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Flat lens design using phase correction technique for horn antenna applications

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ABSTRACT

A design of a flat dielectric lens is presented in this study to enhance directivity of a pyramidal horn antenna. The horn antenna is proposed to cover frequency of medical imaging system, which is between 5 and 6 GHz, and dielectric lens is designed based on phase correction techniques. The spherical waves produced by conventional horn antenna is being transform to planar waves by resorting flat lens in order to achieve a highly directive radiation in the farfield region. This is done by drilling numerous holes with different diameters through the dielectric material to produce different phase delay. The radiation characteristics of the lens are simulated using CST Microwave Studio and then compared with measured results. The results showed a good performance for radiation pattern when the lens is attached. This proposed design shows a significant increment of sidelobe level and 3-dB beamwidth between 5 and 6 GHz.

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1. INTRODUCTION

Recently, the benefit of designing a lightweight and high directivity antenna for various applications such as horn antenna is being explored because of the actively growing number of communication systems at certain frequency. Horn antenna can provide an easy free-space measurement of microwave material [1-3], instead of complex measurement setup of waveguide [4-6] and resonator techniques [7-9]. In conventional approach, the design of high gain antenna is usually heavy and absurd long horn antenna, which is impractical. Another approach is by increasing the flare angle, but it will reduce the size of the horn antenna and will cause the horn having large quadratic phase error. The flare angle of the horn is an important factor to be considered because if it is too small, the radiated beam will not be directive. Alternatively, high gain antenna can be achieved by using lenses. Lenses are used to transform the radiation pattern of the dominant feed into some high gain radiation pattern. Lens is widely used to convert a spherical wave into planar waves for converging optical rays to a single point. The plane waves will lead to a highly directive radiation in the farfield region [10].

In previous study, two-steps and three-steps zoned dielectric lenses were designed to correct the phase of conical horn antenna at high frequency to overcome the hyperbolic lenses that is heavier and complicated in design. The stepped lenses perform best and provide comparable performance. The three-step lens response seems to be tuned high in frequency but the two-step lens is preferred as it provides nearly the same gain at both frequencies and it is uncomplicated mechanically [11]. However, the limitation of zone plate is its small operating bandwidth as compared to a lens. As the frequency is shifted away from the design frequency, the zone boundaries and thicknesses no longer satisfy the design equations, resulting in reduced focusing ability.

However, one of the dominant challenges for lens antenna is choosing the suitable materials. The lenses are often containing several different materials. These materials may not be available in commercial off-the-shelf (COTS) form [12]. Due to the lack of material demanding, it might lead to higher cost. The materials that frequently used in designing lens for a horn antenna is metamaterials. When zero refractive record metamaterials spread as a superstrate on the outside of an antenna, the radiation properties would be directive and the gain will be increases [13]. But, the fabrication processes of the metamaterials-based lenses are sometimes burdensome In addition, metamaterials often suffer for narrow bandwidth and high losses which is not suitable for communication systems. It has been suggested that dielectric material could be utilized to construct an ideal lens to use in horn antenna. The dielectric lens can minimize the phase variations and also increase the directivity of the horn antenna [14]. Several low permittivity materials such as teflon ($\varepsilon r = 2.1$), acrylonitrile butadiene styrene (ABS) ($\varepsilon_r = 2.4$) and Polyethylene ($\varepsilon_r = 2.25$) is used and the comparison shows that it offers excellent in main lobe symmetrical, small side lobe level aperture efficiency and low return loss [15-17]. Dielectric materials with low permittivity also can reduce the economic cost and the performance is satisfying [18, 19].

In this paper, the lens for horn antenna is designed using low-cost and low-permittivity polylactic acid (PLA) which is positioned at the aperture of horn antenna in order to overcome the longer horn antenna. The lens is designed to be flat shape rather than hyperbolic shape for easier fabrication. The phase correction technique is utilized as it provides different phase correction at each point at the receiving part so that the waves on the transmitting side having planar wave. The lens possesses different sizes of hole where the phase of each unit cell element can be varied. This paper is organized as follows; section 2 discusses about the theoretical part of phase correction technique while section 3 presents the design of the proposed lens. The simulation results and discussion about the findings is described in section 4. Finally, section 5 concludes all the results from the simulation that have been obtained.

2. PHASE CORRECTION TECHNIQUE

Spherical wave propagates in unwanted outward directions that produced from the source of wave. Figure 1 shows a horn antenna with the propagated signal. The feeder of horn antenna will act as the source of wave and the spherical wave is produced due to the flare of pyramidal horn antenna where the phase is delayed at point A compared to point B. However, for some antenna applications such as biomedical imaging system [20], and through wall-imaging system [21] the planar wave is preferable instead of the spherical waves. The planar waves propagate signal into one direction so that the signal more directive compared to the spherical waves [22-24]. One of the approaches to correct the signal from spherical to planar wave is phase correction technique [25]. This work utilizes the technique where, the phase at point A has to be advanced compared to the phase at point B when pass through a medium such as lens. Phase at point A can be advanced by increasing the velocity of the signal that through at region I of flat lens compared the velocity at region II (refer Figure 1). The velocity of signal propagation at each region can be varied by resorting different material. The relation between material property and velocity, v is represented by (1).

$$v = \frac{1}{\sqrt{\varepsilon_r \mu_r}} \tag{1}$$

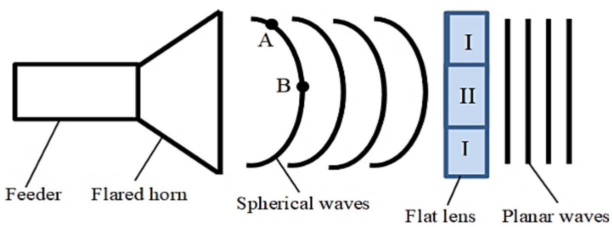


Figure 1. Wave propagates from horn antenna through lens

Where, ε_r and μ_r are permittivity and permeability of medium, respectively. For dielectric material, the permeability is equal to permeability of air, μ_0. Hence, the velocity can be increased by selecting the material that has lower permittivity. There are a few approaches to increase or decrease the permittivity of a medium for example, utilizing different type of dielectric material and different thickness of material. Convex lens is one of conventional approaches that apply different thickness of material where the thickness at the center is the highest. However, due to the complex shape of convex lens, the fabrication process becomes difficult. In this work, the flat lens is used by using only one type of dielectric material. The permittivity of the material is varied by drilling holes. Figure 2 shows different technique to adjust the permittivity of material, which are by increasing number of holes (Figure 2 (a)) or by enlarging the size of the holes (Figure 2 (b)).

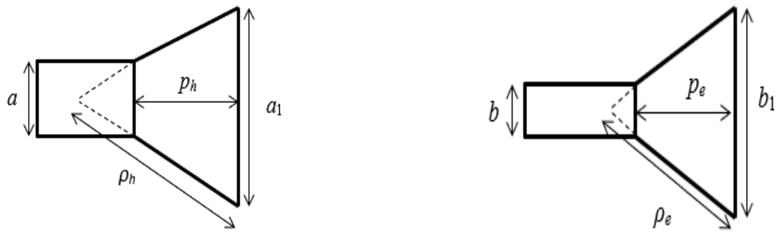
(a) (b)

Figure 2. Varying permittivity technique: (a) increasing number of holes, (b) enlarging size of holes

3. LENS ANTENNA DESIGN

3.1. Horn antenna design without lens

The fundamental design is based on pyramidal horn antenna as shown in Figure 3. All the design is using rectangular waveguide with G-band frequency, which is between 3.95 to 5.85 GHz. The horn antenna is designed to have 15 dB of gain using WR-187 waveguide adapter as rectangular feed waveguide having dimension of 47.55×22.15 mm ($a \times b$) and the center frequency is 5 GHz. The remaining parameters, which are a_1, b_1, ρ_e and ρ_h, are estimated using directivity formula when the directivity is optimum in E- and H-plane. The estimated parameters are shown in Table 1.



(a) (b)

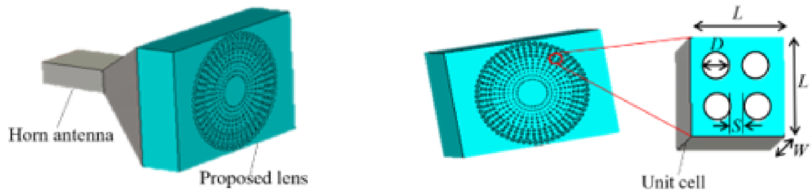
Figure 3. Horn antenna structure for (a) H-plane and (b) E-plane view

Table 1. Dimension of pyramidal horn antenna

Parameter	Value (mm)
a	47.55
b	22.15
a_1	154.73
b_1	114.43
ρ_e	109.12
ρ_h	133.00
p_e	74.94
p_h	74.97

3.2. Horn antenna design with lens

The horn antenna without lens will produce spherical waves, which are then phase-corrected by the proposed flat lens placed at the aperture of the horn. This will provide a different phase correction at each point on its receiving side so that the transmitting wave side will have the planar wave. Planar wave will result in high directive radiation in farfield region. Figure 4 (a) shows the full model of proposed flat lens attached with pyramidal horn antenna, while Figure 4 (b) shows the flat lens that is design based on unit cell. The lens is constructed based on abundant of air holes having different diameter through a dielectric material. PLA with 2.72 of permittivity is chosen as the dielectric material because it is low cost and widely available in market. Before simulating the whole model, the effect of holes toward phase delay is examined by analyzing the lens in a unit cell. The structure of unit cell consists of four drilled holes and it will be analyzed by changing the diameter of hole, D. The unit cell is having two waveguide ports. The waveguide ports are set at the face of the unit cell to permit enough propagation distance and afterward the phase of the signal that is transmitted being determined. The simulation procedure is done by using CST Microwave Software. The dimensions of unit cell are given in Table 2.



(a) (b)

Figure 4. (a) Full model of proposed flat lens attached with pyramidal horn antenna, (b) Lens design based on unit cell

Table 2. List of unit cell parameters and dimensions

Parameter	Dimension (mm)
L	30
W	35
S	$(L–2D)/3$

4. RESULT AND DISCUSSION

4.1. Phase delay analysis

The unit cell with varies in size of holes is simulated to examine the degrees of phase delay when a signal passed through the lens. Figure 5 shows the phase difference when a signal passed through the hole. The diameter of the holes is varied from 0.5-2.0 mm in order to identify the phase that need to be corrected. The thickness of unit cell is 100 mm that is 5/3λ. The unit cell produces almost similar value with acceptable deviation as shown in Figure 5. The transmitted signal of horn antenna will produce the difference in angle. Thus, the angle is used to correct the phase for producing the planar waves.

4.2. Simulation result

The return loss, S_{11}, is simulated as shown in Figure 6 to show the superior performance of the proposed lens. The performance is compared between the antenna with lens and without lens. As we can observed, S_{11} is within the acceptable limit, which is below the -10 dB matching line from 5 to 7 GHz for both cases. It indicates that the strength of signal received during the transmission is stable enough to obtain a good performance, i.e., more than 90% of signal transmitted through the antenna.

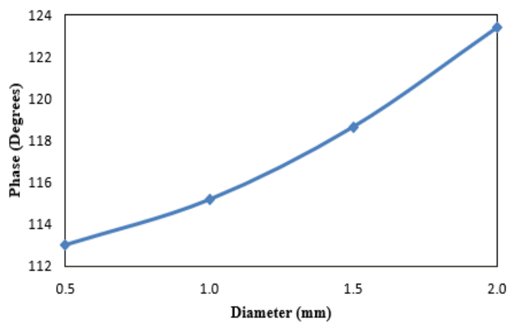


Figure 5. Phase response at 5 GHz

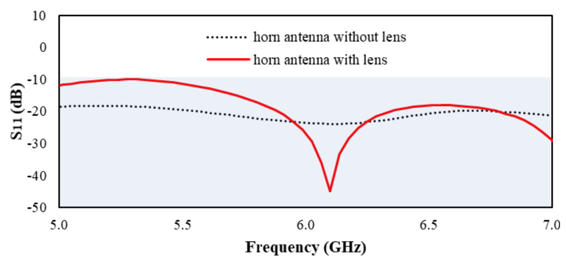
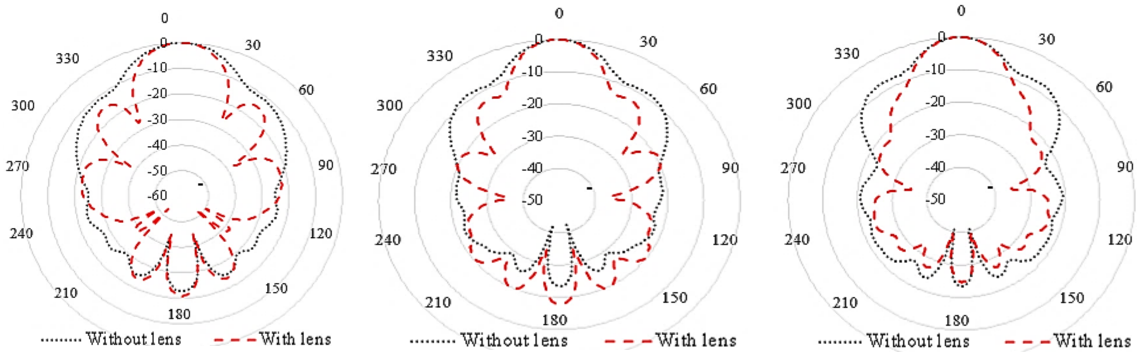


Figure 6. Frequency dependency simulated return loss of the horn antenna

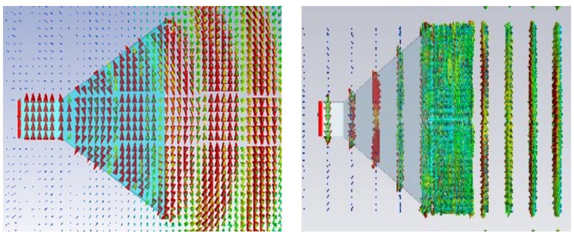
The simulated farfield radiation patterns are shown in Figure 7 for selected frequency range over medical imaging system and Table 3 summarizes comparison of the performance of horn antenna with and without lens. As we can observe from the figure, the proposed lens leads to better performance of horn antenna, for instance, at 5 GHz the sidelobe level (SLL) is suppressed from -11.3 to -14.9 dB, which is 24.16% better when the lens is attached to antenna. SLL at 5.5 and 5.9 GHz also show improvement of 33.85% and 66.82%, respectively. In addition, the superior of the horn antenna with proposed lens can be observed for the 3-dB beamwidth, which is become narrower; from 28.5 to 14.9 degrees (91.27% improvement) at 5 GHz. At 5.5 and 5.9 GHz, 18.06% and 7.56% improvement of 3-dB beamwidth can be seen, respectively. This validates that the performance of the horn antenna with lens had been increased as the lobe is narrower. The narrower main lobe depicts higher intensity of radiation. It is also evident that the levels of the minor lobes and back lobes are much lower for the proposed horn antenna with lens than those without lens. The higher directivity exhibits the stronger signal radiated through the aperture of the horn antenna.



(a) (b) (c)

Figure 7. The simulated far-field pattern at (a) 5 GHz, (b) 5.5 GHz and (c) 5.9 GHz

The guideline of operation of the proposed horn lens antenna is using waveguide port to launch signal from a source into horn antenna. It will create spherical wavefront like electromagnetic (EM) waves as shown in Figure 8 (a), which are then phase-corrected by the proposed lens that is mounted at the horn aperture as shown in Figure 8 (b). The lens will change the EM waves emanated by the horn antenna with spherical wavefront to a planar wavefront in the electric field area, and thus a high directive radiation pattern is formed. The gain of horn antenna with and without lens is shown in Figure 9 from 5 to 7 GHz. The gain for horn antenna with lens is higher compared to horn antenna without lens. This proves that the lens exhibits a good performance for horn antenna to improve the antenna applications.



(a) (b)

Figure 8. Simulated electric field distribution of horn antenna (a) without lens (b) with proposed lens

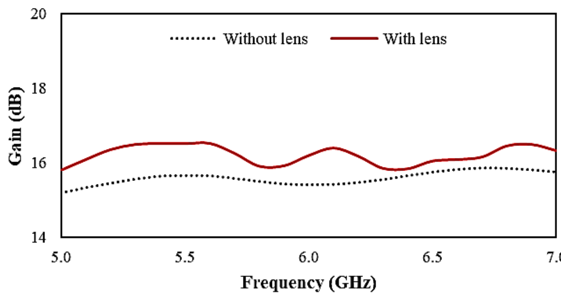


Figure 9. Gain performance of horn antenna with and without lens

Table 3. The simulated radiation characteristic of the horn antenna with and without lens

Frequency(GHz)	SLL (dB)		3-dB Beamwidth (Degrees)	
	Without lens	With lens	Without lens	With lens
5.0	-11.3	-14.9	28.5	14.9
5.5	-8.6	-13.0	25.5	21.6
5.9	-7.4	-22.3	24.2	22.5

4.3. Measurement result

The return loss, S_{11}, is measured using vector network analyzer (VNA) as shown in Figure 10. The performance is compared between the horn antenna with lens and without lens after being fabricated using 3D printer machine. The S_{11} for the antenna without lens is below than -10 dB from 5 to 7 GHz. Based on these performances, the antenna with lens still can be used for medical imaging system because the frequency range for medical imaging system in Malaysia is from 5 to 6 GHz. The measured farfield radiation patterns are shown in Figure 11 for 5 GHz, 5.5 GHz and 5.9 GHz. Please be noted that the value of gain does not represent the real values since the measurement had been done by using vector network analyzer instead of signal generator and spectrum analyzer. Across the frequency range for biomedical imaging, the SLL is below than -3 dB for the antenna with lens, where the SLL is suppressed. While, the 3-dB beamwidth become narrower compared to those without lens at observed frequencies. The summary of the measured values of SLL and beamwidth of horn antenna with and without lens are shown in Table 4. However, if we compare the performance of return loss, SLL and 3-dB beamwidth between the simulated and measured results, the fabricated antenna shows the degradation of the performance. The main factor of this discrepancy is the imperfection during fabrication because of our 3D printer machine limitations. The limitations involve the low density of printing infill, poor accuracy of fabrication, and unsmooth printing surface.

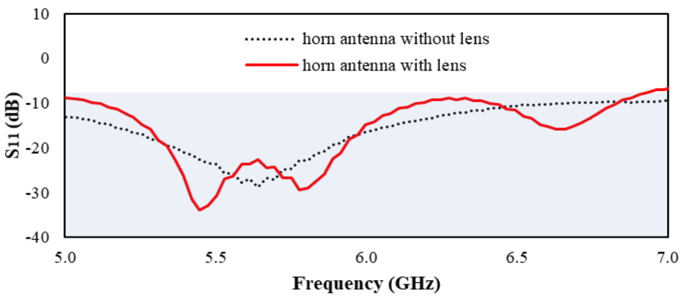


Figure 10. Frequency dependency measured return loss of the horn antenna

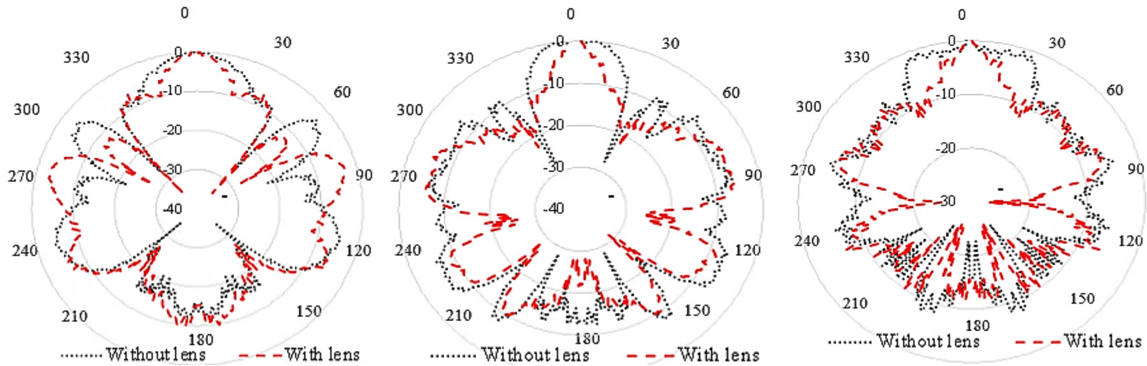


Figure 11. The measured far-field pattern at (a) 5 GHz, (b) 5.5 GHz and (c) 5.9 GHz

Table 4. The measured radiation characteristic of the horn antenna with and without lens

Frequency (GHz)	SLL (dB)		Beamwidth (Degrees)	
	Without lens	With lens	With lens	Without lens
5.0	-10	-7	22	28
5.5	-8	-17	18	26
5.9	-1	-7	24	50

5. CONCLUSION

The design of directive component for horn antenna in biomedical imaging system, using phase correction technique has been presented. A horn antenna with proposed flat lens is designed and simulated. The proposed lens is proved able to enhance the performance of horn antenna. As frequency increases, the directivity and SLL are increasing significantly, which is enough to be used for biomedical imaging system. The lens is able to convert the spherical waves from horn antenna to planar waves where the signal of horn antenna with proposed lens is more directive. The proposed flat lens provided several advantages, which are low-cost and easier to fabricate which can reduce the complexity compared to spherical shape used in classical Luneberg lens.

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