## UNIVERSITY BIRMINGHAM University of Birmingham Research at Birmingham

# Micromachined SU-8-based terahertz 8×8 slotted waveguide antenna array

Mahmud, Rashad H.; Salih, Idris H.; Awl, Halgurd N.; Shang, Xiaobang; Wang, Yi; Skaik, Talal; Lancaster, Michael J.

DOI: 10.1007/s10762-021-00830-6

License: Other (please specify with Rights Statement)

Document Version Peer reviewed version

#### Citation for published version (Harvard):

Mahmud, RH, Salih, IH, Awl, HN, Shang, X, Wang, Y, Skaik, T & Lancaster, MJ 2021, 'Micromachined SU-8based terahertz 8x8 slotted waveguide antenna array', *Journal of Infrared, Millimeter, and Terahertz Waves*. https://doi.org/10.1007/s10762-021-00830-6

Link to publication on Research at Birmingham portal

#### Publisher Rights Statement:

Post-prints are subject to Springer Nature re-use terms https://www.springernature.com/gp/open-research/policies/accepted-manuscript-terms

#### **General rights**

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.

•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.

•User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?) •Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

#### Take down policy

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

# Micromachined SU-8 Based Terahertz 8×8 Slotted waveguide Antenna Array

## Rashad H. Mahmud<sup>1,2\*</sup>, Idris H. Salih<sup>3</sup>, Halgurd N. Awl<sup>4</sup>, Xiaobang Shang<sup>5</sup>, Yi Wang<sup>2</sup>, Talal Skaik<sup>2</sup>, and Michael J. Lancaster <sup>2</sup>

<sup>1</sup> School of Electronics, Electrical and Systems Engineering, University of Birmingham, Birmingham B152TT, U.K;

<sup>6</sup> <sup>2</sup> Physics Department, Salahaddin University-Erbil, Iraq, 44002; <u>rhm11286@yahoo.co.uk</u>

- <sup>7</sup> <sup>3</sup> Mechatronic Engineering, Faculty of Engineering, Tishk International University, Erbil 44001, Iraq.
- 8 <sup>4</sup> Department of Communication Engineering, Sulimani polytechnic University, Sulaimani, 46001, Iraq.
- 9 <sup>5</sup> National Physical Laboratory (NPL), UK.
- 10 \* Correspondence
- 11 Rashad H. Mahmud, School of Electronic, Electrical, and Systems Engineering, University of Birmingham, Birmingham,
- 12 UK.
- 13 Email: <u>rhm11286@yahoo.co.uk</u>

14 Abstract: This article presents the design and fabrication of a micromachined 300 GHz planar array slotted 15 waveguide antenna utilising the silver-coated SU-8 photoresist layer technology. The array is configured to be 16 built from five SU-8 layers of equal thicknesses. The top layer is devoted to form the 8×8 slots. The following 17 three layers are to form the feed and radiating waveguides. The bottom layer is to enclose the design and allocate 18 the input port. An H-plane waveguide bend based on the matching steps is designed and integrated with the 19 proposed array. This is to maintain a precise alignment with the standard waveguide flange WR-03 and facilitate 20 the measurement. Also, two brass-pates are used to clamp the five layers together and tight them via screws in 21 order to minimise the losses. The simulated antenna realised gain is 24.59 dBi, and the 3-dB gain bandwidth is 22 4.5 GHz. The radiation patterns are very directive, having low side lobe levels. The reflection coefficient has 23 been measured and presented. The proposed micromachined antenna array is directional and low-profile, and 24 may find applications in indoor wireless applications and sensors. 25 Keywords: Micromachined Technology; SU-8 layers; terahertz antennas; waveguide antennas; slot arrays; 26 micromachining; waveguide bends; SU-8 layers 27 Acknowledgments: The authors would like to thank the EDT research group at the University of Birmingham, 28 UK, and the Rutherford Appleton Laboratory, Dicot, UK for fabricating and measuring the device. 29 30 31

- 32
- 33
- 34
- 35

#### 36 1. Introduction

The terahertz (THz) electromagnetic waves have received significant attentions more recently not only in the detection and imaging systems [1-3], but also in biology and surveillances [4-6]. This is due to increasing the data rate capability of the communication systems and providing a larger bandwidth [5]. Also, THz waves have a better penetration of materials in comparison with the infrared [7]. This is extremely useful in the surveillance applications to scan and extract information from the luggage without opening it. However, this is applicable only for a short-range distance due to the THz atmospheric path loss [8]. To overcome this, employing a high gain antenna at the THz communication system is considered as one of the ultimate solutions.

- 44 Many THz communication systems employ optical antennas including lenses and reflectors due their 45 fabrication simplicity, and achieving high gain by increasing their electrical sizes [9, 10]. However, packaging 46 these kinds of antennas with the whole THz systems is difficult due to their curvature shape. Horn antennas, which 47 are high gain and very efficient antennas, are also good candidates for THz systems. The flared out shape of the 48 horns and their dramatic size reduction when operating at THz frequencies, which are expensive and difficult to 49 fabricate, make them less desirable [11]. The planar antennas are good candidates to employ at THz systems due 50 to the fact that they integrate with other THz components easily. Also, they are suitable to be fabricated using the 51 micromachining SU-8 multilayer technology which is considered to be one of the most cost-effective techniques 52 [11-15]. Metal-graphene and Metal-assisted chemical etching structures have also been utilized recently in the 53 design of planar components at the THz spectrum [16-18].
- Despite their compactness and good radiation performances, microstrip patch antennas are less desirable applicants to THz systems due to the significant losses [19, 20]. More recently, investigations on achieving high gain and large bandwidth of the periodic reflective surfaces (PRSs) have been conducted at millimeter-wave [21-23] and lower THz frequency bands [24]. Slotted waveguide antennas are high gain antennas which are attractive to THz applications due to their planar structure, low losses, and handling high powers [25-31]. In addition to that, slotted waveguide antennas have structures which are very compatible with the micromachining fabrication Technology [11-13, 32].
- In this paper, we design and fabricate a 300 GHz planar array 8×8 slotted waveguide antenna based on the micromachined SU-8 technology which is available at the University of Birmingham. The array is configured to be built from five SU-8 silver-coated layers. An H-plane bend is designed and embedded with the array in order to facilitate the measurements with the standard waveguide flange WR-03. Fabrication has been made, and the reflection coefficient has been measured. More details follow.

#### 66 2. Antenna Design and Configuration

This section describes the design of the planar array  $8 \times 8$  slotted waveguide antenna operating at centre frequency  $f_0 = 300$  GHz as shown in Fig 1. For clarifications, the outstanding structure in Fig. 1 in the central area shows the hollow radiating waveguides, feeding waveguide, and radiating slots. While the surrounding conductors are set to be transparent.

There are several possibilities to cut the slots in the walls of the rectangular waveguides [33], depending on the desire of the applications [34-36]. In this work, the slots at the centre of the narrow wall of the waveguides are chosen. Because they are more compatible with the micromachined technology [11], which will be utilized in the fabrication of the array as will be discussed later.





76 The slot length  $(S_l)$  and width  $(S_W)$  are determined following the fundamental assumptions of slots on the 77 walls of rectangular waveguide [34], as follows;

$$2\log\left(\frac{\text{Slot length }(S_l)}{\text{Slot width }(S_W)}\right) \gg 1 \tag{1}$$

78 The  $S_l$  and  $S_w$  dimensions are functions to the operating free space wavelength ( $\lambda_0$ ). Where;  $\lambda_0 = c/f_0$ , 79 and c is the speed of the propagation of electromagnetic wave in free space. In order to excite the slots and obtain 80 good radiations, the  $S_l$  needs to be close to  $S_l = 0.464 \lambda_0$ , while the  $S_w = 0.05\lambda_0$  [37]. In this work, these two 81 relationships are taken into account during the design of the proposed  $8\times8$  slots at  $f_0=300$  GHz. Later, the CST 82 genetic algorithm optimisation [38] method is used in order to optimize these two slot dimensions and enhance the 83 reflection coefficient  $(S_{11})$  at 300 GHz. Another parameter, which also needs to be taken into account in the design, 84 is the inter spacing (d) between the slots. The slots here are placed one-guided wavelength ( $d = 1\lambda_q$ ) a part 85 between the centers as shown in Fig. 1. This is to excite all the slots in-phase.  $\lambda_g$  inside the rectangular waveguides 86 is always greater than free space wavelength ( $\lambda_0$ ). It can be calculated, for the dominant mode (TE<sub>10</sub>), as follows 87 [39];

$$\lambda_g = \frac{\lambda_0}{\sqrt{1 - \left(\frac{\lambda_0}{2a}\right)^2}} \tag{2}$$

88 Where *a* is the broad-wall dimension of the waveguide.

According to the antenna array theory principle, the  $1\lambda_g$  is extremely large. It degrades the radiation patterns and yields grating lobes [40]. This has been experienced practically in our previous work [11, 15, 25, 32, 41]. To

- 91 overcome this issue, the slots on a radiating waveguide are altered by  $d_0$  ( $d_0 = 0.5\lambda_g$ ) with the neighbour slots 92 as can be noticed in Fig. 1. By means of this alteration, the *d* value is reduced in the *x*-*y* planes and the grating 93 lobes disappear as will be depicted later. There are 8 radiating waveguides attached to the feeding waveguide, 94 forming 8 T-junctions as highlighted in the enlargement section of Fig. 1. Ridges are introduced at each of the T-95 junctions to achieve matching. The radiating waveguides are short-circuited. This is to yield the same phase 96 between the reflected and incident waves.
- In order to facilitate the measurements, a waveguide bend is integrated with the proposed antenna array. It is seen in Fig. 2 (a) that the bend has three matching ridges in order to be compatible with the configuration of the array. Also, the matching ridges dimensions  $(m_1, m_2, w_1, w_2)$  are optimised so as to obtain a reflection coefficient  $(S_{11})$  from the bend that has negligible impact on the  $S_{11}$  response of the antenna array. The optimised  $S_{11}$  response of the bend is presented in Fig. 2 (b). It can be depicted that the  $S_{11}$  is below -20 dB between 260-
- 102 315 GHz. The physical dimensions of the proposed antenna array and the H-plane bend are summarized in Table
- 103 1.



Figure 2. The H-plane bend embedded to the planar array. (a) the 3D layout of the bend. (b) the solelysimulated response of the bend obtained from CST.

**Table 1.** Dimensions of the proposed THz 8×8 planar array slotted waveguide antenna.

Symbols	Dimensions in mm		
$a \times b$	$0.864 \times 0.432$		
d	1.226		
$l_1 \times l_2$	$9.903 \times 4.723$		
$S_l \times S_w$	$0.578 \times 0.134$		
$d_0$	0.613		
$r_l \times r_w$	$0.131 \times 0.123$		
$b_1$	0.288		
$d_1 \times d_2$	0.307  imes 0.920		
$d_{01} \times d_{02}$	1.014  imes 0.401		
$w_1 \times w_2$	$0.187 \times 0.139$		
$m_1 \times m_2$	0.1  imes 0.9		
	Symbols $a \times b$ $d$ $l_1 \times l_2$ $S_l \times S_w$ $d_0$ $r_l \times r_w$ $b_1$ $d_1 \times d_2$ $d_{01} \times d_{02}$ $w_1 \times w_2$ $m_1 \times m_2$		

- 107 The proposed planar antenna array is simulated using the CST simulator [38] as shown in Fig. 3. The Silver 108 material is chosen in CST to build the antenna because the SU-8 layers is planned to be coated by sliver after the 109 fabrications as discussed in Section 3. The simulated  $S_{11}$ , realised gain, and directivity variations versus the 110 operating frequencies are shown in Fig. 4. It can be seen that there is a very good matching of  $S_{11}$  at  $f_0 = 300$
- 111 GHz. Also, the fractional bandwidth (FBW) is ~1 % at  $S_{11}$ = -10 dB. The peak directivity and realised gain are
- 112 25.2 dBi and 24.6 dBi, and they are very close to each other particularly at  $f_0 = 300$  GHz. This indicates that the 113 antenna is efficient as can be noticed in Fig. 5. The 3-dB gain bandwidth is 4.5 GHz. The radiation patterns for
- antenna is efficient as can be noticed in Fig. 5. The 3-dB gain bandwidth is 4.5 GHz. The radiation patterns for both the E- and H-planes are shown in Fig. 6. They are extremely directive and the main beam is stable from 298-
- 115 302 GHz. The side lobe levels are very low especially in the E-plane, which is less than -22 dB below the main
- beam. This is due to having large radiating area in that plane. The performance of the proposed antenna array is
- 117 summarized in Table 2.



119

Figure 3. The proposed antenna array modeled in CST with the simulated 3D radiation pattern.



120 Figure 4. Variation of the simulated realised gain, directivity, and  $S_{11}$  of the antenna array.



#### 121 Figure 5. Variation of the simulated total efficiency of the antenna array.



122 Figure 6. The Simulated radiation patterns of the proposed antenna array at 298, 300, and 302 GHz 123 respectively. (a) E-plane. (b) H-plane.

 Table 2. Electrical performances of the proposed THz 8×8 planar array slotted waveguide antenna.

Parameters	Frequency	Directivity	Realised	FBW	3 dB	Beam	Side lobe Level
	(GHz)	(dBi)	gain (dBi)	(%)	width (°)		(dB)
Magnitude	300	25.2	24.6	1	E-plane = 13.5 H-plane = 5.1		E-plane = -24.4 H-plane = -13.4

#### 124 3. Fabrication and Measurement

125 The antenna presented here was fabricated using the micromachining SU-8 lithography technique as 126 discussed in [11, 13, 24, 32, 42]. This technique has been chosen due to providing high aspect ratio to form the 127 rectangular waveguide structure and excellent side wall quality [43]. The antenna was configured to be built out 128 of five SU-8 layers with a thickness of 0.288 mm. Only one mask is needed to define all the five SU-8 layers as 129 shown in Fig. 7. Two brass-plates have been designed and utilized to clamp the five layers together and strengthen 130 the device as illustrated in Fig. 8. The designed brass-plates have small influence on the  $S_{11}$  and the realised gain 131 variation versus frequencies as can be noticed in Fig. 9.







Figure 8. 3D view of the proposed 8×8 slotted waveguide antenna with the brass plates and the required
holes labeled for alignment with the waveguide flange WR-03.





136 The SU-8 layer is an ultraviolet sensitive photoresist insulator, which is able to build 3D structure. In the 137 design of a circuit like slotted waveguide antenna, it usually needs to be coated by a conductor. It has been 138 investigated in [12] that the losses in a rectangular waveguide based on an SU-8 sliver coated are very comparable 139 with a solid metal. In this work, five silver coated SU-8 layers is utilized in the design of the antenna array. It 140 should be mentioned that the thickness of the SU-8 layer was originally designed to be 0.432 mm [11]. However, 141 in this work, the thickness has been reduced to 0.288 mm in order to have a better sliver coating of the narrow side 142 walls of the waveguides, slots, and the matching ridges. The fabrication process is comparatively simple, which 143 can be performed following the four steps, as discussed below.

144 First, the thickness of the SU-8 was controlled by the amount of the resist weight. Here, 3.5 gram of SU-8-145 50 was used for each of a 0.288 mm layer thickness. The liquid SU-8 was span coated on a four inches silicon 146 wafer. Then, the edge bead was removed directly. Second, two steps were used for the soft bake. In the first step, 147 the bake was performed for 20 minutes at  $65^{\circ}$ C. In the second step, the bake time was raised to 90 minutes at 148 95°C. Third, the wafer was placed in a mask aligner (Canon PLA501) to expose a 365 nm ultra violet for 2 minutes 149 interval. To eliminate the ultraviolet radiation, the PL360 filter was used. Moreover, to make a strong crosslink 150 but with fewer stress, the post exposure bake was started for 2 minutes at 65°C and then 30 minutes at 95°C. 151 Later, the wafer was left to cool down gradually to room temperature. The Ethylene Carbonate (EC) solvent was 152 used to develop the SU-8 layers and make them more robust. Hard bake was performed eventually for 15 minutes 153 at 150°C. 10 % of the Potassium hydroxide (KOH) solution was used to release the SU-8 layers from the wafer. 154 Finally, the released SU-8 layers were placed in the Cressington 308R evaporator in order to evaporate a 0.2 155 micron-thickness sliver and coat the side-walls of the waveguides and slots. To achieve homogenous coating, the 156 SU-8 layers were tilted in an angle that the sliver evaporation was able to reach and cover the narrow side walls 157 of the waveguides and the slots. It is important to mention here that the skin depth for a block of silver with 158 conductivity of  $(6.3 \times 10^7 \text{ S/m})$  is 291 nm at 300 GHz, which is much smaller than 2 microns. This confirms that 159 the 2 microns silver coating does not introduce significant losses to the proposed antenna array. The five sliver 160 coated SU-8 layers were assembled together with the brass-plates in a very precise manner in order to form the 161 final device as shown in Fig. 10. The precision alignment pins were used to accurately align the device with the 162 waveguide flange WR-03 and facilitate the measurement.



**Figure 10.** Photograph of the fabricated planar array 8×8 slotted waveguide antenna based on the micromachined SU-8 technology. (a) Radiating side. (b) Back side.

165 The  $S_{11}$  parameter was measured in free space using the Agilent N5250-A Vector Network analyzer (VNA) 166 at the University of Birmingham. Before connecting the antenna with the WR-03 extended port, one-port 167 calibration (short-open-load aperture) was carried out. The measurement of the  $S_{11}$  was repeated for four times at 168 the frequencies 220-325 GHz as presented in Fig. 11. It is seen that all the four responses are similar to each other, 169 with some minor differences in the poles fluctuation magnitude. This goes back to the tightness of the screws used 170 during the measurement each time to connect the antenna with the WR-03 extended port, and the insignificant 171 misalignments which may have occurred.



172 **Figure 11.** Measuring four times of  $S_{11}$  of the planar array 8×8 slotted waveguide antenna for validation of 173 the measurement process.

174 On the other hand, there are some obvious differences depicted between the simulated and measured  $S_{11}$ 175 responses. To find the reason, a closer attention was paid to the SU-8 layers using a digital microscope. Then, we 176 have found that the top SU-8 layer has delaminated, as can be noticed from the top view of the actual device shown 177 in Fig. 12. Therefore, the design is modified and re-modeled in the light of the delamination as shown in Fig. 13 178 in order to realize the delamination influence on the  $S_{11}$  response. It should be mentioned that the delamination 179 has created a gap (g) between the top layer and the rest of the design. the g value is very small from both sides of 180 the top SU-8 layer. However, it starts increasing until it reaches to its maximum value (gm) (gm~0.1 mm) at almost 181 at the centre of the top SU-8 layer. This has been validated using the digital microscope. After taking many points 182 into account and trying to make sure the re-modeled design looks like the same as the fabricated one, the antenna 183 is then re-simulated. The re-simulated  $S_{11}$  response is compared with the measured in Fig. 14, and they are now 184 comparable to each other. There are still some inconsistency between the re-simulated  $S_{11}$  response and the 185 measured one. This could be due to the delamination manner, which is not exactly homogenous through the entire 186 top SU-8 layer, while during the re-modeling in the CST we assume that it is homogenous.



189 **Fig. 12**. Visualization of the delaminated SU-8 layer of the planar array 8×8 slotted waveguide antenna.



### 190



Fig. 13. CST model of the antenna design including the top SU-8 delaminated.



193 Fig. 14. Measured  $S_{11}$  of the planar array 8×8 slotted waveguide antenna compared with the simulated 194 including the delamination.

Due to the lack of facilities, the radiation pattern was not measured. However, in order to validate the simulated radiation pattern, a comparison was made with the measured radiation pattern of an 8×8 antenna array waveguide based presented in [44]. It has been concluded that there are very close agreement between the simulated and measured patterns.

199

#### 200 4. Conclusions

201 A micromachined 8×8 slotted waveguide antenna array has been demonstrated at lower THz frequencies. 202 The antenna design was configured to be adapted to the micromachining SU-8 technology using five silver coated 203 SU-8 layers. All the five layers were made out of a single SU-8 wafer. Two brass plates were designed and utilised 204 to ensure the contact between the layers. The impact of the brasses on the antenna radiation performance is 205 negligible. An H-plane bend has been embedded to the design to facilitate the interconnection with the VNA test 206 port. Alignment pins were defined in all the SU-8 layers in order to avoid misalignment. The fabrication of the 207 antenna was made. It was found that the top SU-8 layers were delaminated upwards. To maintain a reliable 208 comparison between measured and simulated results, the antenna is re-modeled in the CST including the modifications occurred due to the delamination. After this, the measured  $S_{11}$  is very comparable with the 209 210 simulation. The proposed antenna has planar structure which could simply be integrated with other components 211 when employing in some indoor wireless systems and sensors. The proposed fabrication process for the antennas 212 operating at THz frequencies is simple and cost-effective.

213

- Funding: This work was supported partially by the U.K. Engineering and Physical Science Research Council
   under Contract EP/H029656/1.
- 216 Conflicts of Interest: The authors declare no conflict of interest.
- 217 Availability of data and material: Not applicable
- 218 **Code availability:** Not applicable
- 219 Author Contribution: Conceptualization: Rashad H. Mahmud, Michael J. Lancaster, and Xiaobang Shang;
- 220 Methodology: Rashad H. Mahmud, Michael J. Lancaster, and Xiaobang Shang; Formal analysis and investigation:
- 221 Yi Wang, Halgurd N. Awl, Idris H. Salih, and Talal Skaik; Writing original draft preparation: Rashad H.
- 222 Mahmud; Writing review and editing: Michael J. Lancaster, Yi Wang, Talal Skaik, Idris H. Salih; Supervision:
- 223 Michael J. Lancaster.
- 224 **Ethics approval:** Not applicable
- 225 **Consent to Participate:** Informed consent was obtained from all authors.

226 **Consent for publication:** The authors confirm that there is informed consent to the publication of the data 227 contained in the article.

#### 229 References

- [1] H. Lu, X. Lv, K. Zhou, and Y. Liu, "Experimental realisation of micromachined terahertz waveguide-fed
  antipodal tapered slot antenna," *Electronics letters*, vol. 50, pp. 615-617, 2014.
- [2] C. Debus and P. H. Bolívar, "Terahertz biosensors based on double split ring arrays," in *Metamaterials III*,
  2008, p. 69870U.
- [3] N. Llombart, K. B. Cooper, R. J. Dengler, T. Bryllert, and P. H. Siegel, "Confocal ellipsoidal reflector system
- for a mechanically scanned active terahertz imager," *IEEE Transactions on Antennas and Propagation*, vol.
  58, pp. 1834-1841, 2010.
- P. H. Siegel, "Terahertz technology in biology and medicine," *IEEE transactions on microwave theory and techniques*, vol. 52, pp. 2438-2447, 2004.
- P. H. Siegel, "THz instruments for space," *IEEE Transactions on Antennas and Propagation*, vol. 55, pp.
  240 2957-2965, 2007.
- [6] S. Galoda and G. Singh, "Fighting terrorism with terahertz," *Ieee Potentials*, vol. 26, pp. 24-29, 2007.
- Y.-S. Lee, *Principles of terahertz science and technology* vol. 170: Springer Science & Business Media,
  243 2009.
- [8] K. R. Jha and G. Singh, *Terahertz planar antennas for next generation communication*: Springer, 2014.
- P. H. Siegel, "Terahertz technology," *IEEE Transactions on microwave theory and techniques*, vol. 50, pp.
  910-928, 2002.
- [10] D. F. Filipovic, S. S. Gearhart, and G. M. Rebeiz, "Double-slot antennas on extended hemispherical and
  elliptical silicon dielectric lenses," *IEEE Transactions on microwave theory and techniques*, vol. 41, pp.
  1738-1749, 1993.
- [11] Y. Wang, M. Ke, M. J. Lancaster, and J. Chen, "Micromachined 300-GHz SU-8-based slotted waveguide
  antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 573-576, 2011.
- [12] X. Shang, M. Ke, Y. Wang, and M. J. Lancaster, "WR-3 band waveguides and filters fabricated using SU8
   photoresist micromachining technology," *IEEE Transactions on Terahertz Science and Technology*, vol. 2,
   pp. 629-637, 2012.
- [13] X. Shang, Y. Tian, M. J. Lancaster, and S. Singh, "A SU8 micromachined WR-1.5 band waveguide filter,"
- *IEEE microwave and wireless components letters*, vol. 23, pp. 300-302, 2013.

- 257 [14] Y. Wang, X. Shang, and M. J. Lancaster, "Micromachined 3D millimeter-wave and terahertz devices," in
- 258 2015 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF

and THz Applications (IMWS-AMP), 2015, pp. 1-3.

- [15] R. Mahmud, T. He, M. Lancaster, Y. Wang, and X. Shang, "Micromachined travelling wave slotted
   waveguide antenna array for beam-scanning applications," in *10th Loughborough Antennas and Propagation Conference, LAPC*, 2014.
- 263 [16] J. Zhang, Q. Hong, J. Zou, Y. He, X. Yuan, Z. Zhu, et al., "Fano-Resonance in Hybrid Metal-Graphene
- 264 Metamaterial and Its Application as Mid-Infrared Plasmonic Sensor," *Micromachines*, vol. 11, p. 268, 2020.
- [17] P. Granitzer, R. Boukherroub, D. J. Lockwood, and H. Masuda, "Pits & Pores 6: Nanomaterials-in Memory
  of Yukio H. Ogata," 2015.
- [18] G. J. Lee, H. M. Kim, and Y. M. Song, "Design and Fabrication of Microscale, Thin-Film Silicon Solid
  Immersion Lenses for Mid-Infrared Application," *Micromachines*, vol. 11, p. 250, 2020.
- [19] S. Sekretarov and D. M. Vavriv, "A wideband slotted waveguide antenna array for SAR systems," *Progress in Electromagnetics Research*, vol. 11, pp. 165-176, 2010.
- [20] K. Sakakibara, J. Hirokawa, M. Ando, and N. Goto, "High-gain and high-efficiency single-layer slotted
  waveguide array for use in 22 GHz band," *Electronics Letters*, vol. 32, pp. 283-284, 1996.
- [21] R. Gardelli, M. Albani, and F. Capolino, "Array thinning by using antennas in a Fabry–Perot cavity for gain
  enhancement," *IEEE Transactions on Antennas and Propagation*, vol. 54, pp. 1979-1990, 2006.
- [22] C. Mateo-Segura, G. Goussetis, and A. P. Feresidis, "Sub-wavelength profile 2-D leaky-wave antennas with
  two periodic layers," *IEEE Transactions on Antennas and Propagation*, vol. 59, pp. 416-424, 2010.
- [23] S. A. Muhammad, R. Sauleau, and H. Legay, "Small-size shielded metallic stacked Fabry–Perot cavity
  antennas with large bandwidth for space applications," *IEEE Transactions on antennas and propagation*,
  vol. 60, pp. 792-802, 2011.
- [24] K. Konstantinidis, A. P. Feresidis, Y. Tian, X. Shang, and M. J. Lancaster, "Micromachined terahertz Fabry–
  Perot cavity highly directive antennas," *IET Microwaves, Antennas & Propagation*, vol. 9, pp. 1436-1443,
  282 2015.
- 283 [25] R. H. Mahmud and M. J. Lancaster, "High-gain and wide-bandwidth filtering planar antenna array-based
- solely on resonators," *IEEE Transactions on Antennas and Propagation*, vol. 65, pp. 2367-2375, 2017.

- [26] H. Guan-Long, Z. Shi-Gang, C. Tan-Huat, and Y. Tat-Soon, "Broadband and high gain waveguide-fed slot
  antenna array in the Ku-band," *IET Microwaves, Antennas & Propagation*, vol. 8, pp. 1041-1046, 2014.
- 287 [27] M. Ando, J. Hirokawa, T. Yamamoto, A. Akiyama, Y. Kimura, and N. Goto, "Novel single-layer waveguides
- for high-efficiency millimeter-wave arrays," *IEEE transactions on microwave theory and techniques*, vol.
  46, pp. 792-799, 1998.
- [28] Y. Kimura, Y. Miura, T. Shirosaki, T. Taniguchi, Y. Kazama, J. Hirokawa, *et al.*, "A low-cost and very
   compact wireless terminal integrated on the back of a waveguide planar array for 26 GHz band fixed wireless
- access (FWA) systems," *IEEE transactions on antennas and propagation*, vol. 53, pp. 2456-2463, 2005.
- [29] J. Hirokawa, M. Zhang, and M. Ando, "94GHz fabrication of a slotted waveguide array antenna by diffusion
  bonding of laminated thin plates," in *SENSORS, 2009 IEEE*, 2009, pp. 907-911.
- [30] J. Hirokawa, M. Ando, N. Goto, N. Takahashi, T. Ojima, and M. Uematsu, "A single-layer slotted leaky
  waveguide array antenna for mobile reception of direct broadcast from satellite," *IEEE transactions on vehicular technology*, vol. 44, pp. 749-755, 1995.
- [31] M. Ando, "Planar waveguide arrays for millimeter wave systems," *IEICE transactions on communications*,
  vol. 93, pp. 2504-2513, 2010.
- R. H. Mahmud, "Synthesis of waveguide antenna arrays using the coupling matrix approach," University of
   Birmingham, 2016.
- 302 [33] R. C. Johnson and H. Jasik, "Antenna engineering handbook," *New York, McGraw-Hill Book Company,*303 1984, 1356 p. No individual items are abstracted in this volume., 1984.
- 304 [34] A. Stevenson, "Theory of slots in rectangular wave-guides," *Journal of Applied physics*, vol. 19, pp. 24-38,
  305 1948.
- 306 [35] R. Stegen, "Slot radiators and arrays at X-band," *Transactions of the IRE Professional Group on Antennas* 307 *and Propagation*, vol. 1, pp. 62-84, 1952.
- 308 [36] A. Oliner, "The impedance properties of narrow radiating slots in the broad face of rectangular waveguide:
   309 Part I--Theory," *IRE Transactions on Antennas and Propagation*, vol. 5, pp. 4-11, 1957.
- 310 [37] R. Elliott and L. Kurtz, "The design of small slot arrays," *IEEE Transactions on Antennas and Propagation*,
- 311 vol. 26, pp. 214-219, 1978.

- 312 [38] C. MWS, "Computer Simulation Technology: Microwave Studio," *Computer Simulation Technology Std*,
  313 2011.
- 314 [39] D. M. Pozar, *Microwave engineering*: John Wiley & Sons, 2009.
- 315 [40] C. A. Balanis, Antenna theory: analysis and design: John wiley & sons, 2016.
- 316 [41] Y. Wang and M. Lancaster, "A micromachined centre-fed slotted waveguide antenna for mm-wave
- 317 applications," in 2012 IEEE MTT-S International Microwave Workshop Series on Millimeter Wave Wireless
- 318 *Technology and Applications*, 2012, pp. 1-3.
- 319 [42] Y. Wang, B. Yang, Y. Tian, R. S. Donnan, and M. J. Lancaster, "Micromachined thick mesh filters for
- millimeter-wave and terahertz applications," *IEEE Transactions on Terahertz Science and Technology*, vol.
  4, pp. 247-253, 2014.
- [43] J. D. Williams and W. Wang, "Study on the postbaking process and the effects on UV lithography of high
  aspect ratio SU-8 microstructures," *Journal of Micro/Nanolithography, MEMS, and MOEMS*, vol. 3, pp. 563569, 2004.
- [44] A. Vosoogh and P.-S. Kildal, "Corporate-fed planar 60-GHz slot array made of three unconnected metal
  layers using AMC pin surface for the gap waveguide," *IEEE Antennas and Wireless Propagation Letters*,
  vol. 15, pp. 1935-1938, 2015.
- 328

329