3D printed 1.1 THz waveguides

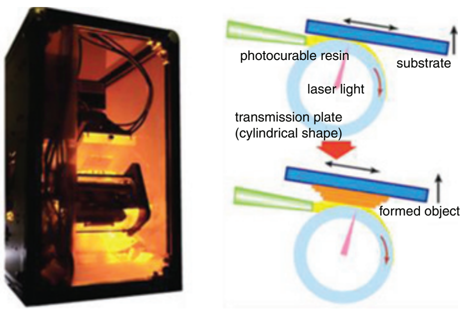
W.J. Otter, N.M. Ridler, H. Yasukochi, K. Soeda, K. Konishi, J. Yumoto, M. Kuwata-Gonokami and S. Lucyszyn✉

For the first time, 3D printed metal-pipe rectangular waveguides (MPRWGs) have been demonstrated in the WM-380 (500–750 GHz) and WM-250 (750 GHz–1.1 THz) waveguide bands. The ultra-high spatial resolution offered by the new RECILS additive manufacturing technology enables the precision fabrication of these prototype MPRWGs at such high frequencies. This enabling technology avoids the need for access to expensive microfabrication resources and, thus, opens up the terahertz spectrum to the low-cost manufacture of passive components.

Introduction: 3D printing is revolutionising the manufacture of RF guided-wave components. Not least, this is due to the ease of production with complex geometries integrating both the functional component and associated mounting brackets, dramatically reducing total costs. In 2015, the authors demonstrated 3D printed metal-pipe rectangular waveguides (MPRWGs) having measured performances commensurate with conventional commercial MPRWGs at both X-band (8–12 GHz) and W-band (75–110 GHz) [1].

In this Letter, we demonstrate the first 3D printed terahertz (THz) MPRWGs above 500 GHz, with measured results benchmarked against commercial 25.4 mm long gold-plated machined waveguides.

Fabrication: The MPRWGs were fabricated from acrylic plastic using the new RECILS 3D printing technology. This technology controls the 1D liquid level of the photocurable resin (eliminating the need for a large resin storage tank), as seen in Fig. 1 [2, 3]. A glass cylinder and planar substrate are positioned to make a 1D gap height of 10–40 µm, with the resin fed into the precisely controlled gap. The UV laser light, modulated according to the object design, scans along the gap through the glass cylinder. After a line of cured resin had formed, the planar substrate moves to the right and the next line of a cured resin is formed. When the line-by-line formation of a layer is complete, the substrate moves up by the gap height, and the next layer is deposited. This process offers high resolution and easy detachment of objects from the transmission plate without damage. These attributes allow for the fabrication of complex structures with fine features.



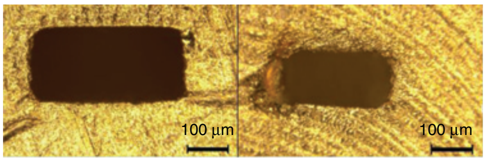
a b

Fig. 1 *RECILS 3-D printing technology*
a Photograph of RECILS 3D printer
b Illustration of associated 1D liquid level control principle

Meeting the new IEEE standard waveguide specifications [4, 5], the MPRWGs were 5 mm long – corresponding to $\sim 5\lambda_g$ and $10\lambda_g$ at the lower and upper band edges, respectively, for the WM-380 exemplar (where λ_g is the guided wavelength), and $8\lambda_g$ and $15\lambda_g$ for the WM-250 exemplar. These lengths support a single mode of operation (TE_{10}) and are sufficiently long enough to suppress any evanescent mode coupling between the input and output ports.

The acrylic surfaces were first electroless metal plated with 1-µm-thick nickel, followed by electroless plating of 30-nm-thick gold, and finally a 1-µm-thick layer of gold is deposited using conventional plating. The final gold layer being >5 skin depths at the lowest frequency of operation. Fabricated MPRWG apertures are shown in Fig. 2, for the WM-380 and WM-250 exemplars (where 380 and 250 correspond to the associated broad-wall dimensions, in microns, and the apertures having a 2:1 aspect ratio).

Measurement setup: Performance measurements were carried out at the UK's National Physical Laboratory, using a Keysight PNA-X vector network analyser configured with either a pair of VDI WR-1.5 or VDI WR-1 frequency multiplier heads (covering the 500–750 GHz and 750–1100 GHz bands). As shown in Fig. 3, two-port measurement reference planes, located at the flanges, were defined across the full waveguide bands using the recommended short, offset-short, line, and thru) 12-term calibration algorithm.



a b

Fig. 2 *Micrographs of 3D printed MPRWGs*
a WM-380
b WM-250

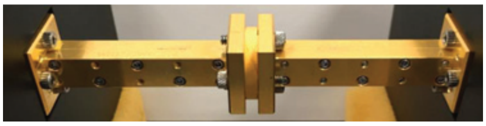


Fig. 3 *Measurements setup for 3D printed MPRWGs*

Measured results: For straight thru lines, the total power attenuation is given by $\alpha_T = \alpha_R + l\alpha'_D$ [dB], where α_R [dB] is attributed to impedance mismatch reflection losses at the flange, α'_D [dB/m] is attributed to dissipative (or ohmic) losses associated with the internal metal walls, and l [m] is the physical length of the line. Since a designer can control α_R, given a stable manufacturing process, only α'_D reflects the quality of a given manufacturing technology [1]. It can be shown that [1]

$$\alpha'_D = -\frac{10\lambda_g}{l}\log_{10}\left(\frac{|S_{21}|^2}{1-|S_{11}|^2}\right)\ [\mathrm{dB}/\lambda_g] \qquad (1)$$

where S_{11} and S_{21} are the measured input voltage-wave reflection coefficient and forward voltage-wave transmission coefficient, respectively. These are shown in Figs. 4 and 5 for the WM-380 and WM-250 bands, respectively.

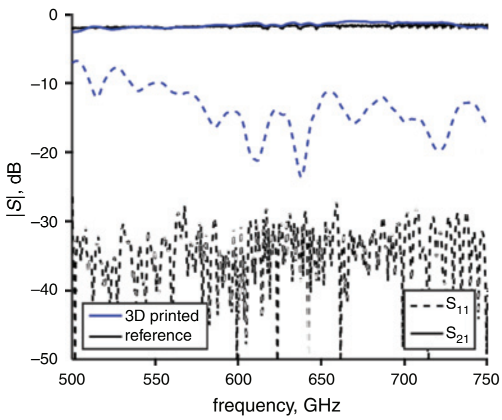


Fig. 4 *Measured S-parameters for gold-plated WM-380 5-mm-long 3D printed thru line (blue) and 25.4-mm-long reference waveguide (black)*

Fig. 6 shows the dissipative attenuation for both WM-380 MPRWGs. The reference waveguide has attenuation levels of 0.083 and 0.028 dB/λ_g at the lower and upper band edges, respectively. These are very close to a theoretical gold waveguide, which has respective attenuation levels of 0.065 and 0.022 dB/λ_g [4]. The 3D printed thru line has attenuation levels of 0.28 and 0.15 dB/λ_g at the lower and upper band edges, respectively, although in parts of the band has only twice the loss of the reference waveguide.

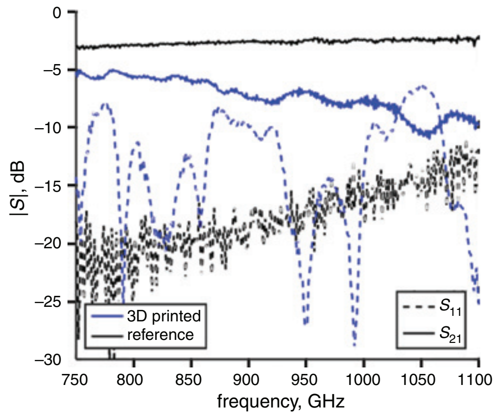


Fig. 5 *Measured S-parameters for gold-plated WM-250 5-mm-long 3D printed line (blue) and 25.4-mm-long reference waveguide (black)*

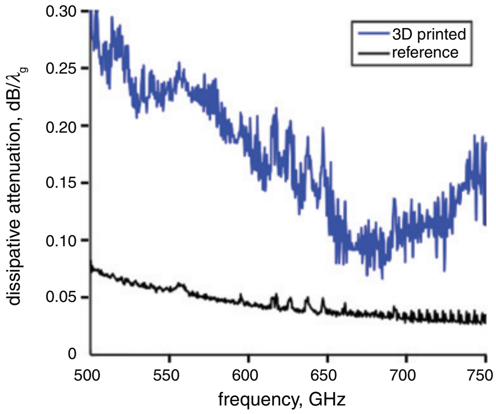


Fig. 6 *Calculated dissipative attenuation for WM-380 5 mm 3D printed line (blue) and 25.4 mm reference waveguide (black)*

Fig. 7 shows the dissipative attenuation for both WM-250 MPRWGs. The reference waveguide has attenuation levels of 0.078 and 0.026 dB/λ_g at the lower and upper band edges, respectively. These are very close to a theoretical gold waveguide, which has respective attenuation levels of 0.087 and 0.029 dB/λ_g [4]. The discrepancy between measured and theoretical results is due, in part, to the measurement error of the VNA, which is no longer negligible for the WM-250 band. The 3D printed waveguide has attenuation levels of 0.67 and 0.64 dB/λ_g at the lower and upper band edges, respectively. This order of magnitude increase can be attributed to insufficient plating thickness and poor side-wall definition of the waveguide aperture (as shown in Fig. 2).

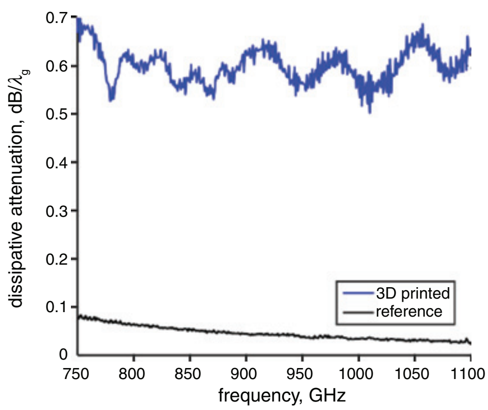


Fig. 7 *Calculated dissipative attenuation for WM-250 5-mm-long 3D printed line (blue) and 25.4-mm-long reference waveguide (black)*

Table 1 shows a comparison of measured mid-band attenuation for 3D printed MPRWGs that can operate within the THz band (i.e. from 300 GHz to 10 THz). To the best of our knowledge, this table includes all reported results published in the open literature.

Table 1: Comparison of state-of-the-art THz 3D printed waveguides (bold values indicate results presented in the work)

3D Printing technology	Waveguide band	Frequency (GHz)	Mid-band attenuation (dB/λ_g)	Ref.
SLM	WM-864	220–330	0.16	[6]
SLA	WM-864	220–330	0.018	[7]
Polyjet	WM-570	325–500	0.42	[8]
RECILS	**WM-380**	**500–750**	**0.15**	**here**
RECILS	**WM-250**	**750–1100**	**0.60**	**here**

Conclusion: This work has pushed the upper frequency limit of 3D printing of MPRWGs; demonstrating a 1.1 THz thru line using the new RECILS technology. All the prototypes were measured at the UK's National Measurement Laboratory, to provide confidence in the measured results. With these initial prototypes the measured mid-band dissipative attenuation levels are 0.15 and 0.60 dB/λ_g for the WM-380 and WM-250 MPRWGs, respectively.

This work clearly demonstrates the future potential of this high-resolution manufacturing technology, offering the advantages of light-weight rapid prototyping/manufacturing and relatively very low cost when compared with traditional (micro)machining.

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One or more of the Figures in this Letter are available in colour online.

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