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Analysis and Design of Highly Transparent Meshed Patch Antenna Backed by a Solid Ground Plane

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Abstract—This paper analyzes rectangular and circular patch antennas fabricated from meshed conductors and backed with solid ground planes. Because of the meshing, the antennas are rendered optically transparent, where the transparency is determined by the mesh geometry. It is found that although there is a compromise between the antenna's efficiency and the optical transparency of the meshed patch, it is possible to optimize the antenna by refining mesh lines to certain extent. The limiting factors for refining mesh lines include material handling and fabrication process as well as the increased line impedance when being refined, which accordingly causes loss in antenna's efficiency. A refined mesh with thin linewidth increases both antenna performance and transparency. Additionally, it is found that the reduction of certain mesh lines increases the optical transparency with minimal hindrance to the antenna's efficiency, leading to further enhancement to the see-through percentage. Although it is possible to refine mesh lines to improve the antenna's efficiency or gain, it is seen that there is a limit for such an optimization method. This limit is closer to the efficiency of a solid patch for a lower transparency, whereas it is lower for increased transparency. Cross polarization level was also examined, and there was no significant effect on such a parameter due to meshing.

1. INTRODUCTION

Meshed patch antennas have properties similar to normal microstrip patch antennas [1] while using less metal [2, 3] and being optically transparent [4–6]. Having less metal and hence less heat dissipation and being optically transparent, they find applications in integration with window glass [2] and solar cells [4]. Other methods to design planar transparent antennas, such as using silver coated polyester (AgHT) [7] and indium tin oxides (ITO) films [8–10], were reported. But the optical transparency of those antennas is not high enough for applications such as solar cell integration, especially at lower GHz frequencies. Although Clasen and Langley presented a comprehensive study on meshed patch antennas with solid and meshed ground plane, it only considered mesh lines with fixed linewidth [1]. Other studies on meshed antennas did not capture the effect of linewidth on the antenna functionalities [2, 11]. As will be shown in this paper, the width of the mesh lines is an important design parameter, and it is practical to easily create different mesh geometries using conductive ink. This paper aims to present a design guideline of highly transparent meshed antennas that have the potential to be integrated on top of solar cells. The majority of this study is through experiments. The operational frequencies used in these experiments are around 2.2 GHz for rectangular meshed antennas and 2.5 GHz for circular meshed antennas. But the design principle is also valid for higher frequencies.

2. MESHED PATCH ANTENNA TOPOLOGY

The mechanism of a transparent meshed patch antenna is relatively straightforward, where the optical signals can transmit through the openings of the mesh while the conductor still acts as a valid radiator

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at microwave frequencies. This, of course, requires that the design have enough mesh lines to prevent significant leakage of microwave signals.

Although meshed patch antennas find applications in many areas [2, 11], the main interest of this study is to provide a transparent antenna design to be integrated with the solar panels of Cube Satellites (CubeSats) in order to save very limited surface real estate [12, 13]. Typically, the solar panel of a CubeSat has a solid metal backing (i.e., metallic shielding of the satellite), as illustrated in Fig. 1. This metal plane can serve as the ground plane for the antenna whereas the photovoltaic layers and solar cell cover glass can serve as the substrate for the antenna. Due to this solar panel application focus, this paper only studies the meshed antenna backed by a solid ground plane. It is noteworthy that Yekan and Baktur have quantified the effects between solar cells and integrated antennas [12, 13] by looking at both solid patch and meshed patch. Yet, since the scope of the study was to understand the interaction between the photovoltaic and electromagnetic components, optimized design for the mesh antenna was not performed as focused in their papers.

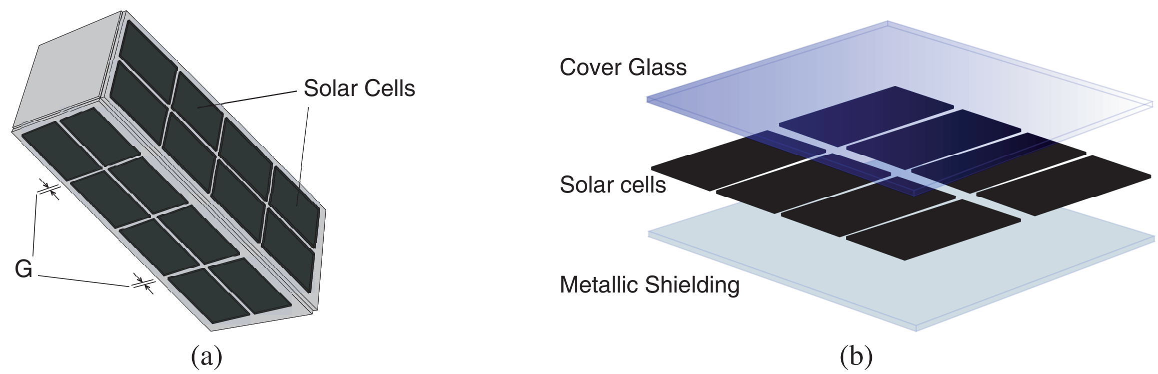


Figure 1. Solar panel of a CubeSat: (a) isometric view of a CubeSat; (b) solar panel structure.

The mesh patterns can be designed following the guidelines presented in [3], where the mesh geometry of the antenna should follow the current paths of a certain radiation mode. This ensures not only predictable antenna properties but also suppression of undesired radiation modes. Thus, this paper focuses on rectangular and circular meshed patches that primarily radiate in the fundamental mode, as shown in Fig. 2, given their relatively simple mesh patterns. It can be seen that a meshed patch antenna consists of two sets of mesh lines. The first set of lines are responsible for carrying the desired currents whereas the second set are orthogonal to the current path lines to form a patch.

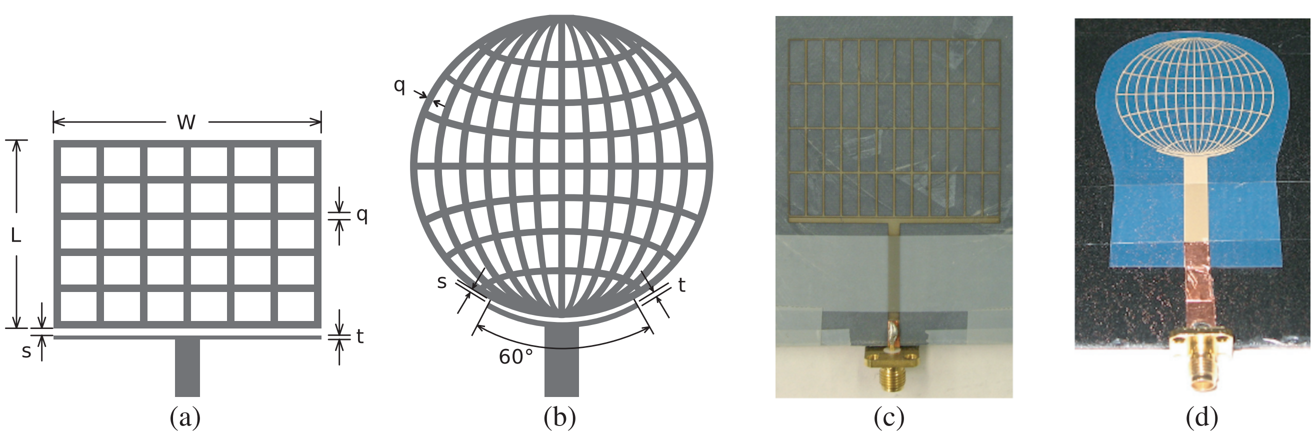


Figure 2. T-coupled meshed patch antennas: (a) rectangular design; (b) circular design; (c) rectangular prototype; (d) circular prototype.

The optical transparency of such meshed patches is defined as the percentage of the see-through area of the patch. For example, the formula to calculate the transparency (T_{rect}) of a rectangular meshed patch which has dimensions of W (width) by L (length) is as follows:

$$\begin{aligned} T_{rect} &= \left(1 - \frac{A_{conductor}}{A_{patch}}\right) \\ &= \left[\frac{L \cdot W - q(M \cdot L + N \cdot W) + q^2 \cdot M \cdot N}{L \cdot W}\right] \cdot 100\%, \end{aligned} \tag{1}$$

where M is the number of lines parallel to the length of the patch, N the number of lines orthogonal to the length of the patch, and the uniform mesh line thickness is q (Fig. 2(a)). The calculation of a circular meshed patch (Fig. 2(b)) cannot be achieved directly using a simple mathematical equation due to irregular curves involved in the mesh geometry. However, this challenge can be overcome by utilizing basic image processing functions in Matlab. The digital image of a circular meshed patch can be analyzed to calculate the transparency (T_{circ}) with the following equation:

$$T_{circ} = \left(1 - \frac{N_{pixel}^{cond}}{N_{pixel}^{patch}}\right) \cdot 100\%, \tag{2}$$

where N_{pixel}^{cond} and N_{pixel}^{patch} are, respectively, the numbers of pixels in the conductor area and in the entire circular patch area.

As the targeted potential application of the meshed antennas in this study is solar cell integration, it is important to choose a practical feeding method. Most common feed designs [14] would require either drilling holes through solar cells or altering the antenna geometry. Therefore, we chose to apply a proximity coupling method [15–17], as illustrated in Fig. 2, where a T-shaped coupling line parallel to the periphery of the mesh is employed to excite the antenna. This feeding method potentially provides two degrees of freedom for tuning: the branch thickness (t) and the spacing (s) as marked for both rectangular and circular meshed patches in Fig. 2. Although the angle of the arch that is formed by the two branches can be the third parameter for impedance matching in the case of circular meshed patches, it was found that the optimal coupling performance can be achieved when it is 60° [15]. Other benefits of this feeding technique include low insertion loss in dual-port application [17] and improved gain and bandwidth [18]. While it is true that such a feed line may decrease the overall transparency of the antenna, the thick microstrip line can be placed on top of the cover glass above one of the gaps (G in Fig. 1(a)) between solar cells, leaving the thinner branches of the T-shaped line to be the only decreasing factor in the transparency. In this manner, such decrease is manageable and can be overcome by improving the transparency of the meshed patch.

3. RECTANGULAR MESHED PATCH ANTENNAS

It has been reported that the resonant frequency, gain, and efficiency of a meshed patch antenna decrease when transparency of the antenna is increased [2, 3]. This means that one has to compromise the optical transparency and the efficiency of a meshed patch antenna. Clasen also pointed out that the input impedance of a meshed patch antenna becomes higher as its transparency increases, making it more challenging for impedance matching. These previously published studies, however, did not consider the effect of the linewidth on the antenna performance. Instead, these earlier studies varied the transparency by changing the number of lines while keeping the linewidth as a constant value. It is clear from Eq. (1) that one may achieve a more transparent antenna with very thin mesh lines, and therefore it is important to understand how the linewidth (q) affects the radiation properties of a meshed antenna.

A typical method in performing a parametric study on an antenna is through simulation followed by an experimental verification. This process has its advantage of reducing unnecessary time and effort in testing ineffective prototypes. However, we deemed it necessary in our approach to conduct experimental studies for two reasons: 1) we have developed a fast and low-cost antenna prototyping method by printing with conductive ink [19]; 2) the parameters to be studied are limited and relatively simple, and therefore one may skip the step of simulation. The experimental studies were set up to examine how the linewidth of the meshes affects the antenna's performance. Two types of printing methods were used. The first type was screen printing with conductive ink. In this case, the antennas were printed directly on a plexiglass substrate. The second type was inkjet printing, where the conductive ink was printed on thin transparencies and the transparencies were assembled on the plexiglass.

3.1. Experiments with Screen Printed Probe Fed Meshed Patch Antennas

A set of four rectangular meshed patch antennas with the same optical transparency of 70% but different linewidths were screen printed onto plexiglass ($\epsilon_r = 2.6$, $\tan\delta = 0.0057$, $h = 2.032$ mm) using a silver based conductive ink (124-46 by Creative Materials). The substrate (approximately 130 mm by 150 mm) was backed with copper tape to act as the ground plane of the antenna. The antennas have identical dimensions of 45 mm by 37 mm and were excited with a coaxial probe. The linewidth (q) was varied from 0.3 mm to 1.5 mm. It should be noted that the number of lines (M and N) were also adjusted in order to maintain a constant optical transparency.

The measured results are presented in Figs. 3, 4 and 5, where it is evident that the antenna radiation properties are improved with the reduced linewidth. It is seen from Fig. 3 that for a given transparency, the resonant frequency of a meshed patch approaches that of the solid patch of the same size as one refines the linewidth. Table 1 presents the inset distance of the probe of the antenna, and it shows that the input impedance of a meshed patch antenna becomes lower and approaches that of the solid patch of the same size as the mesh lines become thinner. The abnormality of the first data point from $q = 0.3$ mm is most likely due to the loss rising from the inaccurate manufacturing process of screen printing. The printing technique pursued in those tests was not precise, and it was challenging to maintain smooth printed lines, especially when the lines were very thin. It is well known that non-smooth conductive lines are very lossy due to diffraction. Therefore, the loss factor due to non-smooth lines might have offset the improvement in the efficiency by refining lines.

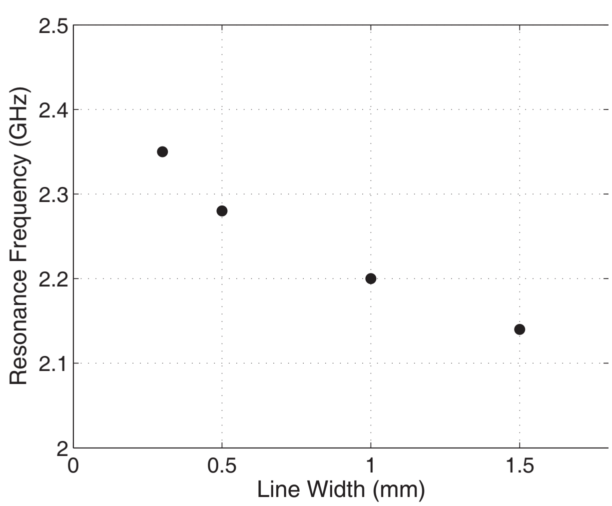


Figure 3. Effect of linewidth on resonant frequency of rectangular meshed patch ($T_{rect} = 70\%$).

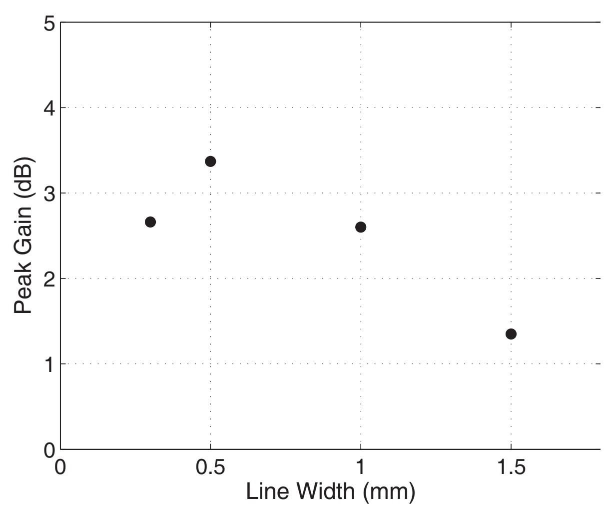


Figure 4. Effect of linewidth on peak gain of rectangular meshed patch ($T_{rect} = 70\%$).

3.2. Experiments with Inkjet Printed Proximity Fed Meshed Patch Antennas

On a solid patch antenna, the current distribution of the fundamental mode is from one radiating edge to the other with higher density at the two non-radiating edges than in the center of the patch [1]. On a meshed patch antenna, the currents were distributed over the mesh lines that are parallel to the non-radiating edges of the patch [1]. We call these lines current path lines. The number of these lines is denoted as M in Equation (1). It can be predicted that the more current path lines are in a meshed

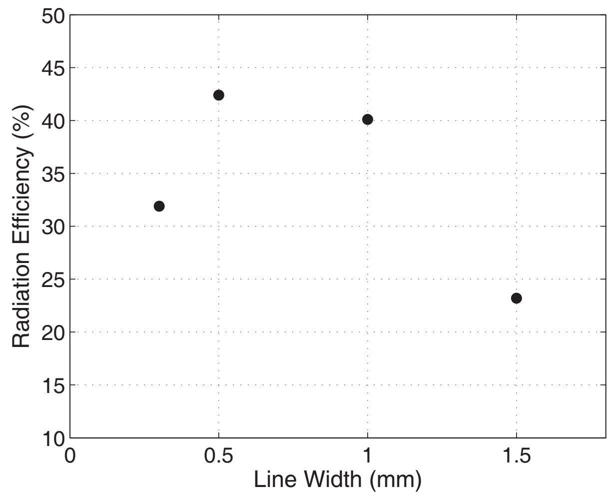


Figure 5. Effect of linewidth on radiation efficiency of rectangular meshed patch ($T_{rect} = 70\%$).

Table 1. Feed point insert distance v.s. linewidth of rectangular meshed patches (45 mm by 37 mm).

Antenna	q (mm)	M	N	d (mm)
A	0.3	24	20	7.1
B	0.5	14	12	6.3
C	1.0	7	6	8.2
D	1.5	5	4	11.0

patch, the better radiation property of the antenna can be achieved. Through this, a mesh can come to have closer resemblance to a solid patch in terms of current distribution.

One straightforward method to achieve more current path lines without sacrificing optical transparency is to refine mesh lines. In order to verify the prediction of more refined current path lines yielding a more effective antenna, and to overcome a precision in prototyping, four meshed patch antennas were prototyped using inkjet printing method that yields much smoother lines. Four rectangular meshed patches (45.6 mm by 38.6 mm) with a fixed number (N) of lines orthogonal to the current path lines were inkjet printed using the nanosilver aqueous dispersive conductive ink (Metalon JS-B25P by Novacentrix) on a thin polyethylene terephthalate (PET) film. The meshes were then assembled onto the same plexiglass substrate as in 3.1. The number of the current path lines and the linewidth were varied to maintain the transparency in the vicinity of 70%. The linewidth of the current path lines and the orthogonal ones remained the same. The details of the geometries of these antennas are provided in Table 2. The antennas were excited using the proximity T-coupling line (Fig. 2(a)), in which the length of the T-coupling line is the same as the width of the antenna. The two parameters t and s were chosen to be 1 mm and 0.6 mm to achieve a good impedance matching.

Table 2. Geometry of inkjet printed rectangular meshed patch antennas (45.6 mm by 38.6 mm).

Antenna	q (mm)	M	N	T_{rect} (%)
A	0.4	18	9	76
B	0.5	14	9	74
C	0.6	12	9	72
D	0.7	10	9	71

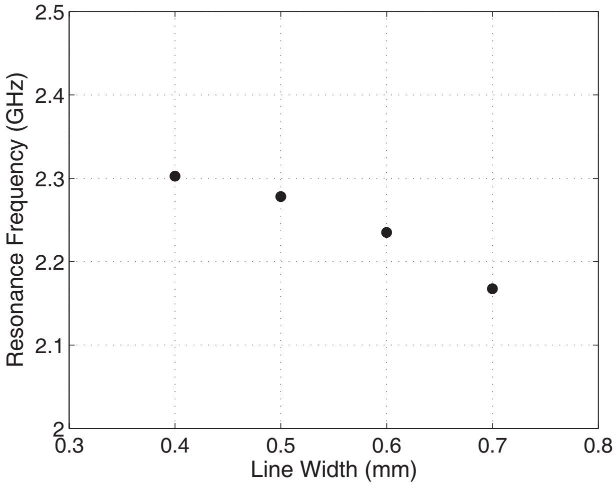


Figure 6. Effect of current path lines on resonant frequency of rectangular meshed patch ($T_{rect} \approx 70\%$).

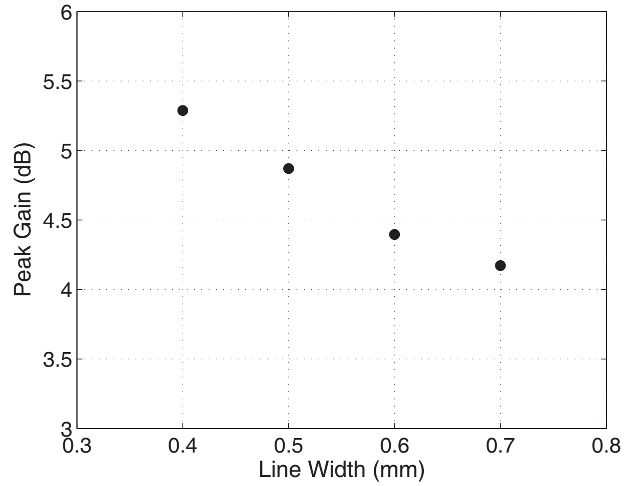


Figure 7. Effect of current path lines on peak gain of rectangular meshed patch ($T_{rect} \approx 70\%$).

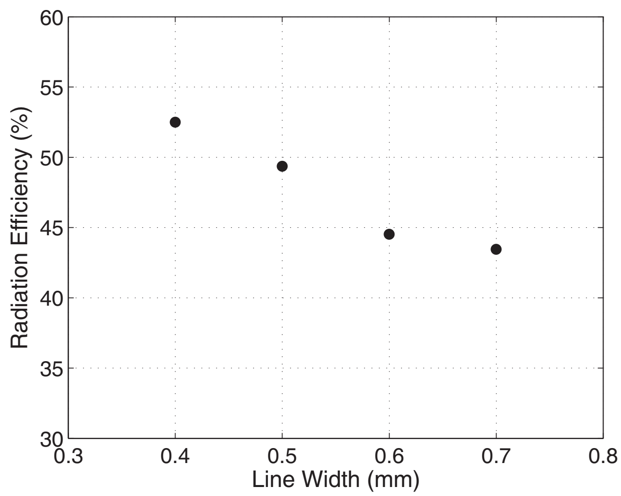


Figure 8. Effect of current path lines on radiation efficiency of rectangular meshed patch ($T_{rect} \approx 70\%$).

The measurements of resonance frequency, gain, and radiation efficiency are plotted in Figs. 6, 7, and 8. It can be observed that, for a given transparency, all those parameters can be improved by refining the mesh lines. Thinner mesh lines give rise to more current path lines and hence a more effective antenna. In fact, it is seen that the transparency of the patch with the thinner lines are higher than those with thicker lines. This further confirms the conclusion that it is possible to obtain an effective antenna with higher transparency by refining its mesh lines.

The radiation patterns of a solid rectangular patch and two of the 70% transparent rectangular meshed patches are plotted in Figs. 9, 10, and 11, respectively. Although meshing a solid patch shifts the resonant frequency, the radiation pattern stays similar to that of the solid patch. This is the case unless there are very few mesh lines, which does not happen when one refines mesh lines at a fixed transparency for better performance because the number of the lines is increased accordingly. It can also be seen that for a fixed transparency, refining the mesh lines does not degrade the cross polarization level. Overall, the cross polarization level for meshed patch antennas is not significantly worse than solid patch antennas. Therefore, one does not need to be concerned with the trade-off between transparency and cross polarization level.

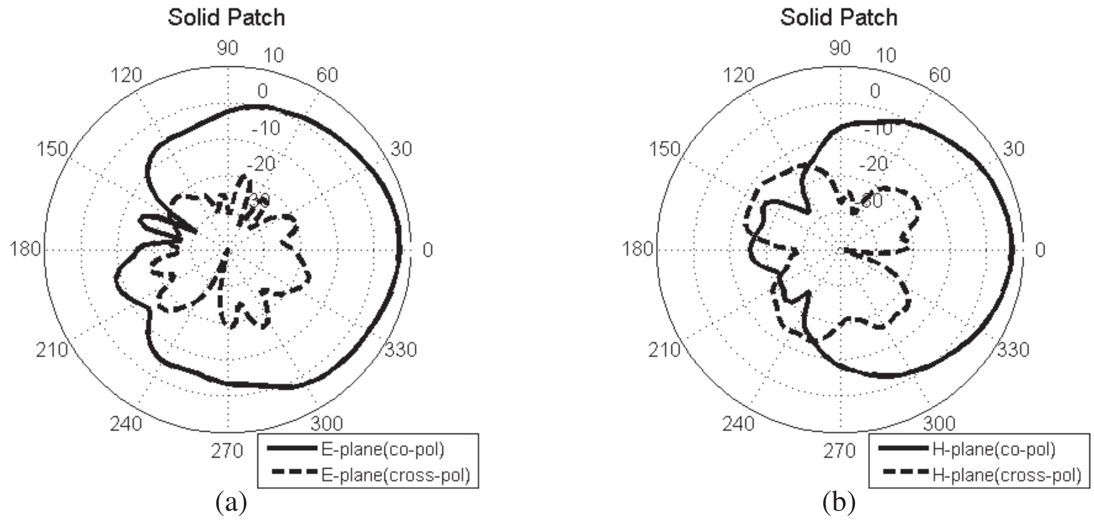


Figure 9. Radiation pattern of solid patch: (a) E-plane; (b) H-plane.

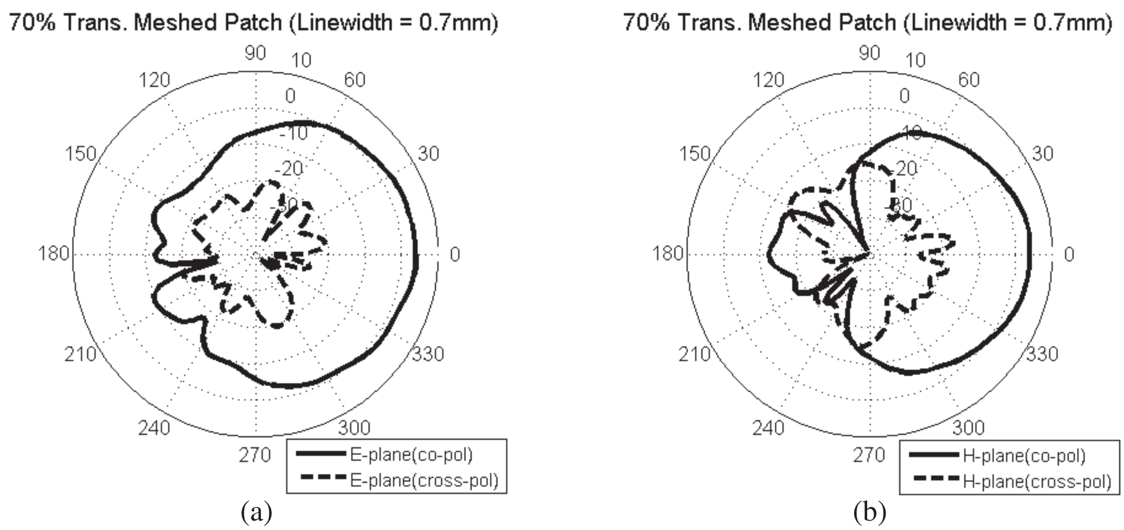
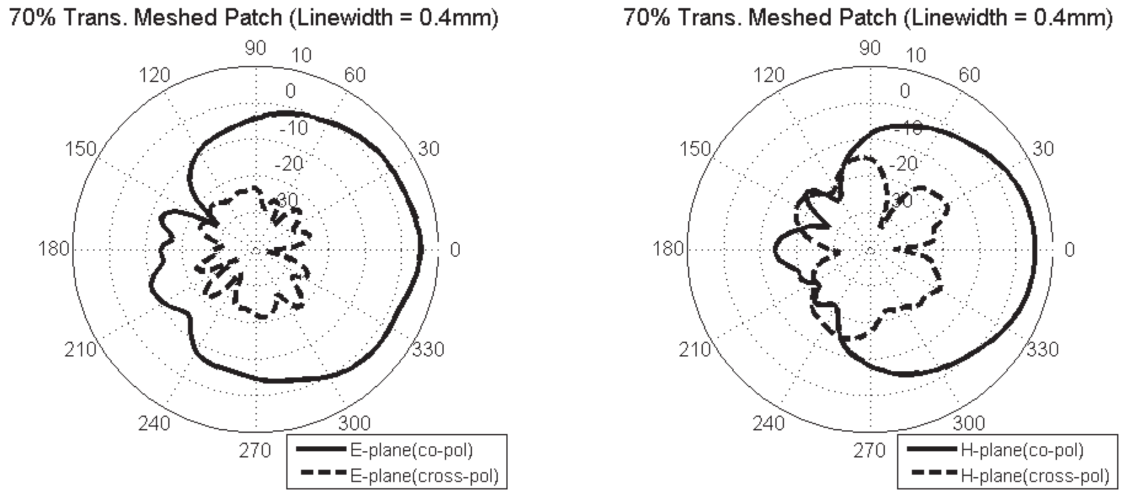


Figure 10. Radiation pattern of meshed patch ($T_{rect} = 70\%$; $q = 0.7$ mm): (a) E-plane; (b) H-plane.

3.3. Effect of Orthogonal Lines

The discussion and results in Subsection 3.2 show that a meshed antenna with more current path lines yields a higher efficiency. Previous research has also suggested a similar claim that the current path lines are more important than the horizontal lines [6]. This suggests that reducing the number of orthogonal lines may not affect antenna properties and that one can achieve extra optical transparency by eliminating some of those lines.

A simulation study using Ansys's High Frequency Structure Simulator (HFSS) was performed to verify the effect of the horizontal lines. The meshed antenna under study has a fixed width and length of 45 mm and 37 mm, and the substrate was the same Plexiglas material as in the previous two studies. The mesh geometry consists of 25 current path lines, and the number of orthogonal lines was varied from 20 to 6 while the linewidth was fixed as 0.3 mm; consequently, the optical transparency ranged from 70% to 79%. The efficiency of these antennas is listed in Table 3. It is observed that reducing the horizontal lines to a certain degree does not affect the antenna's performance significantly. On the contrary, Table 3 suggests reducing horizontal lines yields slightly increased antenna efficiency. This



(a) (b)

Figure 11. Radiation pattern of meshed patch ($T_{rect} = 70\%$; $q = 0.4$ mm): (a) E-plane; (b) H-plane.

Table 3. Effect of orthogonal lines on antenna properties of rectangular meshed patches (45 mm × 37 mm).

Mesh Geometry	q (mm)	T_{rect} (%)	F_r (GHz)	*Eff*. (%)
25 by 20	0.3	69.8	2.32	72.2
25 by 16	0.3	72.5	2.33	72.9
25 by 12	0.3	75.2	2.36	73.1
25 by 8	0.3	78	2.4	73.6
25 by 6	0.3	79.3	2.38	73.7

can be explained through checking the resonant frequency (F_r in Table 3). It is seen that F_r is lower for meshed patches with more horizontal lines. This is because when there are more horizontal lines, there are more possible current paths generated by meandering through vertical and horizontal lines. These meander paths are longer than vertical lines and therefore give rise to lower resonant frequencies. At the same time, longer lines mean higher resistance, and therefore lower efficiency. This study therefore suggests another method to optimize a meshed antenna's optical transparency without sacrificing its efficiency.

We have also noticed that keeping horizontal lines to a minimum instead of fully eliminating them as in some studies [1] helps to maintain good antenna pattern and efficiency. In the case of this particular study in Table 3, the antenna's properties start to be unstable after reducing horizontal lines to less than 6.

3.4. Effect of Meshing

The experiments in Subsections 3.1 and 3.2 showed that the gain and efficiency of a meshed patch antenna can be improved by refining the linewidth for a given transparency. It may give one an impression that it is possible to achieve a meshed antenna as effective as the solid patch without meshing as long as one keeps the linewidth very thin. This would in fact be true if the mesh material was a perfect electric conductor. For a normal conductor such as copper, however, there is a gain loss due to meshing. In addition, when the mesh lines are as thin as the order of the microwave skin depth, the lines will exhibit high loss that will further reduce the antenna's gain.

Using the optimization method discussed earlier, four meshed copper antennas with the same patch size but different transparencies were designed on the substrate ($\epsilon_r = 2.6$, $\tan\delta = 0.002$, $h = 2.032$ mm) backed with solid copper plane to act as the ground. They were then simulated and compared against their solid counterpart using HFSS. The purpose of this study was to examine the meshing effect on the gain of copper patch antennas. The simulation results are listed in Table 4, where it can be seen that the gain loss of the antenna due to meshing is close to 2.5 dB for the 95% transparent meshed patch and that such loss decreases with a reduced transparency. Therefore, it can be concluded that meshing itself in the practical design of meshed patch antennas results in an inevitable loss that depends on the patch transparency. This loss becomes more obvious when the transparency is higher.

Table 4. Effect of meshing on the gain of rectangular meshed copper patch (45 mm by 37 mm).

$G_{0,\text{solid}}$ (dB)	7.32			
T_{rect} (%)	70	80	90	95
Linewidth q (mm)	0.133	0.136	0.100	0.100
$G_{0,\text{meshed}}$ (dB)	6.52	6.08	5.25	4.90
$G_{0,\text{meshed}} - G_{0,\text{solid}}$ (dB)	−0.80	−1.24	−2.07	−2.42

4. INKJET PRINTED CIRCULAR MESHED PATCHES

Circular meshed patch antennas are of the same importance as the rectangular ones. When designing circular meshed patches, the mesh geometry needs to be such that they support the current patterns of the desired resonant mode [3]. Consequently a circular meshed antenna that supports the fundamental mode has a mesh pattern as shown in Fig. 2(b). It is found that simulating a circular meshed antenna with refined linewidth takes a substantial amount of time and memory of a moderate personal computer, whereas direct prototyping using inkjet printing is much faster, cheaper, and easier. Therefore, the following studies on the circular meshed antennas were conducted through experiments.

4.1. Tradeoff between the Optical Transparency and Radiation Properties of a Circular Meshed Patch Antenna with Fixed Linewidth

Six circular meshed patches of the same linewidth but different line numbers were inkjet printed on PET films and then assembled onto the same plexiglass substrate that was used for the study in Section 3.

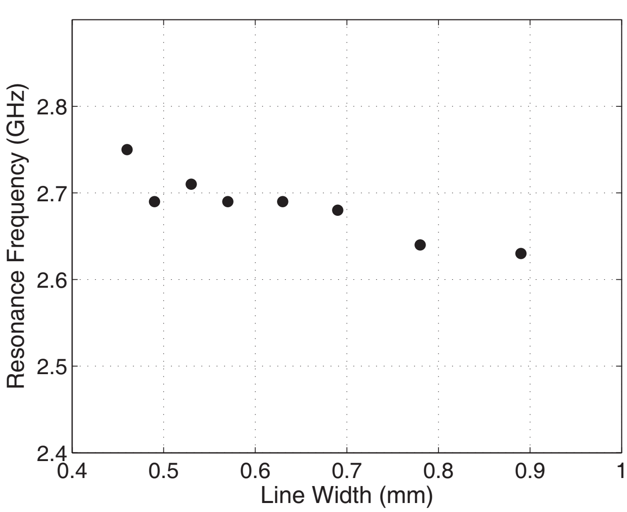


Figure 12. Effect of linewidth on resonant frequency of circular meshed patch ($T_{circ} = 60\%$).

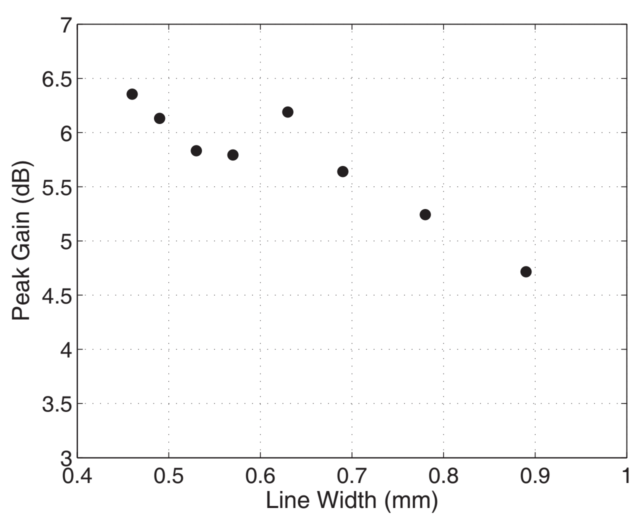


Figure 13. Effect of linewidth on peak gain of circular meshed patch ($T_{circ} = 60\%$).

The conductive ink was Metalon JS-B25P by Novacentrix. The transparency of these antennas was varied from 39.2% to 75.6% by changing the number of lines. All these antennas were fed using the T-coupling line (Fig. 2(b)), where the two parameters t and s were chosen to be 0.5 mm and 0.3 mm for a good impedance matching. The measurement results led to the same conclusion as in [2], where the tradeoff between the optical transparency and the radiation properties is that one has a less effective antenna for an increased transparency.

4.2. Effect of the Linewidth on Antenna Efficiency

In this study, a set of eight circular meshed patches of the same transparency (60%) but different linewidths were fabricated using the inkjet printing method. The conductive ink used was Metalon JS-B25P by Novacentrix. The linewidth of these antennas was varied from 0.46 mm to 0.89 mm. Their measured parameters are compared; and the results are plotted in Figs. 12, 13 and 14. It is seen that, although there is some slight fluctuation in the data, the general trend of numbers suggests the same conclusion as those for the rectangular meshed antennas. That is, by refining mesh lines, one can achieve a more effective transparent antenna that has its properties closer to the non-meshed solid patch.

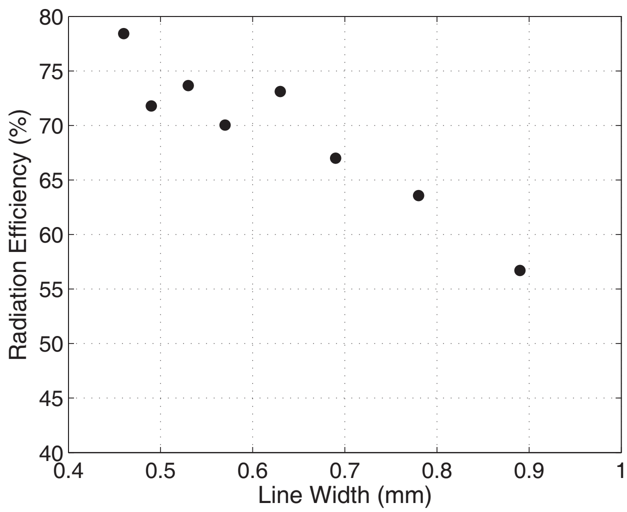


Figure 14. Effect of linewidth on radiation efficiency of circular meshed patch ($T_{circ} = 60\%$).

5. DISCUSSIONS AND CONCLUSION

Experiments performed on both rectangular and circular meshed patch antennas yield the consistent conclusion that one can optimize both transparency and efficiency of a meshed antenna by refining the linewidth. It is noted that the efficiency of the conductive ink printed antennas were low. The reasons for this are slightly different for the two types of printing. For the screen printed antennas, the low efficiency is due to the quality of the ink, thickness of the ink layer, and the smoothness of the printed lines. The conductive ink is not as conductive as a normal conductor such as copper, even after being cured. In most printing methods, the thickness of the ink layer is comparable to the skin depth, and therefore high loss is exhibited. As discussed in Section 3.1, it is challenging to achieve sufficiently smooth lines using screen printing, and, as a result, there is an inevitable loss due to the edge diffraction. For the inkjet printed meshes, the first two reasons for lower efficiency are the same as in the screen printed prototypes, whereas the third one is due to the antenna assembly itself. Inkjet printing yields smooth lines, but using a nonspecialized commericial inkjet printer (e.g., Epson C88), one has to print the structure on a transparency and then assemble the transparency onto the antenna substrate. In doing so, an extra layer of substrate is introduced as well as a small amount of air in between the transparency and the plexiglass substrate. It should also be noted that in both types of prototyping we used copper tape as the ground plane, and this may also introduce additional loss. Finally, the plexiglass has a higher loss tangent that further contributes to low efficiency.

When refining the linewidth to improve a meshed patch antenna's efficiency, there is an upper limit of efficiency for each transparency. This is due to a loss that results from meshing a non-perfect conductor. Such a loss is higher for a meshed antenna with higher transparency. While such loss is less than 1 dB for a 70% transparent rectangular meshed patch antenna, it is about 2.5 dB for a 95% transparent rectangular antenna. It is also observed through our simulation study that meshing a patch antenna does not degrade the cross polarization level. The cross polarization level is not affected significantly by refining the mesh or reducing the horizontal lines.

Although the experimental studies in this paper were for antennas with lower transparencies, the results drawn from the measurements can be applied to achieve a highly transparent antenna with optimized gain. A transparency higher than 90% (in particular, as high as 95%) has a great future application in CubeSat technology, where one may integrate such an antenna directly on top of solar cells. Printing a 0.1 mm line using either an inkjet printer, or other methods, is highly feasible. One may also repeatedly print several times on the same line trace to increase the ink layer to overcome the loss associated with skin depth. When the quality of the ink and printing are not loss factors, our prediction is that one can realistically print an S-band (this band is of interest because it enables a CubeSat to use cell phone technology in its radio) 95% transparent antenna with 0.1 mm mesh lines on a low loss substrate of a reasonable thickness and achieve a gain close to 5.0 dB or an efficiency close to 60%. A transparency of 95% is a highly applicable number for solar cell integration. With such a transparency, a typical S-band antenna will cast less than a 3% shadow on a 10 cm by 10 cm panel. As such, the resulting shadow is comparable to the one cast by the traditional wire antennas after being deployed. Most solar cells for space applications have a thin cover glass and can serve as the substrate for the antenna, although such glass is often too thin to produce an efficient S-band antenna. However, a new type of silicone cover glass has been developed and is gaining popularity (www.vst-inc.com). Besides optical and mechanical advantages, this silicone cover material is thicker and may be a good choice to facilitate antenna integration.

Previous studies have shown that the solar cells affect the antenna's performance as a lossy added substrate and reduce the antenna's gain by about 2 dB [19, 20]. But such a gain reduction is still acceptable when considering overall satellite payload and link budget, and it can be improved by using thicker cover glass. Besides this possible solar cell integration, the optimized design method for meshed antennas presented in this paper will also be useful in producing windshield antennas with very little metal weight that will be highly effective for vehicular communication [2].

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