Phase Gradient Metasurface Radome Offering Beam Angle Translation and Wideband Absorption

Callum J. Hodgkinson, Dimitris E. Anagnostou, Senior Member, IEEE, Symon K. Podilchak, Member, IEEE

Abstract—A novel metasurface radome design is presented which combines the properties of a rasorber as well as a phase gradient metasurface (PGMS). By replacing the traditional frequency selective surface or lossless layer, in a radar absorber (i.e. a rasorber) with a PGMS, a new structure can be realised which provides dual-functionality in terms of both beam pattern control and wideband absorption. In particular, a $60^\circ$ phase gradient metasurface is designed which is composed of six different unit cells (with the same periodicity) while being placed a quarter-wavelength below two lossy (or resistive) layers. By this stack-up configuration, the radome structure supports complimentary beam steering translation whilst providing absorption bands from about 1.3 GHz to 5.5 GHz and 6.1 GHz to beyond 10 GHz. This design, to the best knowledge of the authors, is the first example of a phase gradient metasurface rasorber (PGMSR) and has many interesting applications for future multi-functional radomes. It can also help to reduce the requirements for mechanical steering, antenna beamformers as well as array phase shifting networks.

Index Terms—Radome, PGMS, absorption, beam steering.

I. INTRODUCTION

In recent years, significant efforts have focused on expanding metasurface functionality, with the design motivation to achieve structures that can offer advanced radome features. One of the first studies into this domain was when a frequency selective surface (FSS) was integrated into a Salisbury screen absorber to create the first radome absorber [1], later named rasorber [2]. This combination, which offered absorbing and low loss transmission characteristics, was a great advancement into said domain. These radomes reduce scattering of antennas, which is particularly helpful for narrowband radiators which will be mismatched outside their bandwidth (BW) leading to structure-mode scattering. This also improves upon standard FSS radomes which have the drawback of bistatic scattering.

The initial rasorber structures have been improved over the years by using a Jaumann-type design with multiple resistive layers to provide wideband absorption, polarization insensitivity, and enhanced angular stability [3], [4]. Other works have also researched broader transmission BWs and reduced number of layers [5]–[11]. Advancements in rasorber designs have also led to structures that can: switch between absorber and rasorber modes using PIN diodes [12], [13]; tune the passband by the aid of embedded varactors [3], [14]; and be made reconfigurable using water and graphene [15], [16]. The basic rasorber stack-up, however, has remained generally consistent since its conception, with these structures typically comprised of a passband FSS placed a quarter-wavelength below a resistive sheet of impedance equal to free space [17]. This results in low loss transmission to minimise any antenna or array performance degradation.

Further research into radome technology has also led to the introduction of beam steering metasurfaces [18]–[21]. These surfaces can support beam pattern steering to wider angles, for instance, and therefore can help to minimise the requirements of both mechanical steering and complicated array feeding. Examples of such designs are phase gradient metasurfaces (PGMSs) [21]–[25], which generally consist of a series of unit cells for transmission. These cells also have the same periodicity but vary the transmission phase response. This configuration can achieve a periodically increasing phase gradient for the antenna or array aperture, which can compliment the beam-steering. Moreover, research efforts have led to the creation of domed gradient metasurfaces [18]–[20], the bi-directional PGMS [24], and the reconfigurable PGMS [25], but these structures can have drawbacks in terms of practicality, adaptability and losses. All, however, have modelling approaches that follow the generalised formulation of Snell’s Law [26] to determine the refracted angle.

Following these achievements, a new radome configuration (see Fig. 1) is proposed which can offer both absorbing functionality and translation (or tilting) of the main beam angle. To the best knowledge of the authors, no similar multi-functional radome has been examined previously. The design makes use of a PGMS, but also offers wideband absorption, defining a phase gradient metasurface rasorber (PGMSR).

As further described in this letter, by designing a radome where the typical FSS is replaced by an arrangement of PGMS unit cells, a hybrid structure can be realised. This can result in a low scattering metasurface (MS) which can also improve the steering capabilities of a posteriorly placed antenna or array. This experimentally verified radome is optimised to be low loss and can steer a main broadside beam by about $30^\circ$ at its transmission design frequency of 5.7 GHz. The structure is also shown to translate the steering range of a phased array to wider beam angles and has bands with nearly 75% absorption (or more) from about 1.3 to 5.5 GHz and 6.1 to 10.1 GHz.

II. INDIVIDUAL UNIT CELL DESIGN

To design the proposed radome a phase gradient of $60^\circ$ degrees was selected for the metasurface. To achieve this phase gradient, the individual PGMS unit cells were composed of a square ring with a concentric inner circular plate of varying size, defined by the dimension $CD$ (see Fig. 1 (a)), while maintaining a common periodicity $p$ of 18 mm for all layers. To alter the phase, and maintain periodicity, the inner circular plate diameter ($CD$) was re-sized. Four identical cells were then stacked upon each other using three sheets of Rogers
CuClad 217 (individual thickness of 3.17 mm), to obtain the necessary phase difference between cells. Also, by having this multi-layer PGMS structure, a wideband overlapping resonance could be created that allows for differing phases at a common frequency of high transmission. It should also be mentioned that a phase gradient of 60° was chosen for practical purposes. It allows for a gradual phase change to the incident wave and is divisible into a full period of 360° for a repeatable structure in a finite number of unit cells.

To facilitate the absorption, two resistive layers separated by 12.5 mm air gaps were also placed above the PGMS layers, with each of their unit cells composed of a Jerusalem cross surrounded by a uniform ring (see Fig. 1 (b)). Four tapered dipole arms were then placed around the crosses and loaded with 300-Ω resistors to generate the needed impedance for free-space matching and wideband absorption. These absorbing layers used a Rogers 5880 substrate (0.508 mm thickness).

For the design of these resistive layers, these concentric Jerusalem crosses were selected to obtain a high capacitance within the unit cell. This realised a compact implementation (when compared to the free-space wavelength), while also being of commensurate size to that of the PGMS unit cells. This compact implementation for the lossy layers can assist with angular stability [27], as should the use of multiple resistive layers, creating a Jaumann-like structure as in [3]. Likewise, the tapered dipole arms aim to provide wideband matching and increased absorption. The total cross-sectional view of the complete multi-layer structure; i.e. the PGMSR, is shown in Fig. 1(c) with relevant dimensions in Table I.

<table>
<thead>
<tr>
<th>$d_1$</th>
<th>18 mm</th>
<th>$w_1$</th>
<th>2 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_1$</td>
<td>7.45 mm</td>
<td>$w_2$</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>$l_2$</td>
<td>8.63 mm</td>
<td>$h$</td>
<td>35 mm</td>
</tr>
<tr>
<td>$l_3$</td>
<td>4.68 mm</td>
<td>$l_4$</td>
<td>4.41 mm</td>
</tr>
<tr>
<td>$l_4$</td>
<td>3.19 mm</td>
<td>$CD$</td>
<td>Variable</td>
</tr>
</tbody>
</table>

### III. Simulation Results

Given the above mentioned design approach, the individual PGMSR unit cells, as illustrated in Fig. 1(c), were initially optimised in CST with infinite boundary conditions (all results shown in Figs. 2 and 3). In particular, by simulating the unit cells with varying size, the required dimensions were found to achieve the noted 60° gradient across the complete radome structure.

Figure 2 reports the transmission for the six cells of differing radii. As it can be observed, a common low loss transmission frequency occurs at 5.7 GHz and with a 60° phase difference. It should also be noted that the transmission of the individual cells shows a wide passband centered around 5.7 GHz, but also, a relatively high transmission of about -6 dB even outside said passband. This response for the individual unit cells does not lend itself to an effective rasorber design, since ideally, a narrow passband is required. However, when these six different cells are placed side-by-side, the response becomes more like a FSS (all results not shown). This makes the multi-layer radome structure more suitable for low-loss transmission at the 5.7 GHz design frequency whilst offering a phase gradient, features which can compliment beam steering for an aperture.

To assess the absorption properties for the complete radome, all six cells were then simulated together with periodic boundary conditions to determine the performance of the entire metasurface. This resulted in a high absorption structure with a transmission peak at 5.7 GHz, as observed in Fig. 3. This simulation shows the PGMSR exhibiting absorption bands, of
at least 75%, from 1.23 to 3.46 GHz, 3.61 to 5.47 GHz and beyond 6.1 GHz. In addition, these results are closely replicated (due to cell symmetry) for other TE/TM incident angles and up to 40°. It can also be observed that the lower band is interrupted by a modest decrease of absorption (reduced to about 70%) at 3.5 GHz, and after further investigation, it was realised that this was caused by some multiple reflections within the PGMS layers. Regardless, nearly 75% absorption is still observed over the entire BW, and these findings are competitive when compared to other rasorbers (see Table II).

The result in Fig. 3 confirms that the PGMSR offers absorbing properties as intended, however, this must be accompanied by antenna beam steering studies. Therefore, the capabilities of the radome structure were further simulated using a 9 by 6 unit cell version of the PGMSR which was positioned in the near-field of a 2 × 1 patch array at a distance of 30 mm (as illustrated in Fig. 4). The corresponding far-field simulation results, in Fig. 5 when no phase difference is applied between the elements, show that the PGMSR can steer a 90° (broadside) beam to 61° at 5.7 GHz. This tilted beam also demonstrates a negligible decrease in realised gain (defining minimal structure losses) as well as -7.6 dB sidelobe levels (SLLs) and low cross-polarisation levels (see the simulations, Table III). Other completed studies for this structure also demonstrate that the desired steering functionality and low SLLs are achieved over a transmission BW of at least 60 MHz centered at 5.7 GHz.

To study the capability of the radome structure to translate the angular steering range of an array, the same patch array was phased and placed posteriorly to the PGMSR. The results of these simulations, as reported in Fig. 6 and Table III, demonstrate that when a phase difference is applied to the array elements, and without the PGMSR, the beam can be steered to 71°. With the presence of the PGMSR and the same phased array, however, the beam can be steered to about 43° off-normal (see Fig. 6). Basically, the simulated steered beam angle for the phased array is tilted by an additional 19° (= 71° - 52°, see Table III) when the PGMSR is included.

Additional simulations also demonstrate that the structure can provide steering to antennas that could not do so otherwise. More specifically, a conventional horn antenna was simulated behind the PGMSR, like the array in Fig. 4. The broadside beam was tilted by 29° (similar to result in Fig. 5).

### IV. Measurement Results and Discussions

To further validate the design, the PGMSR structure was manufactured and measured in a calibrated anechoic chamber. To test the functionality of the radome structure, a 2 × 1 patch array was measured with and without the PGMSR cover (see Fig. 4). Figure 5 reports the realised gain patterns for the array, with equal phase applied to the ports. Measurements demonstrate that the beam has been tilted by 28° (= 90° - 62°, see Table III), with a decrease in gain of only 0.6 dB and with low SLLs. Figure 6 also reports the phased array measurements with and without the PGMSR, where the phase difference was created using external delay lines. As can be observed, by the use of the PGMSR, the steered angle (for a similar SLL) has been changed by 19°; i.e. from 70° to 51°.

The PGMSR (with no patch array) was also tested using two far-field reference horns to measure the transmission and reflection, with calibrations performed using a metal plate of the same size to form a short. The corresponding matching and absorption for the upper and lower bands are shown in Figs. 7

### Table II

<table>
<thead>
<tr>
<th>Rasorber</th>
<th>Thickness</th>
<th>Lower Absorption BW</th>
<th>Upper Absorption BW</th>
<th>Beam Steering</th>
</tr>
</thead>
<tbody>
<tr>
<td>[3]</td>
<td>0.12λ₀</td>
<td>1.3 to 4.8 GHz (114.8%)</td>
<td>6.6 to 9.7 GHz (38%)</td>
<td>No</td>
</tr>
<tr>
<td>[8]</td>
<td>0.12λ₀</td>
<td>3.3 to 8.0 GHz (63.2%)</td>
<td>No Band</td>
<td>No</td>
</tr>
<tr>
<td>[9]</td>
<td>0.09λ₀</td>
<td>1.7 to 3.2 GHz (58.8%)</td>
<td>5.1 to 7.0 GHz (31.4%)</td>
<td>No</td>
</tr>
<tr>
<td>[17]</td>
<td>0.13λ₀</td>
<td>2.6 to 5.2 GHz (66.7%)</td>
<td>No Band</td>
<td>No</td>
</tr>
<tr>
<td>Proposed Design</td>
<td>0.14λ₀</td>
<td>1.2 to 5.4 GHz (127.3%)</td>
<td>6.1 to 10.8 GHz (63%)</td>
<td>Yes</td>
</tr>
</tbody>
</table>

λ₀ is the free-space wavelength at the lowest frequency for 75% absorption. *There is a minor dip below 75% absorption for about 0.35 GHz.
and 8, respectively. Measurements are in good agreement with simulations, in that a similar wideband response is shown, with about -10 dB matching, high absorption, and angular stability. In particular, at least 75% absorption was measured from 2.8 to 5.5 GHz and 6.0 to 10.1 GHz, for all angles up to 40°. Further simulations of the fabricated PGMSR confirm that the absorbing properties of the structure minimise monostatic scattering. When compared to a metal plate of the same size, the finite PGMSR reduces the scattering by at least 5 dB from 1.7 to 10.9 GHz, with maximum reduction of 25.6 dB.

The total transmission and absorption could not be measured properly at the transmission band by following standard rassorber measurement procedures, and this is related to the desired refraction of the PGMSR. Regardless, this is not of concern since the transmission features have been validated by realized gain pattern measurements in Figs. 5 and 6 at 5.7 GHz. Also, for consistency with Fig. 8, a common frequency profile was reported in Fig. 7. Simulations and measurements anyway show broadband impedance matching with values of about -10 dB (or less) over the entire operating radome BW.

These measurements demonstrate consistency with the simulations, and some minor differences can be attributed to tolerance issues from the manufacturing. Regardless, there is still general agreement, with very similar beam angles and realised gains being observed. For example, as outlined in Table III, the main broadside beam was tilted from 90° to 61° (in the simulations, for equal phase feeding) and 62° (for the measurements). These findings are also corroborated by the generalised Snell’s Law, more specifically, Eq. 2 as in [24], which calculates that the beam should be positioned at 60.85°. All these results support the conclusion that the capabilities of the PGMSR radome, both wideband absorption and beam translation, have been experimentally demonstrated.

V. CONCLUSION

This letters reports on the design of the first ever PGMSR, which provides both low scattering and complimentary beam steering for antennas and arrays. For example, results suggest that the multi-layer design can tilt a beam from broadside by about 30° and with minimal losses of only 0.6 dB. The radome structure also offers a significant absorption BW with values of about 75% or more. The developed radome can also potentially minimise beamformer, mechanical rotation, and phase shifter requirements whilst reducing the scattering of a phased array placed behind it. Future research can aim to improve the transmission BW, making the MS radome structure curved or conformal, and mitigating broadside insertion loss (as in [19]) which can be reduced by using a non-linear phase profile by following [20]. Further work can also investigate making the layers reconfigurable for tuning performances and possible bi-directional beam-steering with pattern symmetry across the aperture by applying the appropriate phase gradient.

<table>
<thead>
<tr>
<th>Simulations:</th>
<th>Main Lobe Direction</th>
<th>Realized Gain</th>
<th>Side Lobe Level (SLL)</th>
<th>Cross-Pol. at Beam Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array (Equal Phase), No PGMSR</td>
<td>90°</td>
<td>8.8 dBi</td>
<td>-12.2 dB</td>
<td>-47.2 dB</td>
</tr>
<tr>
<td>Phased Patch Array, No PGMSR</td>
<td>71°</td>
<td>6.5 dB</td>
<td>-4.2 dB</td>
<td>-14.5 dB</td>
</tr>
<tr>
<td>Array (Equal Phase), With PGMSR</td>
<td>61°</td>
<td>7.9 dB</td>
<td>-7.6 dB</td>
<td>-25.9 dB</td>
</tr>
<tr>
<td>Phased Patch Array, With PGMSR</td>
<td>53°</td>
<td>6.7 dB</td>
<td>-5.8 dB</td>
<td>-19.3 dB</td>
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<tr>
<td>Measurements:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Array (Equal Phase), No PGMSR</td>
<td>90°</td>
<td>8.9 dB</td>
<td>-17.6 dB</td>
<td>-24.3 dB</td>
</tr>
<tr>
<td>Phased Patch Array, No PGMSR</td>
<td>70°</td>
<td>7.6 dB</td>
<td>-5.9 dB</td>
<td>-19.2 dB</td>
</tr>
<tr>
<td>Array (Equal Phase), With PGMSR</td>
<td>62°</td>
<td>8.3 dB</td>
<td>-9.3 dB</td>
<td>-13 dB</td>
</tr>
<tr>
<td>Phased Patch Array, With PGMSR</td>
<td>51°</td>
<td>7.6 dB</td>
<td>-5.7 dB</td>
<td>-17.8 dB</td>
</tr>
</tbody>
</table>
REFERENCES


