

Polymer-based 3D Printed Millimeter-wave Components for Spacecraft Payloads

Stepan Lucyszyn
Department of Electrical and
Electronic Engineering
Imperial College London
London, United Kingdom
s.lucyszyn@imperial.ac.uk

Xiaobang Shang
Engineering, Materials and
Electrical Science Department
National Physical Laboratory
Teddington, United Kingdom
xiaobang.shang@npl.co.uk

William J. Otter
Department of Electrical and
Electronic Engineering
Imperial College London
London, United Kingdom
w.otter@imperial.ac.uk

Connor W. Myant
Dyson School of Design
Engineering
Imperial College London
London, United Kingdom
connor.myant@imperial.ac.uk

Ran Cheng
Department of Electrical and
Electronic Engineering
Imperial College London
London, United Kingdom
ran.cheng16@imperial.ac.uk

Nick M. Ridler
Engineering, Materials and
Electrical Science Department
National Physical Laboratory
Teddington, United Kingdom
nick.ridler@npl.co.uk

Abstract—This paper summarizes the current state of research & development within the U.K. for polymer-based 3D printed guided-wave and quasi-optical components for spacecraft payloads. Preliminary measured results look promising and show that this emerging technology may well overtake existing machined technologies in the not too distant future for general aerospace applications.

Keywords—Additive manufacturing, 3D printing, millimeter-wave, waveguide, horn antenna, mirror, spacecraft payload.

I. INTRODUCTION

In only the past three years, the U.K. has played a leading role in additive manufacturing using 3D printing for radio frequency application from microwave to terahertz frequencies [1]-[9]. With many proof-of-principles having already been demonstrated at component and subsystems levels within academia, there is now growing commercial interest in applying this technology to solve real engineering problems. One example is within the aerospace industry, where size, mass, development time and ultimately cost are key drivers.

This paper summarizes some of our recent results from a one-year pilot project (funded by the UK Space Agency) to apply 3D printing to spacecraft payloads within G-band (140 to 220 GHz). Spacecraft payload applications can be categorised into three main areas, communications, military and scientific. A scientific payload example is the high frequency instrument on board the Planck spacecraft, performing background radiation measurements at 143 and 217 GHz. By far, the most common example of G-band payloads is found on-board weather satellites. The main examples are operated by the National Oceanic and Atmospheric Administration (NOAA) and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), with satellites provided by NASA and ESA. The various generations of these

satellites have numerous payloads operating across the frequency spectrum; a G-band example being the microwave sounder having channels at 150.0, 183.311 and 190.311 GHz.

II. TARGET APPLICATIONS

Communications payloads usually operate in the Ku-band (12 to 18 GHz) and Ka-band (26.5 to 40 GHz). Previously, the National Physical Laboratory – Imperial College London team have demonstrated that the electromagnetic performance of polymer-based 3D printed waveguides at X-band (8.2 to 12.4 GHz) and W-band (75 to 110 GHz) are commensurate with commercial waveguides [2] [3]; while also demonstrating a hybrid technology (low-cost passive components with high performance plug-in active devices) up to 500 GHz [9] and even metal-pipe rectangular waveguides operating up to 1.1 THz [7] [8].

From a brief review of spacecraft payloads, it is clear that the main application for G-band is meteorological satellites having millimeter-wave multichannel sounder payloads; where guided-wave and quasi-optical components (horn antenna and mirror) are of interest. To further prove the technology, benchmarking against commercially available waveguide through lines is required to demonstrate their suitability at G-band. Furthermore, commercially available rectangular horn antennas and mirrors have been ‘replicated’, using CAD files that are openly available on the internet; such that their commercial counterpart can be used as benchmarks against which the measured performance of our 3D printed replicas can be compared.

A. Metal-pipe Rectangular Waveguides (MPRWGs)

Two different lengths (25.4 and 50.8 mm) of straight section waveguide have been designed to allow them to be directly compared and contrasted with commercially-available G-band waveguides; the flanges adopt the new IEEE

This work was funded by the UK Space Agency under grant NSTP3-FT-046. This work was also supported by the U.K. Engineering and Physical Sciences Research Council, under Grant EP/M001121/1 "TERACELL."

specification [10]. An E-plane split-block design, shown in Fig. 1, was developed because of the small waveguide aperture (having internal dimensions of only $1.2950 \times 0.6475 \text{ mm}^2$ [11]), when compared to its length, which would normally create problems with conventional electroplating. Specifically, there will be a depletion of the electro(less) plating solution inside the waveguide, which may not necessarily be refreshed, causing insufficient metal coating inside the waveguide.

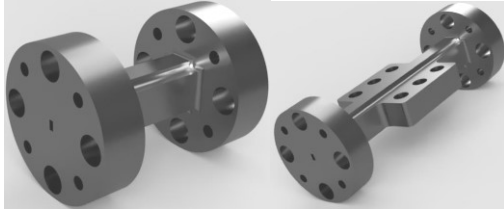


Fig. 1. CAD drawings of E-plane split-block 25.4 mm (left) and 50.8 mm (right) long MPRWGs.

B. 20 dBi Standard Gain Rectangular Horn Antenna

A commercial Flann Microwave Ltd. 20 dBi Standard Gain Rectangular Horn Antenna (model 30240-20) was chosen, because standard gain antennas are very well understood and there is a comprehensive datasheet available enabling replica 3D printed versions to be made. A shell of 2 mm had been used in the initial design, as shown in Fig. 2, while flanges were chosen that adopt the new IEEE specification [10].

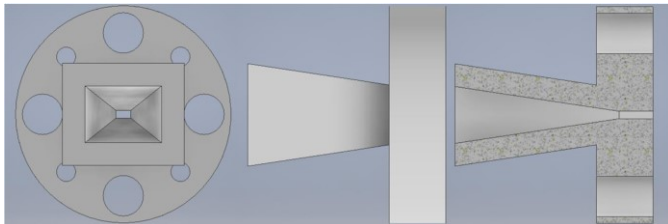


Fig. 2. CAD drawings of the replica 20 dBi gain rectangular horn antenna.

C. Off-axis Parabolic Mirror

An Edmund Optics 63188 off-axis parabolic mirror was chosen for the mirror to benchmark against. This parabolic shaped surface represents a complex curved structure to test the limits of the surface roughness achievable with the chosen 3D printing process. Unlike the rectangular waveguide structures, which will start to multimode at frequencies above the operating band, the mirror can operate throughout the THz frequency band and beyond; limited by the metal coating and surface roughness. The design is shown in Fig. 3.

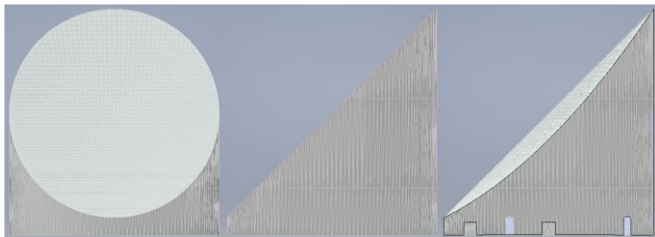


Fig. 3. CAD drawings of the replica off-axis parabolic mirror.

III. FABRICATION

The Objet Connex series of polymer jetting (Polyjet) 3D printers provide state of the art in terms of feature size (minimum resolution of $20 \times 20 \times 16 \mu\text{m}^3$ across a maximum build area of $340 \times 340 \times 200 \text{ mm}^3$) for a commercially-available printer, while also being dimensionally stable (i.e., not exhibiting shrinkage). To achieve the necessary resolution, it uses a wax-like support material that has to be completely removed using a water jet wash, chemical treatment and/or mechanical cleaning. As a result, the minimum feature size is much larger than the resolution quoted. For this work, the Objet 30Pro was chosen (minimum resolution of $100 \times 100 \times 16 \mu\text{m}^3$ across a maximum build area of $300 \times 300 \times 150 \text{ mm}^3$), as the worst-case surface roughness of $100 \mu\text{m}$ is sufficient for G-band (having an upper-band-edge free space wavelength of 1.364 mm) and uses a support material that should melt away from the structure when heated; there is no requirement for mechanical cleaning, as with the Connex printers.

The bulk of the support material melted away in an oven, when baked at 60°C (recommended by the manufacturer). However, this does not fully remove all the support material, which will limit the adhesion of the metal coating (consisting of a flash coating of electroless nickel, followed by a $20 \mu\text{m}$ thick layer of copper). To achieve complete removal, without the use of mechanical polishing, an additional chemical method for clean was adopted, with the results shown in Fig. 4.



Fig. 4. Polyjet 3D printed rectangular horn antenna and parabolic mirror (prior to metal plating).

IV. PRELIMINARY MEASUREMENTS

Measurements were undertaken at the U.K.'s National Physical Laboratory using their vector network analyser (VNA) with G-band extension heads and Imperial College's imaging setup (employing their new 1024 pixel Terasense TERA-1024 sub-THz imaging camera, which can operate between 70 and 390 GHz).

The two-inch (50.8 mm) long waveguide is shown in Fig. 5, along with its preliminary measurements. It can be seen that insertion loss is less than 5 dB across G-band; at the near-mid-band frequency of 172 GHz, insertion loss is approximately 3 dB, corresponding to 0.059 dB/mm or $0.139 \text{ dB}/\lambda_g$.

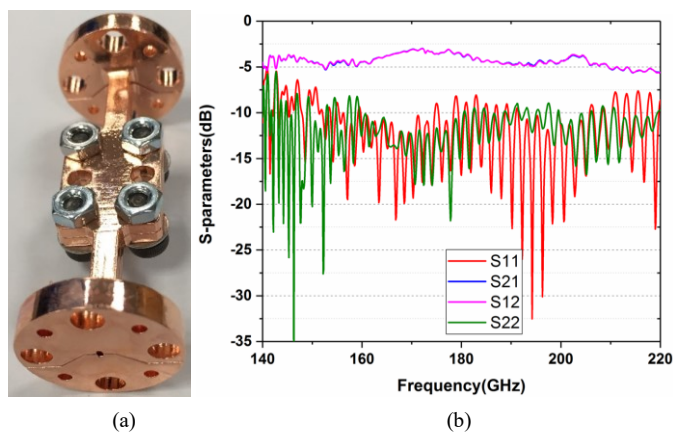
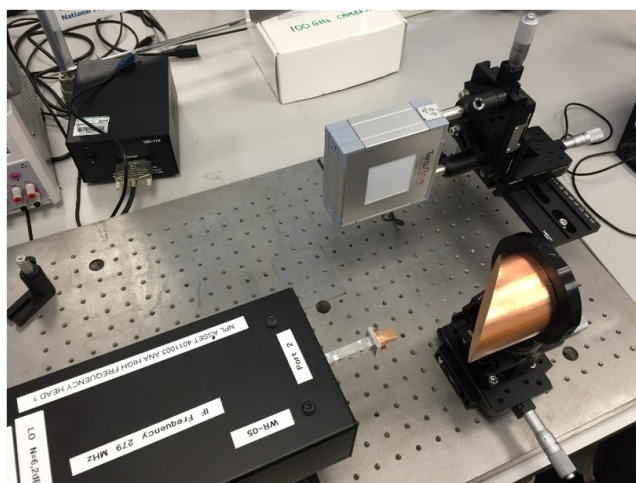
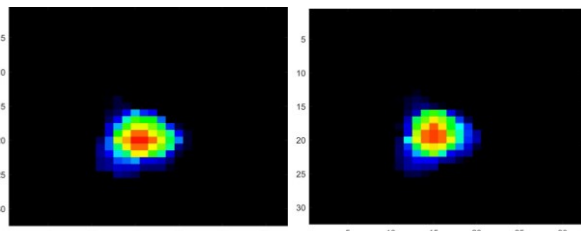


Fig. 5. (a) Assembled two-inch G-band E-plane split-block MPRWG; and (b) preliminary measured performance.

The quasi-optical measurement setup for testing the horn antenna and mirror is shown in Fig. 6. Preliminary measured results show almost no difference in performance when the commercial components are replaced by their 3D printed replica counterparts.



(a)



(b)

Fig. 6. Quasi-optical measurement setup: (a) showing the G-band 3D printed rectangular horn antenna and parabolic mirror (after plating); and (b) preliminary field intensity plots at 160 GHz without background noise cancellation – (left) from commercial components, (right) from 3D printed components.

V. CONCLUSION

This paper has summarized the current state of research & development within the U.K. for polymer-based 3D printed guided-wave and quasi-optical components for millimeter-wave spacecraft payloads. While the preliminary measured results look promising, there are a number of improvements that are currently being investigated across the technology (from design to manufacture and even with metrology); since the turn-around time for development is inherently short with 3D printing technology more and better results will be reported. Regardless, it is believed that this emerging technology may well overtake existing machined technologies in the not too distant future for general aerospace applications.

ACKNOWLEDGMENT

The authors would like to thank Flann Microwave Ltd., an industrial partner for our project. In addition, the technical support from Dr. M. M. Ahmad., Hang Ren and Usman Waheed is appreciated.

REFERENCES

- [1] C. Guo, X. Shang, M. J. Lancaster, and J. Xu "A 3-D printed lightweight X-band waveguide filter based on spherical resonators," *IEEE Micro. and Wireless Comp. Lett.*, vol. 25, no. 7, pp. 442-444, Jul. 2015.
- [2] M. D'Auria, W. J. Otter, J. Hazell, B. T. W. Gillatt, C. Long-Collins, N. M. Ridler and S. Lucyszyn, "3-D printed metal-pipe rectangular waveguides", *IEEE Trans. on Components, Packaging and Manufacturing Technology*, vol. 5, no. 9, pp. 1339-1349, Sep. 2015.
- [3] C. Guo, X. Shang, J. Li, F. Zhang, M. J Lancaster, and J. Xu, "A lightweight 3-D printed X-band bandpass filter based on spherical dual-mode resonators," *IEEE Micro. and Wireless Comp. Lett.*, vol. 26, no. 8, pp. 568-570, Aug. 2016.
- [4] X. Shang, P. Penchev, C. Guo, M. J. Lancaster, S. Dimov, Y. Dong, M. Favre, M. Billod, E. De Rijk, "W-Band waveguide filters fabricated by laser micromachining and 3-D printing," *IEEE Trans. on Microwave Theory and Techn.*, vol. 64, no. 8, pp. 2572-2580, Aug. 2016.
- [5] B. T. W. Gillatt, M. D'Auria, W. J. Otter, N. M. Ridler, and S. Lucyszyn, "3-D printed variable phase shifter", *IEEE Micro. and Wireless Comp. Lett.*, vol. 26, no. 10, pp. 822-824, Oct. 2016.
- [6] X. Shang, P. Klasmann, and M. J Lancaster, "A compact Ka-band waveguide orthomode transducer fabricated by 3-D printing," *46th European Microwave Conference (EuMC)*, pp. 365-368, Oct. 2016.
- [7] W. J. Otter and S. Lucyszyn, "Printing: the future of THz", *IET Electronics Letters*, vol. 53, no. 7, p. 433, Mar. 2017.
- [8] W. J. Otter, N. M. Ridler, H. Yasukochi, K. Soeda, K. Konishi, J. Yumoto, M. Kuwata-Gonokami, and S. Lucyszyn, "3D printed 1.1 THz waveguides," *IET Electronics Letters*, vol. 53, no. 7, pp. 471-473, Mar. 2017.
- [9] W. J. Otter and S. Lucyszyn, "Hybrid 3-D-printing technology for tunable THz applications", *Proceedings of IEEE*, Special Issue on Additive Manufacturing of Radio-Frequency Components, vol. 105, no. 4, pp. 756-767, Apr. 2017.
- [10] IEEE standard for rectangular metallic waveguides and their interfaces for frequencies of 110 GHz and above – part 2: waveguide interfaces, IEEE Standard 1785.2-2016, 2016.
- [11] IEEE standard for rectangular metallic waveguides and their interfaces for frequencies of 110 GHz and above – part 1: frequency bands and waveguide dimensions, IEEE Standard 1785.1-2012, 2012.