introduction

Reconfigurable antennas have been realized by including mechanical or electrical components to change their structures or parameters, such as the center frequency, gain, radiation pattern, among others. For example, in [1], a mechanically reconfigurable bent horn antennas with two movable flap provides different gains by changing the half-power beamwidth from 58.7° down to 16.5°. A mechanically reconfigurable gain can be also achieved by modifying the length of an patch antenna using two adjustable shorting screws as shown in [2], which changes the gain from 3.01 dBi to 5.53 dBi. Movable parasitic patches that varies the slot length is another way to get a changeable antenna gain as presented in [3].

Small-satellite applications can benefit from the reconfigurable capability of beam steering of antennas as presented in [4]. One type of reconfigurable antennas with the beam steering capability is the leaky-wave antenna (LWA), which is a structure that produces radiation leaking of a traveling wave using a uniform or periodic modulation along the structure [5]. LWAs provide high directivity, wide bandwidth, and frequency beam scanning ability, as well as a low profile when they are made of microstrip line [5], [6]. The use of composite right/left-handed (CRLH) structures increases the angle scanning capabilities without degrading the gain and the main lobe of the radiation pattern from backward end-fire to end-fire angles [7].

3D-printing has been successfully used in RF and microwave device manufacturing successfully, which enables rapid and low-cost prototyping using novel materials and geometries [8], [9]. Different additive manufacturing (AM) processes have been proposed for 3D-printed structures for leaky-wave antennas [10]–[13]. For example, Polyjet is combined with a sputter deposition of copper to manufacture leaky-wave antennas based on microstrip line and substrate integrated waveguide (SIW). The half-width microstrip leaky-wave antenna operates above 6 GHz, and it provides a gain of 6.82 dBi while the compact waveguide leaky-wave antenna operates in the X and Ku band providing a gain of 8 dBi at 10 GHz [10], [11]. In [12], a 3D-printed millimeter-wave bullseye antenna was fabricated using stereolithography (SLA) and electroplating processes; showing a gain of 17 dBi at 96 GHz. Lastly, soft lithography was used to create a liquid-metal reconfigurable leaky-wave antenna at 24 GHz, which exhibits a variable gain from 13 dBi to 17 dBi when the main lobe of the radiation pattern scans from -60° to 20° by stretching the structure [13]. In this paper, a leaky-wave antenna based on a microstrip structure has an extended ground plane that enables gain reconfigurability by placing it at different angles. The antenna is manufactured using direct-print additive manufacturing (DPAM), which combines fused deposition modeling (FDM) with microdispensing [14]. The 3 dB scanning range is from -32° to 70° in the operating band of 4.65 GHz to 7.4 GHz. Measurements show a tunable gain up to 2 dB as a function of elevation angle of the ground plane and the frequency. The resulting antenna has a measured peak gain of 10.07 dBi at 6.5 GHz when the ground placed is placed at a elevation angle of 0°.

II. Geometry and Manufacturing Process

The design process of the multi-via loaded composite-right/left-handed (CRLH) leaky-wave antenna is detailed in [15]. However, in this work, a 45 mm mechanically reconfigurable ground plane is added on each side of the radiating structure to increase the gain up to 2.3 dBi depending on the elevation angle of the ground plane. As shown in Fig. 1, the ground plane of the leaky-wave antenna can be mechanically reconfigurable by hinges, which enables the positioning of the extensions at different elevation angles. The geometric parameters of the microstrip leaky-wave antenna and the unit cell are presented in Fig. 2, whose dimensions are optimized using HFSS from ANSYS Electronic Desktop 2017.2.0. Table I shows the dimension of the leaky-wave antenna after optimization.

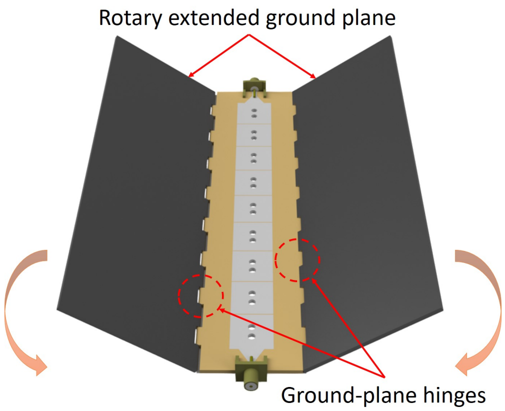


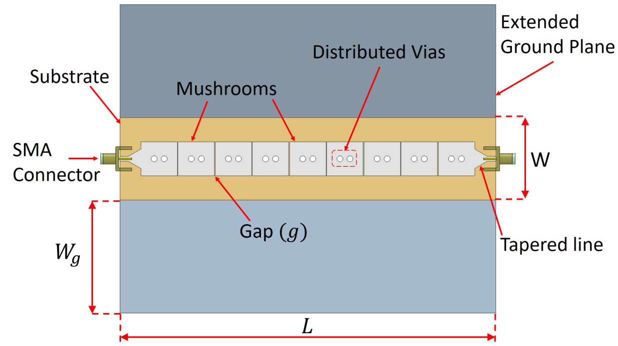
Fig. 1. Leaky-wave antenna with a mechanically reconfigurable ground plane

TABLE I
DIMENSIONS OF THE DESIGNED ANTENNA (UNITS IN MM)

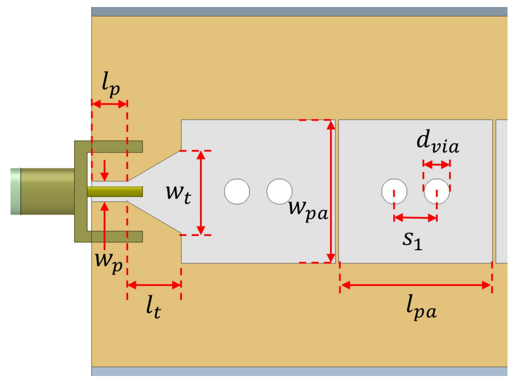
w_{pa}	l_{pa}	W	g	d_{via}	s_1
13.5	14.5	33	0.3	2.4	4
w_p	l_p	w_t	l_t	h	W_g
1.95	3.4	7.8	5	1.57	45

The antenna unit cell is a mushroom structure with distributed vertical interconnect access (vias) to reduce the diameter of each via. Each via has a diameter (d_{via}) equal to 2.4 mm, and they are separated from each other at a distance s_1 equal to 4 mm. Also, the antenna has tapered lines on both sides to match the antenna with 50 Ω, as well it is terminated with a 50 Ω load to suppress the reflected wave.

ULTEM 9085 is selected because of its low-outgassing properties, and it is often used inside the International Space Station (ISS) for 3D-printing applications. The ULTEM substrate is 1.57 mm thick, and its permittivity is 2.8. The 1.75 mm ULTEM filament is heated up to 375 °C, and then, it is deposited layer-upon-layer on a heated bed at 165 °C using a nScrypt 3Dn-Tabletop. The heated nozzle tip has an inner diameter of 125 μm and an outer diameter of 175 μm. The thickness of each layer is selected at 0.1 mm.



(a) Top view



(b) Close-up view

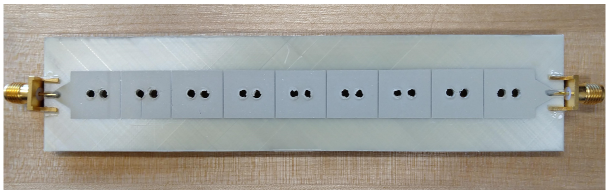
Fig. 2. Structure of the leaky-wave antenna

After the substrate is printed, a DuPont CB028 silver ink is micro-dispensed over the substrate to pattern the ink on the top. The inner diameter of the ceramic tip is 125 μm while the outer diameter is 175 μm. The ink is dispensed at a speed of 8 mm/s with a dispensing gap of 60 μm and a pressure of 2.5 psi. Then, the ink is cured at 120 °C for 30 min. Later, the silver ink is screen-printed on the bottom layer to make the ground plane, and the holes are coated with ink to create the vias, as well as the SMA connectors at the edges. Finally, the silver ink is cured at 120 °C for 30 min.

III. EXPERIMENTAL RESULTS

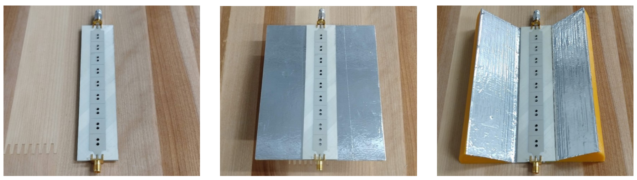
Fig. 3 shows the leaky-wave antenna using DPAM, as a result of patterning the CB028 ink on the ULTEM substrate, where the measured gap between unit cells is around 0.25 mm since the ink spread 25 μm for each patch side. Since the antenna can adjust the gain by rotating the extension of the ground plane at different angles, three platforms are manufactured to hold the ground plane at 0°, 20°, and 40° to mimic the movement of the adjustable planes, as shown in Fig. 4. Here, the platforms are printed using ABS, and they are covered on the top with aluminum foil tape.

The S_{11} parameter is measured using a Keysight E5071C ENA Vector Network Analyzer, which is cali-



(a) Top view

Fig. 3. 3D-printed microstrip CRLH leaky-wave loaded with two vias using ULTEM 9085 and DuPont CB028



(a) Without ground plane (b) Extentions at 0° (c) Extentions at 40°

Fig. 4. 3D-printed antenna on the different platforms for the extended ground plane

brated by a Keysight N4433A ECal module from 4 GHz to 7 GHz. Fig. 5 depicts the behavior of the parameter S_{11} when the extended ground plane is located at the elevation angles of 0°, 20°, and 40°, respectively. By comparing the results, it is noticed that S_{11} changes slightly by placing the ground plane at different elevation angles; however, the antenna bandwidth has no significant changes in the tested cases or in simulations. All measured results indicates that $|S_{11}|$ is below -10 dB from 4.61 GHz to 6.76 GHz, which represents a 10 dB bandwidth of 18.9%.

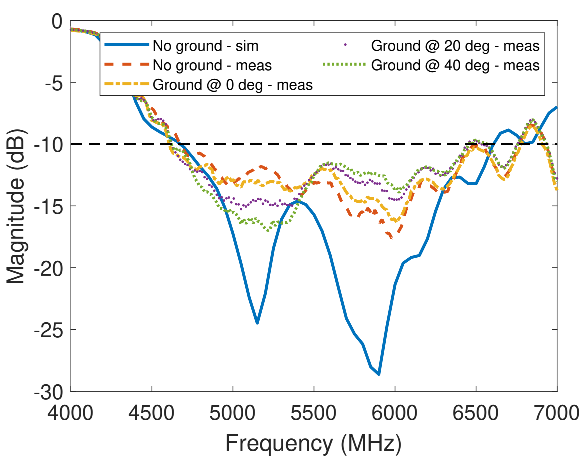


Fig. 5. Simulated and measured S11 parameter for the different positions of the extended ground plane

The radiation pattern of the 3D-printed antenna is measured using an ETS-Lindgren anechoic chamber at 4.65 GHz, and then, from 5 GHz to 7 GHz using a step of 500 MHz. Fig. 6 shows the normalized E-plane when the extended ground plane is located at 0°, where the simulations and measurements agree closely. Also, it is found the 3 dB beam scanning range is from -32° to 70° when the frequency increases from 4.65 GHz to 7.4 GHz. However, the antenna is able to scan continuously from -52 ° to 70° considering a gain variation greater than 3 dB, where the lower simulated gain is 6.56 dBi located at -52° at 4.4 GHz.The simulated antenna has a realized gain of 10.49 dBi at 6.15 GHz located at an scan angle of 32°. Measurements of the E-plane shows a gain of 10.3 dBi at 6.3 GHz located at an scan angle of 32°. This difference exhibited in the gain and the frequency response of the antenna is caused by variation of the electrical properties of the material, small changes in the geometry, and measurement error, such as the antenna alignment and calibration gain. From the measurements of E-plane, it is noted that the maximum gain is 10.07 dBi at 52° when the ground plane is placed at 0°, and the operating frequency is 6.5 GHz.

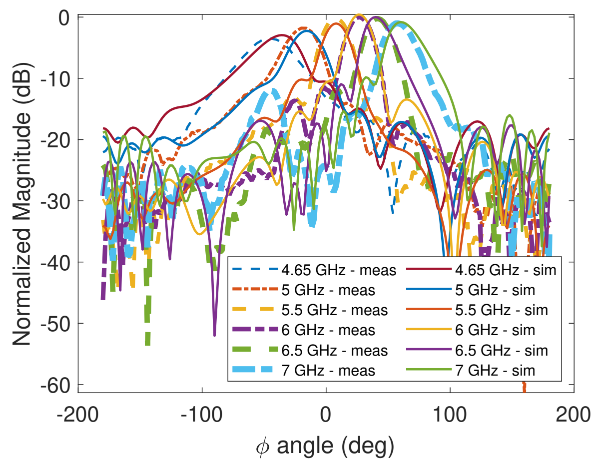


Fig. 6. Simulated and measured E-plane for the extended ground plane @ 0°

Fig. 7 shows the E-plane of the 3D-printed antenna at 6 GHz without the extension of the ground plane, as well as the results of placing the elevation angle of the ground plane at 0°, 20°, and 40°. From simulations, the antenna gain increases up to 2.3 dB at 5.9 GHz and 6.5 GHz when the elevation angle of the ground plane is placed at 40°. However, the gain increment is a function of the frequency and the elevation angle. Simulations also show a limit of the gain improvement beyond 40°. For example, at an angle elevation of 60°, the gain drops by 2.5 dB, and it keeps dropping by increasing the rotating angle of the ground planes. Finally, the measurements of the H-plane at 6.5 GHz of the lobe located at a scan angle of 52° show that the gain changes from 10.07 dBi to 12.03 dBi when the elevation of the ground plane varies from 0° to 40°, which implies a tunability close to 2 dB. .

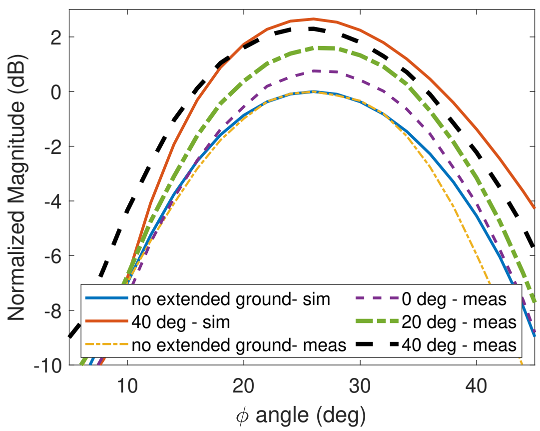


Fig. 7. Close-up of the simulated and measured E-plane for different elevation angles of the extended ground plane at 6 GHz

IV. Conclusions

In this work, a double-via loaded composite-right/left-handed (CRLH) leaky-wave antenna is successfully fabricated using DPAM. The 3D-printed antenna exhibits a continuous beam scanning range of 122° in the azimuth plane when the frequency is swept from 4.4 GHz to 7.4 GHz. The manufactured antenna provides a 10 dB return loss bandwidth of 2 GHz with a minimal change due to the mechanical reconfiguration of the ground planes. The use of the rotary ground plane provides an extra gain tunability up to 2.3 dB with respect to the antenna without the extension. The reconfigurable gain capability can compensate the gain variation during the frequency beam steering to keep it constant over the frequency by changing the elevation angle of the ground plane. The fabricated antenna can be used for space applications to increase the reliability of inter-satellite link during a a CubeSat swarm mission without adding complexity during the beam steering.

Acknowledgment

The authors wish to thank Embry-Riddle Aeronautical University for the financial support to perform the research of this publication. This material is based upon work supported by the National Science Foundation under Grant No. 1944599. In addition, the authors would like to offer our special thanks to nScrypt for their extensive assistance during this project, as well as Blake Roberts from the WiDE Lab for his assistance during the measurement of the radiation patterns.

References

[1] A. Jouade, M. Himdi, A. Chauloux, and F. Colombel, “Mechanically pattern-reconfigurable bended horn antenna for high-power applications,” *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 457–460, 2017.

[2] A. Boukarkar, X. Q. Lin, Y. Jiang, Y. J. Chen, L. Y. Nie, and P. Mei, “Compact mechanically frequency and pattern reconfigurable patch antenna,” *IET Microwaves, Antennas Propagation*, vol. 12, no. 11, pp. 1864–1869, 2018.

[3] I. T. Nassar, H. Tsang, D. Bardroff, C. P. Lusk, and T. M. Weller, “Mechanically reconfigurable, dual-band slot dipole antennas,” *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 7, pp. 3267–3271, 2015.

[4] C. G. Christodoulou, Y. Tawk, S. A. Lane, and S. R. Erwin, “Reconfigurable antennas for wireless and space applications,” *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2250–2261, July 2012.

[5] D. R. Jackson, C. Caloz, and T. Itoh, “Leaky-wave antennas,” *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2194–2206, July 2012.

[6] D. K. Karmokar, D. N. P. Thalakotuna, K. P. Esselle, L. Matekovits, and M. Heimlich, “Reconfigurable half-width microstrip leaky-wave antenna for fixed-frequency beam scanning,” in *2013 7th European Conference on Antennas and Propagation (EuCAP)*, April 2013, pp. 1314–1317.

[7] S. S. Haghighi, A. Heidari, and M. Movahhedi, “A three-band substrate integrated waveguide leaky-wave antenna based on composite right/left-handed structure,” *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 10, pp. 4578–4582, Oct 2015.

[8] C. R. Mejias-Morillo, A. Gbaguidi, D. W. Kim, S. Namilae, and E. A. Rojas-Nastrucci, “Uhf rfid-based additively manufactured passive wireless sensor for detecting micrometeoroid and orbital debris impacts,” in *2019 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE)*, Oct 2019, pp. 41–47.

[9] C. R. Mejias-Morillo, , and E. A. Rojas-Nastrucci, “Z-meandering miniaturized patch antenna using additive manufacturing,” in *2020 IEEE Radio and Wireless Symposium (RWS)*, Jan 2020, pp. 31–34.

[10] V. Gjokaj, P. Chahal, L. Kempel, and E. Rothwell, “A novel 3d printed half-width microstrip leaky-wave antenna,” in *2017 IEEE International Symposium on Antennas and Propagation USNC/URSI National Radio Science Meeting*, July 2017, pp. 1249–1250.

[11] V. Gjokaj and P. Chahal, “A design study of 3d printed reduced height waveguide structures,” in *2018 IEEE 68th Electronic Components and Technology Conference (ECTC)*, May 2018, pp. 125–130.

[12] U. Beaskoetxea, S. Maci, M. Navarro-Cía, and M. Beruete, “3-d-printed 96 ghz bull's-eye antenna with off-axis beaming,” *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 1, pp. 17–25, Jan 2017.

[13] C. Wang, H. Chu, and Y. Guo, “Realization of a reconfigurable leaky-wave antenna with fixed-frequency beam scanning capability using liquid metal,” in *2019 IEEE MTT-S International Wireless Symposium (IWS)*, May 2019, pp. 1–3.

[14] E. A. Rojas-Nastrucci, H. Tsang, P. I. Deffenbaugh, R. A. Ramirez, D. Hawatmeh, A. Ross, K. Church, and T. M. Weller, “Characterization and modeling of k-band coplanar waveguides digitally manufactured using pulsed picosecond laser machining of thick-film conductive paste,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 9, pp. 3180–3187, Sep. 2017.

[15] D. K. Karmokar, S. Chen, T. S. Bird, and Y. J. Guo, “Single-layer multi-via loaded crlh leaky-wave antennas for wide-angle beam scanning with consistent gain,” *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 2, pp. 313–317, Feb 2019.