Additive Manufacturing of a Terahertz Back-to-back Horn Antenna for Use in Life Sciences

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Abstract—A 3D-printed, 0.3 THz, back-to-back, smooth-walled, horn is presented. It was made from “material” as mating symmetric halves, with internal surfaces metallised with gold-plate. The junction of the back-to-back horns host a 1 mm² micro-fluidic aperture for feeding analytes undergoing dielectric properties’ characterisation of typically solvated proteins. The configuration allows for enhanced beam-sample interaction and efficient detection than would be conventionally achieved with either traditional quasi-optical or cavity resonator circuits. The horn-pair was designed for 0.3-0.32 THz operation. It can, however, work over a wider domain of frequencies, namely, 0.2-0.32 THz, if restrictions on cross-polarisation and matching are relaxed. Initial measurements of the horn-pair have shown that there is an increase of 2.5 dB in the signal strength when the horn apertures are equidistant from the focusing mirrors of a defocused quasi-optical transmissometer system.

Index Terms—Back-to-back Horn, 3D-Printing, Quasi-Optical Transmissometer, Terahertz, Life Sciences

I. INTRODUCTION

Dielectric spectroscopy for analysis [1] and identification [2-6] of bio-fluids, e.g. solvated protein, solutions at mm and sub-mm electromagnetic probe wavelengths is technically challenging by virtue of inherently high signal absorption by water [7-9]. This band of wavelengths is conventionally mediated via quasi-optical (QO) circuits coupled to a vector network analyser (VNA). Samples are typically of ‘batch’ form in that a vessel or ‘cuvette’ holding the fluid-specimen of study is placed at a focal-point in a QO circuit. Microfluidics are otherwise used to convey the sample into the region of the probe-beam. They are preferred in order to minimise kinematic errors that otherwise come from manual handling and allow for uninterrupted computer-controlled variation in experimental parameters such as sample concentration and pH, for example. The volumes of bio-liquid samples are commonly small, being of the order of pL to µL. For QO system, this demands creating a high quality beam-focus. Consequently, controlling diffraction and signal aberration is of special importance with QO circuits [10]. Some avoid this by otherwise working with high-Q cavity systems [11, 12]. But while QO circuits are inherently wideband, resonator methods trade bandwidth for narrow-band precision. The back-to-back horn configuration described here is a compromise between QO circuit and waveguide methods in which the microfluidics can be fully integrated. It is intermediate between an outer-lying pair of off-axis ellipsoidal mirrors working in tandem with an inner-pair of fast parabolic mirrors. This arrangement is to ensure efficient signal conditioning to couple the beam field from an ultra-Gaussian, corrugated, source horn, into the throat of one horn in the back-to-back horn-pair, and to efficiently transport the emerging beam to an identical receive horn. Successive back-to-back pairs in a suite of pairs, can allow continuous coverage and hence dielectric characterization of the micro-fluids over the THz band [13].

In this work the design and the characterization of a 3D printed plastic back-to-back horn, with a gold coating on the inner surface is, presented. At the centre of the back-to-back horn there is a cavity designed at WR-3 (220-325 GHz) band dimensions as shown in section II, which is created to accommodate biological samples. In section III we discuss the manufacturing process to create such a prototype. Measurements of the back-to-back horn at WR-3 are shown in section IV, and a feasibility test is done to ensure that the horn is capable of probing biological samples. Section V concludes the results presented in this paper.

II. BACK-TO-BACK HORN DESIGN

Original horn design specifications were dictated by a configuration of the existing measuring facilities at the THz and Quasi-Optics Laboratory at Queen Mary University of London (QMUL). Detailed information will be later given in the paper. The measurement setup includes a Z-shaped bench, which produces an 8-to-9 mm beamwaist at the focal point of the system. In order to match the beamwaist of the system, also

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known as a transmissometer [14, 15], a horn ought to have an aperture not less than 9 mm. In order to produce reliable measurements in two states of orthogonal polarisation, clear polarisation requirements for the horn need to be established. Also, and very important in this case, manufacturing limitations should be carefully considered. Taking that into account, horn specifications are as follows: Frequency domain – ideally 0.22 to 0.325 THz; VSWR at the throat of the horn < 2; Cross-polarisation level < -20 dB; Flare-angle < 30 degrees. The first design considered was a corrugated horn as shown in Fig. 1. A corrugated back-to-back horn was chosen since corrugations in horn antennas offer up to 30 % bandwidth matching and suppress the cross-polar content of the radiation pattern of the horn. Additionally, the corrugated horn was fabricated to test the limits of fabrication using the 3D-printing technology discussed in this paper. It consists of two standard, linear-tapered, corrugated horns. They can be found as a feed in many single and dual-reflector configuration for communication systems, radio-astronomy, etc. The horn is designed using in-house software implementing the modal matching technique, which has been successfully applied in various previous designs [16]. Matching is achieved by varying slot-depth at the throat of the horn, as by Clarricoats et al [15]. However, instead of varying depth inside the horn, matching was achieved by varying depths in the throat. Technically, it can be called as an $H_{11}$-HE$_{11}$ transformer. Good performance characteristics were achieved as follows: VSWR is in the range of 1.1-1.6 over 0.27 – 0.33 THz, which is expected for such a class of horn where bandwidth is around 20% only. Matching slots are used to assure the optimum performance in terms of matching
(VSWR) in a large frequency bandwidth. The procedure is comprehensively explained in [17]. In the work here, however, a better value of VSWR is sacrificed for more convenient geometrical dimensions of manufacture. A dominating issue is the number of slots per wavelength. Taking into account manufacturing challenges of such complex structures at sub-mm frequencies, the number of slots per wavelength has to be minimized. However, this degrades the performance of the horn, where less than two slots per wavelength have been found to be just enough to keep corrugated horn performance as desired. A compromise has been found by using 2.5 slots per wavelength. Usually, 3-4 slots per wavelength are chosen to guarantee the best performance. A typical radiation pattern of the corrugated horn with a semi-flare angle of 12°, an aperture of approximately 10 mm and matching within the throat of the horn is shown in Fig. 2. Fig 2 was generated using an in-house code following Model Matching Technique (MMT). It is seen that for the horn shown, theoretical performance is exceptionally good. Unfortunately, all attempts to manufacture the horn using various 3D printing techniques, described in detail in the following Section, failed. One of the manufactured horns is shown in Fig. 6a. A decision was made to terminate further attempts. The next possible candidate to be used in a dual polarisation system is a symmetrical pyramidal horn. A schematic view, taken from FEKO, a part of Altair Hyperworks Suite, where it had been designed, is shown in Fig. 3. Pyramidal horns, while inferior in performance to corrugated horns, can however be used when bandwidth and high cross-polarisation purity are not constraining requirements. A typical VSWR and radiation pattern of the pyramidal horn is shown in Fig. 4 and Fig. 5 respectively. It clearly shows that the radiation pattern is asymmetrical in principal polarisation planes but, nevertheless, VSWR and cross-polarisation level, depicted as a Ludwig III Cross, are at an acceptable level. However, its bandwidth is twice smaller than for the corrugated horn discussed earlier. In relaxing VSWR and non-symmetry requirements, the horn can operate over almost the entire WG-3 band. Results are satisfactory, so a back-to-back horn based on this design with an insertion window was developed using Autodesk Inventor and sent for manufacture. The horn was successfully fabricated using 3-D printing. The following Section will describe the manufacturing process and show the first set of measurements to the performance viability of the horn.

III. MANUFACTURING OF 0.3 THZ HORN USING 3-D PRINTING TECHNOLOGY

Manufacturing of high gain antennas using 3D printing technology has become prominent since advancements in 3D printing techniques such as FDM (Fused deposition modelling), SLA (Stereolithography apparatus), and SLS/SLM (Selective Laser Sintering/ Selective Laser Melting). Techniques like SLS/SLM print sub-THz horn antennas and waveguide structures directly in metal. [18, 19]. However, FDM or SLA prints only dielectric structures. These printed structures, around sub-THz or THz frequencies, require not only fabrication accuracy, but also smooth surfaces where rms surface roughness is less than $\lambda/20$. This is because post-printing metallization defines the performance of these devices.
Here, we have used post-printing metallisation technique to fabricate the back-to-back horn.

Fabrication of corrugated horn: The corrugated horn antenna is fabricated by 3D printing the structure of the antenna using a polymeric resin, whose surface is then metallised using rotocoating kit. An EnvisionTEC SLA 3D printer is used with a photopolymer (R5 photosensitive resin) to provide the high resolution required to accurately fabricate the corrugations of the bottle-necking shape of the antenna which prevented homogeneous flow of paste inside the antennas’ cavities.

Fabrication of pyramidal horn: To overcome the challenges of the fabrication of a corrugated antenna, a different manufacturing method is implemented for the pyramidal horn antenna. To be able to access the internal faces of the pyramidal horn the structure is 3D printed in mating halves along the long-axis of the antenna as shown in Fig 5b. Each half was sputter coated with gold while internal faces were placed upward towards the gold sputtering target. The outer faces of the antenna were masked to avoid leaking the sputter coating to the outer faces of the antenna. This process is repeated three times while the structure is tilted sideways to fully coat the internal vertical walls of the antenna. The two halves of the antenna were joined as shown in Fig 5d using conductive paste to prevent any discontinuity of electrical conductivity.

IV. Measurements

Fig. 7 shows a QO transmissometer system. In a QO transmissometer system, the normalised transmission, in terms of scattering (S)-parameters, through the sample interface, which is at the focal point, is measured using a vector network analyser (N5244A VNA). The VNA in turn is connected to two frequency multiplier heads, supplied by OML, Inc., to up-convert its baseband to 0.22 - 0.325 THz. The multiplier heads then feed the high gain Gaussian horn antennas. Typically, this sort of setup is used for high frequency materials’ characterisation [22, 23]. The fast-focusing mirrors (F) reform the collimated beam into a focused beam. The typical beam-waist around the focal point of such systems at 0.1 THz is 8 to 9 mm [24]; however this beam-waist will be smaller at 0.3 THz. Since the beam waist is narrow, small non-linear elements can be excited using such a system [25]. Here, however, we place a 3D-printed back-to-back horn at the focal point of the QO transmissometer system, in order to collect all the energy from the fast-focusing mirrors and concentrate it to the centre of the back-to-back horn. Fig. 7a shows the positioning of the back-to-back horn in the focused QO transmissometer system. Two irises have been used to mount the back-to-back horn in position so that its centre is at the focal point of the system. It is observed that with the focused system (i.e. the QO transmissometer has a focal point at S as shown in Fig. 7), the back-to-back horn has an insertion loss of around 18 dB at 0.3 THz. Fig. 9a shows a comparison between the insertion loss in
the system due to a 2 mm thick Teflon sample and the back-to-back horn. The positions 1 and 2 in Fig. 9a describes the position of the back-to-back horn being placed horizontally and flipped 90° in the axis of wave propagation respectively. The transmission at the two positions appear polarisation-invariant at the operational introduced in the QO transmissometer system. This is because square waveguide, with dimensions 0.9 mm × 0.9 mm, at the centre ensures two orthogonal polarisations of the propagating wave inside the waveguide.

The reason for such a drop in transmission is due mainly to the fast expanding beam-waist of the QO transmissometer system and the large size of the back-to-back horn. The beamwaist being bigger than the horn aperture results in a mismatch. The reflection from the back-to-back horn, as shown in Fig. 9b, indicates that most of the signal from the horn aperture is scattered, and possibly some absorbed by the dielectric parts of the back-to-back horn, whilst some may not be coupled into the horn but is blocked by the irises (see Fig 8a). Furthermore, another reason for such a large drop can be attributed to the presence of a seam, due to the limitations of fabrication, between the two printed halves of the horn. Hence, in order to mitigate the losses due to mismatch, the QO transmissometer system is adjusted improve the match between the horn aperture and the incident beam. The distance between the fast mirrors is increased and the position of the back-to-back horn is correspondingly adjusted. That is done by displacing the fast mirrors at a distance exactly equal to the horn length, as seen in Fig. 9b. In such a configuration the transmissometer is supposed to have two foci at the horns' apertures. Indeed, optimum settings hold when the location of the horn’s phase centre is accounted for. However, being the first attempt to demonstrate the principal operation of such a system, it was decided to leave it as described. As the transmissometer requires fine tuning after each movement of the mirrors, an extensive study of the dependence of a system response to the distance between the fast mirrors at a distance exactly equal to the horn length, as seen in Fig. 9b. This realignment process with the new mirrors at a distance exactly equal to the horn length, as seen in Fig. 9b. This realignment process with the new mirrors at a distance exactly equal to the horn length, as seen in Fig. 9b.

V. CONCLUSION

This paper has presented the first 3D printed back-to-back horn antenna for use in a QO system for the purpose of characterising bio-fluids at THz frequencies. Stereolithography, followed by gold sputtering, was used to fabricate the back-to-back horn with a central cavity allowing for the integration of microfluidics. The results obtained from extensive measurements show that the defocused QO transmissometer, in conjunction with the 3D-printed back-to-back horn, can be used as a system for THz biomedical and chemical spectroscopy. It has been observed that in the focused QO system the focal point is not located at the aperture of the back-to-back horn. The losses seen are from under-coupling of the beam and the aperture, manufacturing defects of the back-an oversized beamwaist due to the distance of each aperture to-back horn, and waste of electromagnetic energy as a result of from its respective fast mirror. Further improvement can be achieved by fine tuning the distance between mirrors in the defocusing configuration, as well as adjusting for the phase-centre of the horn, which does not lie exactly at its aperture.

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