DESIGN OF FLAT LENS USING HUYGENS' METASURFACE

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Abstract

An ultrathin, dual-layer Huygens' transmitarray lens is designed for 10 GHz applications, with a metallic element etched on both sides of a dielectric substrate. Induced EM response between the layers allows the metalens to achieve full 360° phase coverage and transmission amplitude greater than –0.97 dB. The simulated results show a maximum gain of 26.5 dBi at 10 GHz, a 2 dB gain bandwidth from 9.9 GHz to 10.4 GHz (4.57%), and an aperture efficiency of 35.8%. From the measured results, the metalens achieves a 9.8 dB improvement in gain compared to the horn feed, and an estimated total gain of 23 dB. This Huygens' metalens is cheaper and easier to fabricate, offering promising applications in centimetre-wave communication systems.

1. INTRODUCTION

Antenna beamsteering is required for directing signals to specific locations, such as in wireless communications. Conventional curved dielectric lenses utilise differing thickness of the lens medium to produce differential phase delays resulting in converging waves. However, they are heavy and bulky due to the required thickness of the lens, especially at microwave frequencies [1]. Transmitarrays, on the other hand, are planar, lightweight and cheap. A transmitarray lens is a flat phase-shifting surface which focuses electromagnetic radiation from a source antenna, such as a horn antenna, placed a suitable distance away to perform beamsteering or focusing [2]. It consists of an array of unit cell elements with spatial periodicity. Each element is individually designed with patterns of differing sizes or shapes to compensate for the different path lengths from the feed to each element on the planar array and produce corresponding phase delays at each position. This allows the flat transmitarray to replicate the effect of a curved lens [3].

The unit cells usually use microstrip patches, tunable metamaterials or frequency selective surfaces to produce phase shifts. The designs are etched on a copper-covered substrate using Printed Circuit Board (PCB) technology, making it easier and cheaper to fabricate compared to conventional lenses [2]. As the number of layers in each unit cell increases, the transmitarray would be able to produce phase delays of a wider range to better direct the electromagnetic radiation from the source towards a specific direction. However, a key challenge in transmitarray design is that the insertion loss also increases with the number of layers, hence reducing gain. Three layers has been found to be the minimum required to obtain the complete phase coverage and reduce reflection losses, but this does not fully optimise cost and efficiency [4].

In recent years, researchers have proposed metasurfaces as a novel method of shaping the wavefront during wave propagation to achieve functions like beam focusing and beam refraction. Metasurfaces are artificially fabricated sheet materials of sub-wavelength thickness with an array of sub-wavelength elements on the surface of the material. Engineering the array of sub-wavelength elements allows the manipulation of electromagnetic waves between the two sides of the metasurface. This allows the metasurface to achieve the same effect as a regular transmitarray lens made with natural materials, while being thinner and smaller. Compared to traditional volumetric metamaterials, which are three-dimensional artificial materials with properties not found in nature, metasurfaces have the advantage of low loss, easy fabrication and compactness [5]. Metasurfaces have thus gained extensive attention in recent literature.

The metasurface employed in this paper is the Huygens metasurface (HMS). It is based on the Huygens' equivalence principle [6], which states that every point on a wavefront acts as a source of secondary spherical wavelets. By altering the parameters for each subwavelength unit cell, the coupling between the electrical and magnetic dipoles can be taken advantage of to achieve the required phase delays at each point on the metasurface, while maintaining a high transmission amplitude. The Huygens' metasurface can achieve a full 360^o range of transmission phase control despite only being dual-layered, making it cheaper and easier to fabricate as compared to a multi-layered planar lens [7].

In this paper, we propose a double-layer Huygens' metasurface, with both layers using the same design, but laterally inverted. Each unit cell resembles the letter 'E', with three horizontal strips and one vertical strip of varying lengths for each unit cell. The design is adapted from [8] where it was designed to produce three-dimensional helical beams at 5.8 GHz. For our design, it is engineered to operate at 10 GHz by approximately scaling the dimensions of the unit cell in [8]. This design uses only two layers, compared to other 10 GHz transmitarrays which use more layers [9, 10], making it cheaper and simpler to fabricate. The simulated results show a maximum gain of 26.5 dBi at 10 GHz, a 2 dB gain bandwidth from 9.9 GHz to 10.4 GHz (4.57%), and an aperture efficiency of 35.8%.

2. UNIT CELL DESIGN

The configuration of the proposed Huygens' unit is shown in Figure 1. The E-shaped element is designed on the substrate F4B, with permittivity $\varepsilon_r = 2.55$, loss tangent $\tan\delta = 0.002$, and thickness d = 1mm. The periodicity of the unit cell is p = 13 mm (0.433λ at 10 GHz), and the distance of the metal patch to the element boundary is 0.5mm. The metal element is made up of three horizontal strips and one vertical strip on each layer. Since the designs of the top and bottom layers of the cell are inverse, the induced current is in opposite directions on the two layers, forming current loops that produce magnetic fields. Of the three horizontal strips, the top and bottom strips are of length l and thickness b, while the middle strip is of length h and thickness e = 1.5 mm. The vertical strip is of length 12 mm and thickness s = 0.3 mm. By varying parameters b, h and l, the transmission amplitude and phase of the unit cell were tuned to operate at 10 GHz to achieve a phase range of 360^o with transmission amplitudes greater than -1 dB, as shown in Table 1.

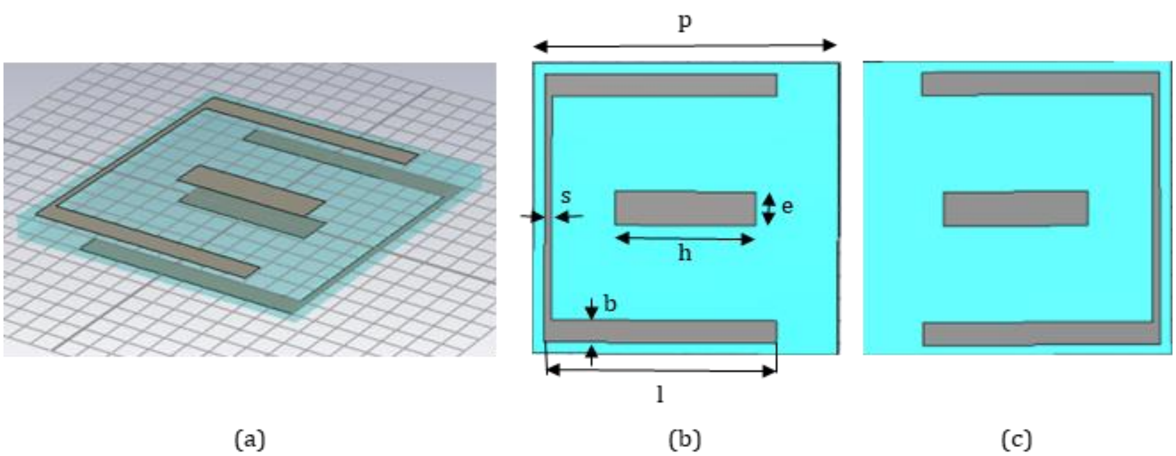
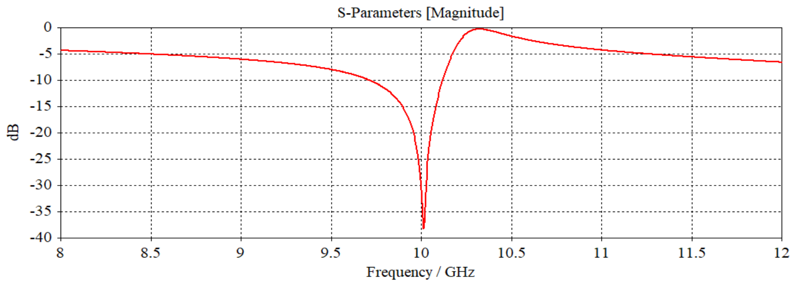


Figure 1. (a) 3D view, (b) top view, and (c) bottom view of the unit cell.

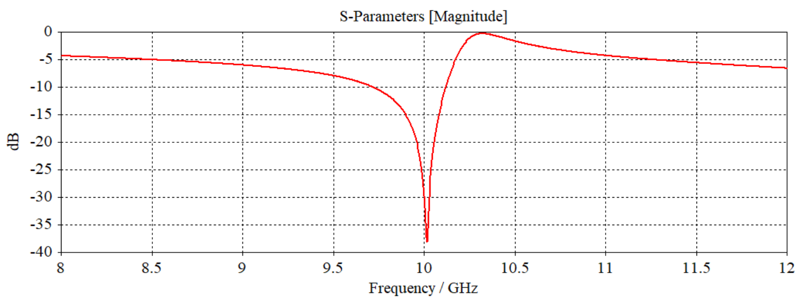
Table 1. Geometrical properties of unit cells for 360º phase range.

b (mm)	*h* (mm)	*l* (mm)	Transmission amplitude (dB)	Transmission phase (º)
2	9.1	9.7	-0.73	0
2.4	9	9.7	-0.66	20
0.5	7.5	9	-0.04	40
0.6	6	9	-0.50	60
0.8	6	10	-0.18	80
1.1	6	10	-0.25	100
1.4	6	10	-0.27	120
1.5	6	10	-0.27	135
1.55	6	10	-0.36	150
1.7	6	10	-0.55	170
2.2	6	10.1	-0.73	180
2.5	6	10.1	-0.75	200
2.3	6	10.05	-0.58	220
2.7	6	10.05	-0.4	235
3.1	6	10.05	-0.37	250
3.7	6	10.05	-0.28	260
3	10.4	10	-0.54	280
3	10.2	9.95	-0.83	300
3	9.8	9.95	-0.97	315
0.95	9.1	9.7	-0.41	335
1.1	9.1	9.7	-0.53	345
2	9.1	9.75	-0.65	360

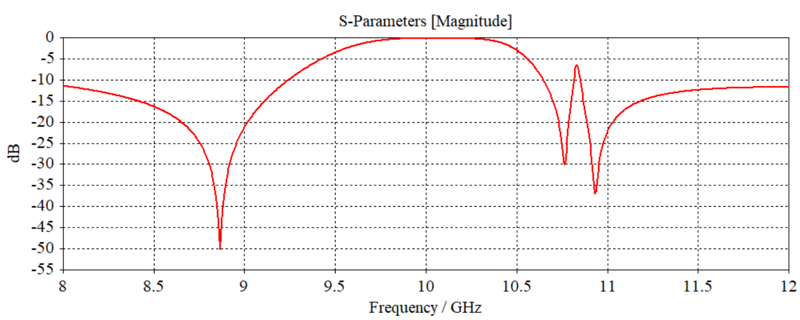
To demonstrate Huygens' resonance, we will first consider the parameters b = 2.65 mm, h = 9 mm, l = 9.7 mm. Commercial software CST Microwave Studio was used to simulate and analyse the EM responses of the unit cell. When only the top patch is used, there is a transmission dip at around 10 GHz (see Figure 2(a)). Similarly, a transmission dip appears at around 10 GHz when only the bottom patch is used (see Figure 2(b)). However, when both layers are put together on the dielectric substrate, a fascinating phenomenon occurs, as shown by a transmission peak from 9.8 GHz to 10.3 GHz, with transmission amplitudes consistently greater than -0.4 dB, as shown in Figure 2(c). This phenomenon is known as Huygens' resonance. The coupling between the top and bottom electric dipoles on the dielectric substrate induces the magnetic dipoles, and the impedance matching between the electric surface admittance (Y_{es}) and magnetic surface impedance (Z_{ms}) causes a resonant transmission effect [1, 7].



(a)



(b)



(c)

Figure 2. Transmission amplitude of (a) top element, (b) bottom element, (c) entire unit cell.

3. TRANSMITARRAY LENS

Appropriate unit cells are arranged in an array to function as a transmitarray metalens. The phase profile φ *(m, n)* of the metalens is calculated from equation (1) to produce a broadside beam [7]

$$\varphi(m,n) = \frac{2\pi}{\lambda}\left(\sqrt{(mp)^2 + (np)^2 + F^2} - F\right) \quad (1)$$

where. φ *(m, n)* is the phase difference between the unit cell at the position (*m*, *n*) on the surface and that at the origin (0, 0), λ is the working wavelength, and *F* is the focal length.

The required phase distribution (refer to Appendix for code) is shown in Figure 3 for a working wavelength of λ = 30 mm (at 10 GHz) and a focal length of *F* = 200.2 mm. The focal length is obtained for an edge taper of –10 dB for a metalens of size 299 × 299 mm^2 (23 × 23 units), corresponding to a focus-to-diameter ratio (F/D) was 0.47.

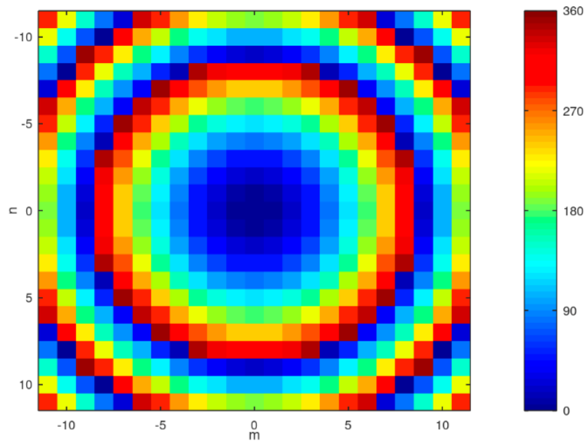
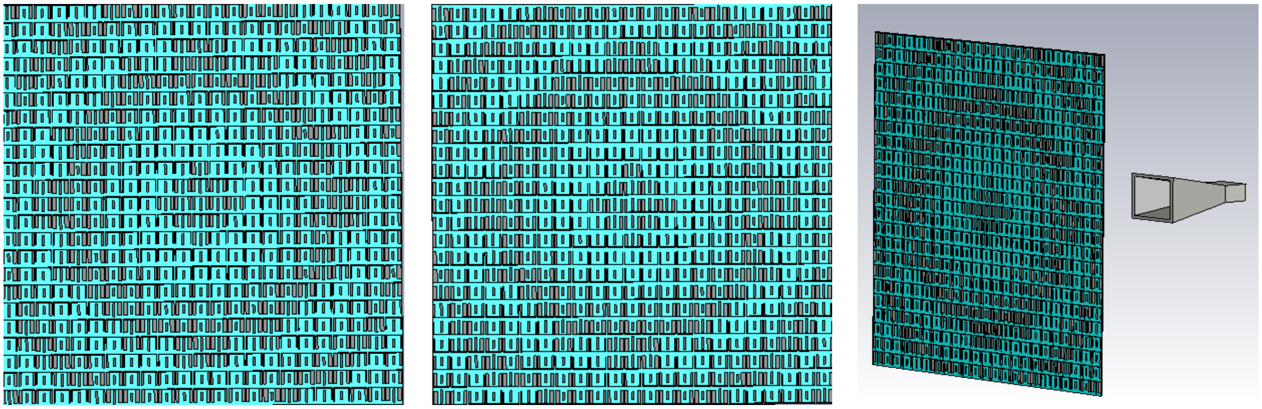


Figure 3. Required phase distribution.

From the phase distribution, the design of the lens was constructed by matching each unit cell to a design that produces the required phase at every point, as shown in Figure 4.



(a) (b) (c)

Figure 4. (a) Top view and (b) bottom view of the metalens; (c) simulated metalens and horn.

The completed metalens was simulated in CST, and the simulated radiation pattern at 10 GHz is given in Figure 5. The maximum realised gain along the E-plane is 26.49 dBi, while the maximum realised gain along the H-plane is 26.44 dBi, corresponding to an aperture efficiency of 35.8%.

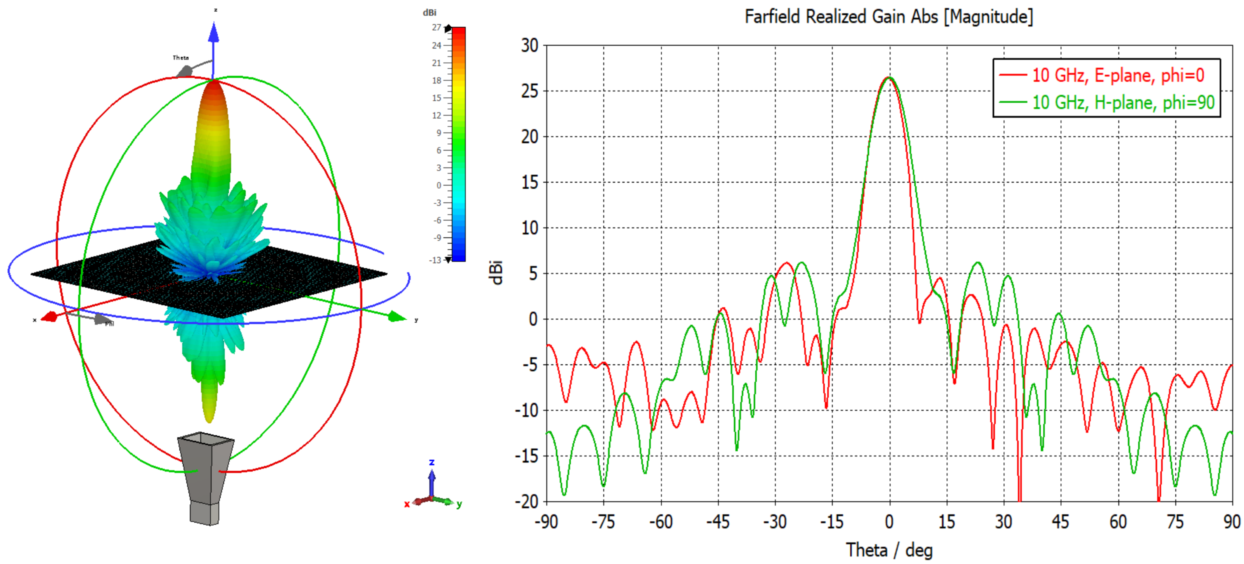
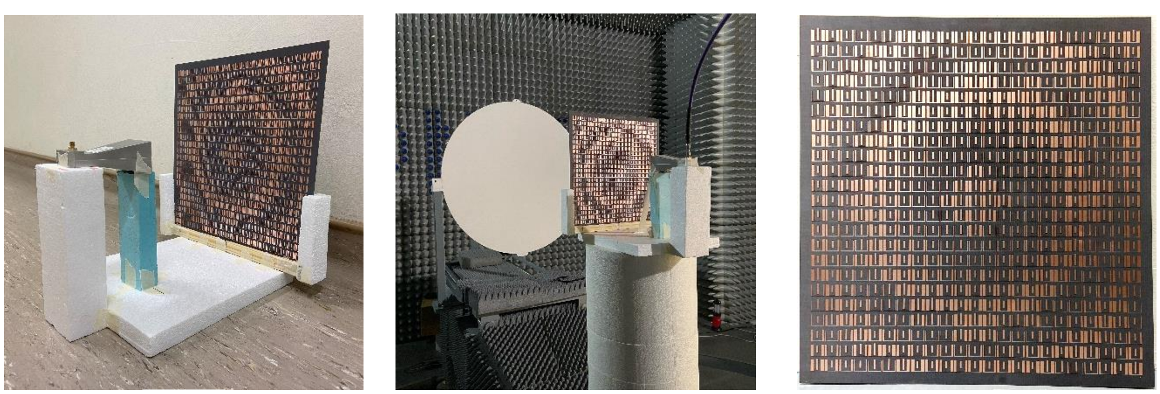


Figure 5. Simulated radiation pattern of metalens.

4. MEASUREMENT RESULTS

The metalens was fabricated using Printed Circuit Board (PCB) fabrication technology, where the copper elements were etched on two sides of a sheet of F4B material 1 mm thickness. The metalens was then measured in a bistatic chamber at TL@NUS as shown in Figure 6. The horn antenna was set at 200.2 mm away from the lens using a supporting structure made of wood and styrofoam and held down by masking tape. It was connected to a Vector Network Analyser (VNA) to measure the power values. A half-lens was used to focus the electromagnetic radiation onto a receive antenna.



(a) (b) (c)

Figure 6. (a) Horn antenna and metalens set up, (b) the metalens set up in the bistatic chamber and (c) the fabricated metalens.

The experiment was then repeated without the metalens and the readings were recorded to measure the gain of the horn antenna. The measured results of the metalens are shown in Figure 7 and Figure 8. Figure 7 compares the measured gain with and without the metalens. The 9.8 dB increase in maximum gain obtained when the metalens was used shows that the lens is able to improve the gain of the horn by almost 10 times. When added to the simulated gain of the horn, the estimated gain of the metalens is around 23 dB. The peak gain was slightly off-centre by -4° due to alignment errors. The maximum gain was also less than the simulated gain of 26.44 dB due to perfect conditions assumed in the simulations and losses due to experimental errors such as misalignment and accuracy of distance measurement. Figure 8 compares the simulated and measured gain of the lens and shows that the measured shape of the main beam corresponds to the simulated results.

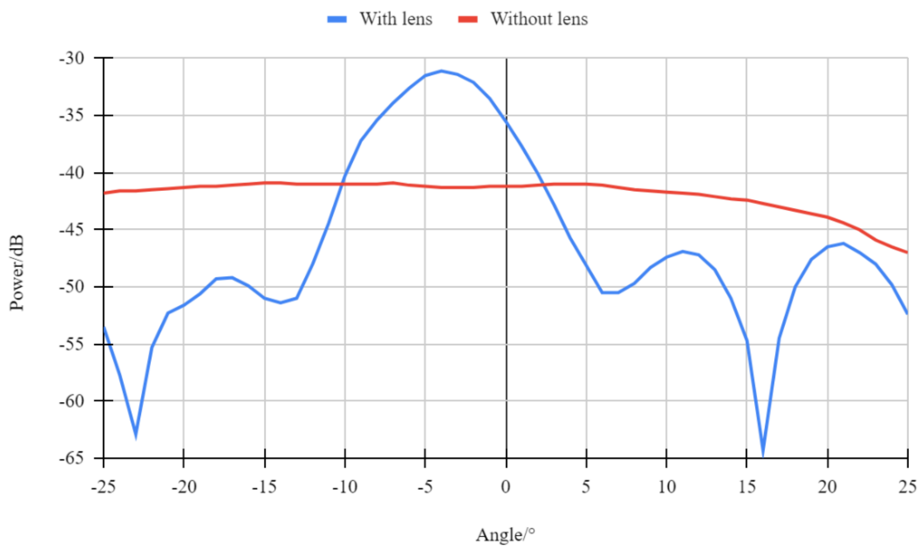


Figure 7. Radiation pattern of horn with and without the metalens.

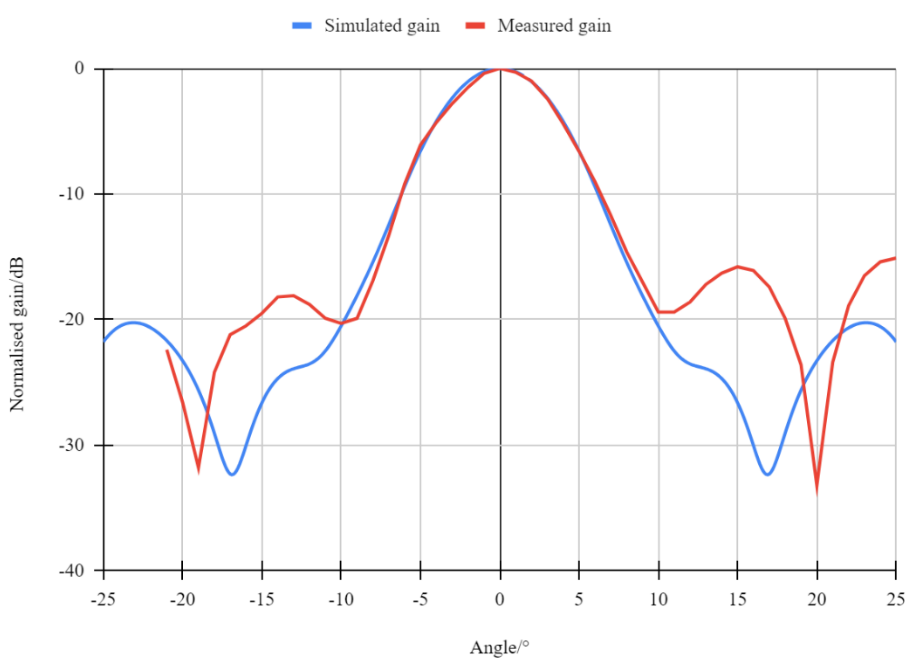


Figure 8. Comparison of normalised measured and simulated radiation patterns.

The simulated bandwidth of the metalens is 0.457 GHz (or 4.57%) for gain of 26.04±1 dB as shown in Figure 9.

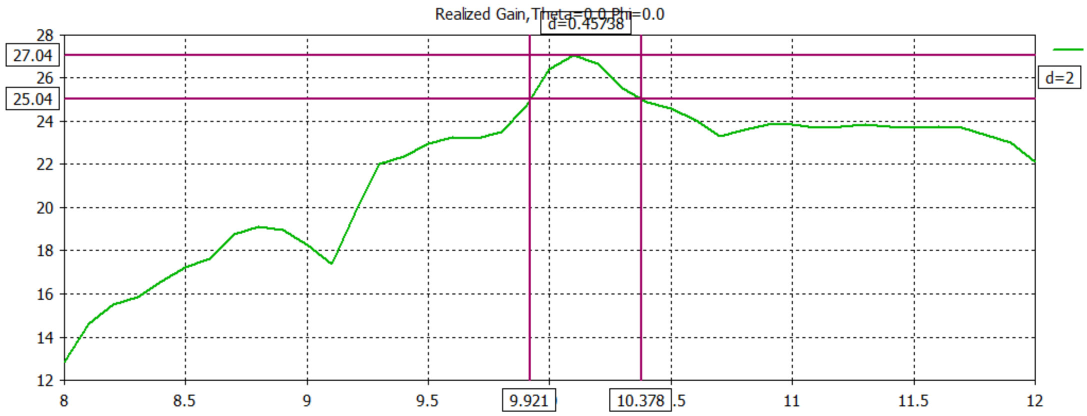


Figure 9. Graph of gain vs. frequency.

5. FURTHER WORK

To determine the optimum focal length, F, which is the distance between the source antenna and the lens that produces the highest efficiency, the illumination and spillover efficiencies can be calculated using the method outlined in [11]. Taking the feed radiation pattern in the E field and H field planes to be $F_E(\theta) = \cos^{q_E}(\theta)$ and $F_H(\theta) = \cos^{q_H}(\theta)$ respectively, $q_E = q_H = 2.60$ was obtained, where the horn is –10 dB below its peak at 36.74°. A graph of efficiency against F/λ was plotted as shown in Figure 10 (refer to Appendix for code).

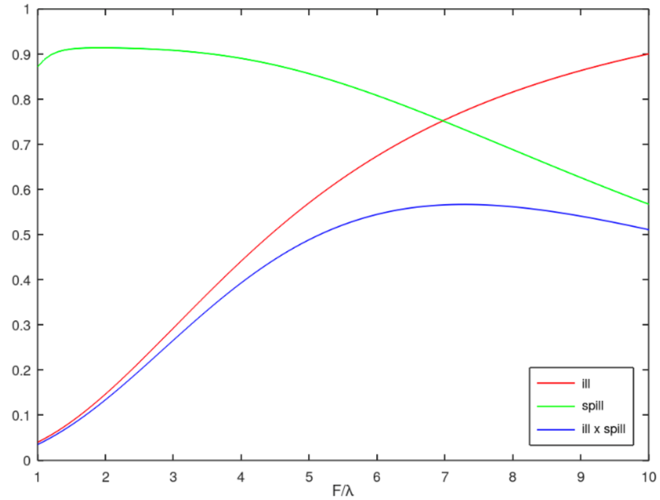


Figure 10. Graph of efficiency against F/λ.

From the graph, the optimum focal length with maximum efficiency (which is the product of the illumination and spillover efficiencies) was 7λ (which equates to 210 mm) with an efficiency of 56.5%. This differs slightly from the focal length used in the above experiments, as the focal length of 200.2 mm was obtained from the –10 dB cut of the horn's simulated radiation pattern, giving an efficiency of 35%. Therefore, the efficiency of the transmitarray can be improved on if the focal length was calculated from the graph.

6. CONCLUSION

In this paper, an ultrathin Huygens' transmitarray lens operating at 10 GHz is proposed, which comprises an E-shaped element on both sides of a dielectric substrate. The unit cells achieved a phase coverage of 360° with a transmission amplitude greater than –0.97 dB. The simulated results show a maximum gain of 26.5 dBi at 10 GHz, a 2 dB gain bandwidth from 9.9 GHz to 10.4 GHz (4.57%), and an aperture efficiency of 35.8%. The Huygens' metasurface was used to design a metalens with only two layers and a simple structure, making it cheaper and easier to fabricate. Measurement shows a 9.8 dB improvement in gain compared to the horn feed. However, the bandwidth is not wide, thus this can be further improved on to expand its function. Nevertheless, we believe that this design can contribute to important applications in high frequency communication.

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APPENDIX

Matlab code for calculation of illumination, spillover & total efficiencies of transmitarray.

```
clear
% define parameters of the feed horn element
qE = qH = 2.60;
kk = 0;
ay = -4.98; by = 4.98;
ax = -4.98; bx = 4.98;
ny = 23; nx = 23;
hy = (by-ay)/(ny);
hx = (bx-ax)/(nx);
ff = 1:0.1:10;
xi = linspace(ax,bx,nx);
yj = linspace(ay,by,ny);

% functions defined according to paper [11]
% power A is the power received by the transmitarray elements and radiated by
the feed, power B is the power radiated by the feed that goes onto the array,
power C is the whole power radiated by the horn into the front hemisphere
% looping through F values from 0 to 10, which is the focal length, the power
values are obtained at each point
for F = ff
  A = 0; B = 0;
  f = @(x,y) (1/sqrt(F^2+x^2+y^2)) * ((F/sqrt(F^2+x^2+y^2))^(qE+2) * (y^2/(x^2+
  y^2)) + (F/sqrt(F^2+x^2+y^2))^(qH+1) * (x^2/(x^2+y^2))); % integral of A
  g = @(x,y) ((F/sqrt(F^2+x^2+y^2))^(2*qE) * (y^2/(x^2+y^2)) + (F/sqrt(F^2+x^2+
  y^2))^(2*qE) * (x^2/(x^2+y^2))) * (F/(sqrt(F^2+x^2+y^2))^3); % integral of B
kk = kk+1;
for i = 1:2:nx
  x = xi(i);
for j = 1:2:ny
  y = yj(j);
AI = f(x-hx,y-hy)+f(x+hx,y-hy)+f(x-hx,y+hy)+f(x+hx,y+hy);
BI = f(x,y-hy)+f(x,y+hy)+f(x-hx,y)+f(x+hx,y);
CI = f(x,y);
A = A + (hx*hy)/9*(AI + 4*BI + 16*CI);
AII = g(x-hx,y-hy)+g(x+hx,y-hy)+g(x-hx,y+hy)+g(x+hx,y+hy);
BII = g(x,y-hy)+g(x,y+hy)+g(x-hx,y)+g(x+hx,y);
CII = g(x,y);
B = B + (hx*hy)/9*(AII + 4*BII + 16*CII);
end
end
ill(kk) = A.*A./((by-ay)*(bx-ax)*B); % calculate illumination efficiency

C = pi * (1/(1+2*qE) + 1/(1+2*qH));

spill(kk) = B./C; % calculate spillover efficiency

illxspill(kk) = ill(kk) * spill(kk); % calculate total efficiency

end

% plot graph of efficiency against focal length
plot(ff,ill,'r',ff,spill,'g',ff,illxspill,'b')
xlabel('F/\lambda')
xlim([1 10])
xticks([1:10])
yticks([0:0.1:1])
legend('ill','spill','ill x spill','Location','southeast')
```

Matlab code for calculation of required phase change of each unit cell.

```
clear
% define parameters of the transmitarray
lambda = 0.03;
p = 0.013;
F = 0.2002;
m = -11:11;
n = -11:11;

[mm,nn] = meshgrid(m,n);
phase_original = rad2deg(((2*pi)/lambda)*(sqrt((mm.*p).^2+(nn.*p).^2+F
^2)-F)); % phase equation
phase = rem(phase_original,360);

% plot phase graph
imagesc(m,n,phase)
colormap jet
colorbar
xlabel('m')
ylabel('n')
caxis([0 360])
cb = colorbar;
set(cb,'YTick',[0 90 180 270 360]);
```