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Low-Cost and Small Size Millimeter Wave (24 GHz) Extended Hemispherical Lens Antenna for Automotive and Industrial Applications Using FR408HR Substrate

Waleed Ahmad[1, *], Furkan Dayi[2], Hamoodur Rehman[3], and Wasif T. Khan[1]

Abstract—For the first time, an extended hemispherical integrated lens antenna on a low-cost substrate, FR408HR, is presented. The antenna is designed for industrial and automotive radar sensor applications operating in the 24 GHz ISM band. The proposed antenna has a gain of 15.2 dBi, low sidelobes, and half-power beamwidth of 16 degrees. To reduce the cost, we used low loss materials; Teflon for the lens and low-cost FR408HR as a patch antenna substrate. The size of the reported 24 GHz antenna is small. The diameter of the base of the lens is 38 mm (3 times of free space wavelength), and its height is 43.5 mm (with an extended height of 24.5 mm). Simulated results match well with measurements.

1. INTRODUCTION

As technology develops rapidly, so does the demand for high-precision radar sensors and wireless sensor networks. Different types and configurations of radar sensors are available for different applications. After having been extensively used in defense applications, radar sensors have found various applications in other domains. Self-driving/driverless cars use radar sensors. The research community has reported short-range, mid-range, and long-range automotive radar sensors [1–4]. 24 GHz and 77 GHz are two popular mm-Wave frequencies for automotive radar development. These sensors are used in automatic cruise control, stop-and-go, and parking aid applications. In addition to advanced driving assistance systems, low-cost radar sensors are also finding their applications in the areas such as intelligent industrial control, precision agriculture, and smart home. Level sensors, imaging sensors, and gesture sensors are some other examples where radar sensors have found their applications.

Because of the growing massive deployment of IoT sensors, 24 GHz ISM band (24 GHz–24.250 GHz) is an attractive option for the development of radar sensors as going up in frequency (e.g., 77 GHz) which increases the development cost. Most of these applications require radar sensors with high gain and narrow beamwidth for sensing requirements but with low cost as they need to be massively deployed. One typical solution to achieve high gain and narrow beamwidth is the use of patch antenna arrays, but this solution comes with the cost of losses caused by large feeding networks for large antenna arrays to meet the requirements of high gain. The most promising solution to avoid these losses and obtain the required performance is the use of lens antenna. It removes the feed-related issues as there is only one feed element. Parabolic reflectors are also one of the candidates to serve the above-mentioned purposes, but lens antenna is better in performance as (for lens antenna case) the feed of lens antenna is located behind the lens thus eliminating the aperture blockage issues. Aperture blockage and supporting struts are the main issues in parabolic reflectors. Lens antenna is a good solution for the applications,

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* Corresponding author: Waleed Ahmad (waleed.ahmed@lums.edu.pk, waleed.ahmad145@gmail.com).

[1] Department of Electrical Engineering, Lahore University of Management Sciences, Pakistan. [2] EBE Elektro-Bau-Elemente GmbH, Germany. [3] National University of Science and Technology, Pakistan.

which provides advantages such as low sidelobes, high gain, low noise temperature, beam agility with low distortions, and cross-polarization [5]. Spherical lens has low scan loss and wide bandwidth with the option of multiple beams from a common aperture. A lot of work has been reported for lens antenna design at 77 GHz [4, 6], 28 GHz [7], and 60 GHz [8], but these antennas are designed at high frequencies using expensive RF substrates like Rogers RT/duroid® 5880. A few 24 GHz antennas have also been reported, but they are also designed on Rogers substrates and use expensive material for lens design. Recently, a published research article [9] reported the characterization of low-cost FR4 based substrates. According to this analysis, the FR408 substrate shows decent performance at 24 GHz, which was confirmed by calculating its electrical parameters by designing a ring resonator at 24 GHz on the FR408HR substrate. The cost reduction ranges from 5 to 7 times compared with LCP and RO3003 materials.

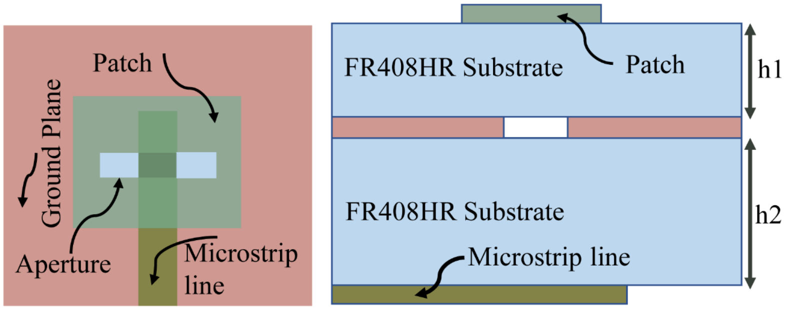
To solve the issue of higher cost of radar sensors, we have used low loss Teflon to fabricate the lens, and for the first time, we are reporting promising results of lens antenna by using a low-cost substrate FR408HR.

This paper particularly proposes and explains the design of an extended hemispherical lens antenna for various short-range applications (industrial robots, intelligent machine control, controlling streetlights, intrusion detection, automotive radars, and other point to point applications), which require small size, low-cost, and narrow beam antennas. This work demonstrates the suitability of a low form-factor antenna with high gain and narrow beamwidth requirements on a low-cost substrate FR408 HR that will facilitate the large scale deployment of such sensors in different domains.

2. ANTENNA STRUCTURE & DESIGN

2.1. Patch Antenna

Lens antenna design is divided into two parts. The basic radiating element for this lens antenna is a compact patch antenna (Figure 1) fed with a microstrip line and excited using an aperture coupling feeding method. It has a compact structure and can be easily integrated with the lens as the feeding antenna. Antenna substrate size is $Lg \times Wg$ (65 mm × 60 mm) as shown in Figure 3. The rectangular patch and feeding network both are designed on a low-cost substrate FR408HR. It has a low dielectric constant ($\epsilon_r = 3.64$) and low loss tangent ($\tan\delta = 0.0092$) with significantly reduced cost compared to Rogers RT Duroid substrates. The antenna substrate has a thickness of $h1$ (12 mils), which is selected to fulfill the stack-up fabrication requirements in such a way that the antenna performance is not disturbed. It is designed and optimized for 24 GHz, which is the desired millimeter-wave frequency (ISM band) at which a radar sensor is to be designed. The lower substrate has a thickness of $h2$ (24 mil). The aperture coupled patch antenna uses a three-layer design with microstrip feed on the bottom side and patch antenna on the top with the ground plane in between them. This layer stack-up allows the integration of radar chipsets on the bottom side to further reduce the footprint of the radar sensor.



(a) (b)

Figure 1. Aperture coupled patch antenna to be used under the lens. (a) Top view. (b) Side view.

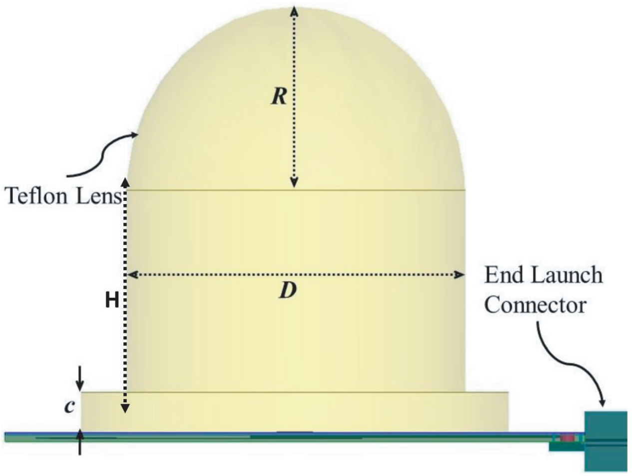


Figure 2. Side view of the Simulated Lens antenna with end launch connector.

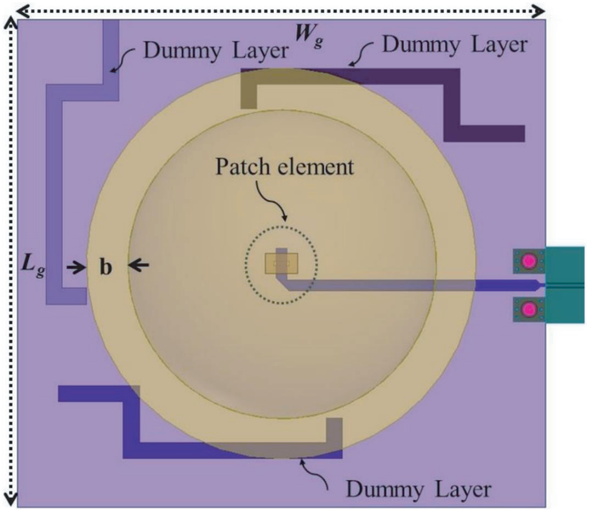


Figure 3. (Top view) Extended hemispherical lens antenna simulated model with connector and dummy layers.

2.2. Extended Hemispherical Lens Antenna Design

The second part consists of the design of the lens as shown in Figure 2. The lens antenna works on the principle of an optical lens. It focusses antenna radiations at a point called the focal point. The radiating source is placed at the focal point to collimate the beam. A lens was designed to increase the gain and reduce the beamwidth. Different types of lenses exhibit different characteristics depending upon their shape and refractive indices. We used an extended hemispherical integrated lens because of its simple shape and ease of fabrication. It consists of half-sphere of radius R, and extended height of H.Directivity of the lens with collimating aperture is given by lens aperture area and calculated using the expression (1) below [10].

$$D_o = 20 \log \left(\frac{2\pi R}{\lambda_o} \right) \tag{1}$$

Here λ_o (12.5 mm) is the free space wavelength, and R (19 mm) is the lens radius. The calculated value of directivity (19.5 dBi) is very close to the designed antenna D_o (18.67 dBi). Gain value (15.2) is lower as it incorporates conductor loss, dielectric loss, and feed spill over losses. We used a ratio (extended length to radius ratio) of 1.2 rather than a typical value of $\frac{1}{\sqrt{\epsilon_r}}$ (0.7) to achieve maximum gain. This higher ratio causes sharpening of both E & H planes with focusing effect [11]. The electromagnetic waves emanating from the hemispherical lens are collimated (parallel) and help to achieve a narrow beam. As far as the selection of material of lens is concerned, we performed different simulations in which different materials were used for the lens, but Teflon ($\epsilon_r = 2.1$, $\tan\delta = 0.001$, $n = \sqrt{\epsilon_r} = 1.1$) performed better because it had low loss, and its electrical properties closely matched the substrate used for patch antenna [12, 13]. The base of the lens has a ring around it to provide better support to the lens on the substrate (using adhesive material or screws). With better adhesive material, this extension ring can be avoided, and the size of the lens can be further reduced. The diameter and total height of of the designed lens are 38 mm and 43.5 mm, respectively. Its height could be reduced [7] by using a lens with high permittivity. Nevertheless, they are expensive, lossy, and make the machining of the lens difficult. Another solution is to create an air cavity and reduce the lens height by decreasing its focal length but at the cost of gain [7].

The following Equation (2) provides a relationship between the diameter of the base of the lens and its associated 3-dB beam width [5]:

$$\begin{aligned}\theta_{3\,\mathrm{dB}} &\approx \frac{68\lambda_o}{D_H}\\ \theta_{3\,\mathrm{dB}} &\approx \frac{57\lambda_o}{D_E}\end{aligned} \tag{2}$$

where D_E (38 mm) and D_H (38 mm) are the lens dimensions in H- & E-planes, respectively.

The above Equation (2) gives calculated values of half-power beam width for H & E planes, 21 degrees and 18 degrees, respectively. The measured values of beamwidth (16 and 15.5 degrees for H & E planes, respectively) are lower as the above expression just counts the effect of radius of the lens without considering the effect of beam sharpening caused by increasing the extended height [11].

Figures 2 & 3 show the top and side views of the lens antenna, respectively. Figure 4 shows the stack-up of the lens antenna. The microstrip line is on the bottom layer to feed the patch element. Above the microstrip line, there are three layers of copper, which are described as dummy layers as shown in Figure 3. Dummy lines were added for testing purpose so that we could check if dc/digital lines running on these layers have any effect on the antenna performance. Through simulations and measurements, it was verified that antenna performance did not deteriorate in the presence of dummy lines. The ground plane (M6 layer) has a rectangular cut in it for aperture coupling to the patch element. The topmost layer has a Teflon lens with an extended hemispherical shape, which acts as a lens and reduces the beamwidth while increasing the directivity. A 4 mil prepreg is used in between two copper layers to realize a multilayer stack up.

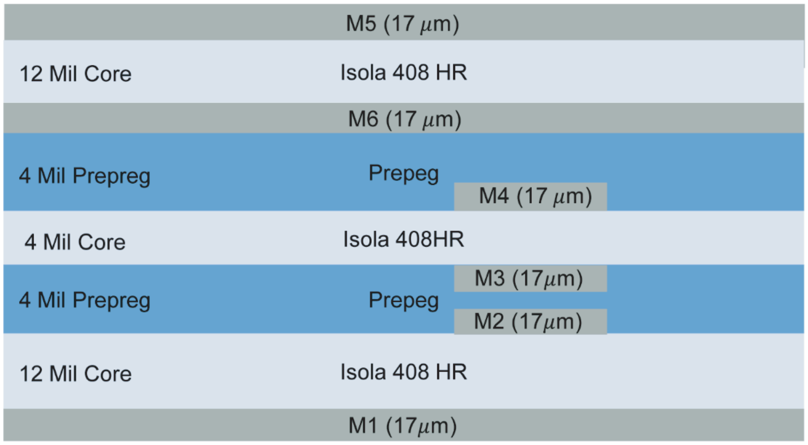


Figure 4. Integrated lens antenna stack-up.

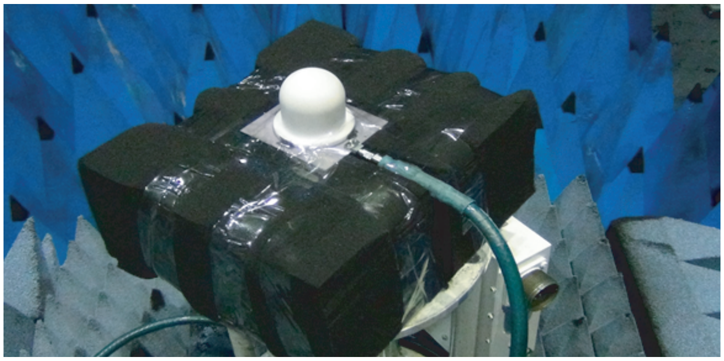


Figure 5. Measurement setup with an EM absorber block on the back of Lens antenna.

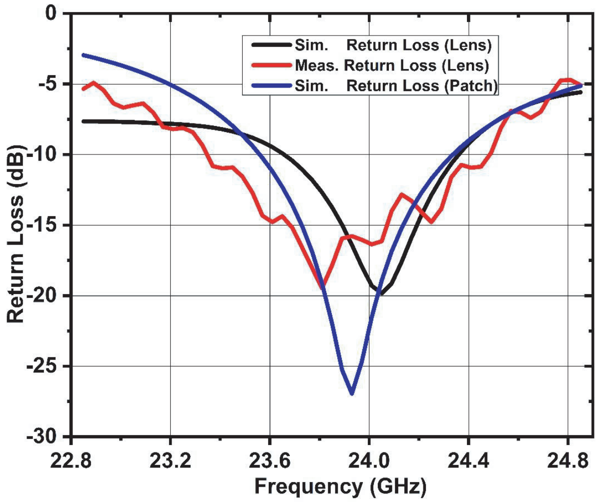


Figure 6. Return loss of single element patch, measured and simulated lens antenna.

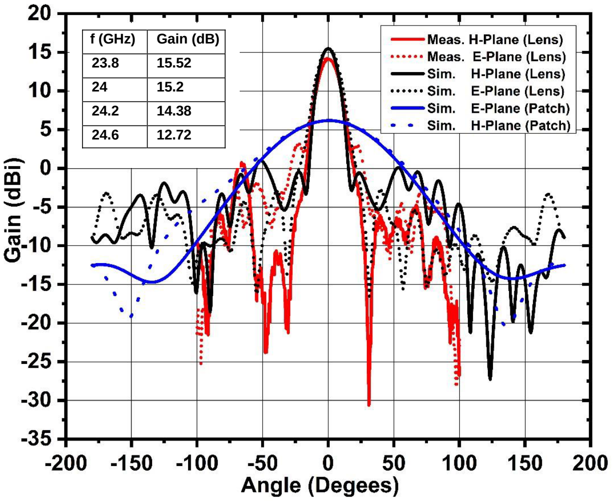


Figure 7. Measured and simulated *E* & *H* plane radiation pattern for individual patch and lens antenna.

3. RESULTS AND DISCUSSIONS

Figure 5 shows the measurement setup in which lens antenna is mounted on an EM absorber in an anechoic chamber. The radiation patterns and return loss of the antenna were measured using this measurement setup.

Figures 6 and 7 show the measured and simulated results for the patch and lens antenna. In Figure 6, the simulated reflection coefficient matches well with measured reflection coefficients of lens antenna. It is evident from results in Figure 6 that impedance bandwidth is 1.4 GHz for simulated and 2 GHz for the measured case with a center frequency of 24 GHz, which is far more than the required bandwidth of 200 MHz for radar applications. Measured and simulated radiation patterns are shown in Figure 7. The radiation patterns are clean with half-power beamwidth of 16 degrees and a gain of 15.2 dBi. A table is also added in Figure 7 showing the values of gain at different frequencies near the center frequency of the lens antenna. It is evident from results in Figure 7 that simulated and measured radiation patterns match well.

One of the most important aspects about this antenna design is its robustness to fabrication tolerances. The performance of the lens antenna is not affected by over-etching effects during fabrication. Moreover, the performance of lens is not disturbed by small misplacement of the Teflon lens as shown

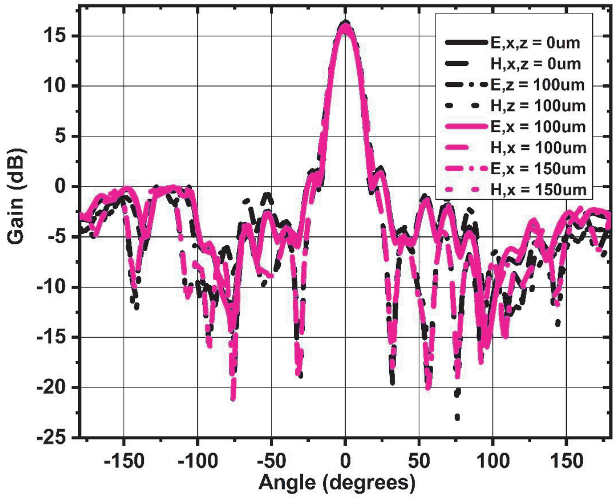


Figure 8. Tolerance analysis of E & H-plane radiation pattern.

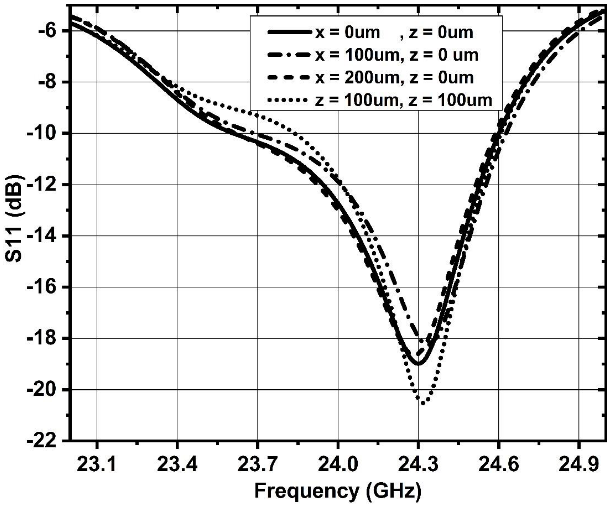


Figure 9. Tolerance analysis of return loss of proposed antenna.

in Figures 8 & 9. Figures 8 & 9 show the tolerance analysis for gain and reflection coefficient, respectively for different offset values in horizontal and vertical directions. The antenna results for both return reflection coefficient and radiation pattern have been measured with 2.92 mm end launch connector manufactured by SV Microwave Corporation. There is no performance deterioration caused by connector attachment, which exhibits antenna robustness to different metal effects in close vicinity of antenna elements.

The work presented in this paper is compared (Table 1) with other lens antenna developments in the literature, and it is clear from Table 1 that the lens antenna presented in this paper has advantage in terms of cost while not degrading the performance of the antenna significantly. The gain of some antennas reported in Table 1 is large because of the large diameter (in terms of wavelength) of the lens.

Table 1. Comparison of performance parameters for the lens antenna.

	Frequency	Gain (dB)	HPBW (Degrees)	Lens Material (εr)	Antenna Substrate (εr)	Lens Diameter	Antenna Subs. Cost
This Paper	24 GHz	15.2	16	Teflon (2.1)	FR408HR (3.64)	$3\lambda_o$	X
[4]	77 GHz	20.2	20	-	Rogers RT/Duroid 5880 (2.6)	$9\lambda_o$	$> 4X$
[7]	28 GHz	21.8	-	Rexolite (2.3)	Rogers Duroïd 5880 (2.23)	$4\lambda_o$	$> 4X$
[14]	77 GHz	-	10	Teflon (2.2)	Rogers Duroïd 5880 (2.23)	$6.4\lambda_o$	$> 4X$
[15]	77 GHz	27	-	Teflon (2.2)	-	$25.7\lambda_o$	-
[16]	60 GHz	16	-	poly-phenylenesulfide (3.2)	Rogers 5870 (2.2)	$5\lambda_o$	$> 4X$

4. CONCLUSION

A state of the art, low cost (that will reduce the cost by 5 to 7 times), and small form factor lens antenna is presented using a low-cost low-loss FR408HR substrate. Placing the lens made of teflon on the patch antenna increases the gain to 15.2 dBi with a narrow 3 dB beamwidth of 16 degrees. Isola FR408HR provided excellent performance without compromising the performance of the antenna and is advantageous in terms of cost saving and massive deployment of radar sensors. The presented work proposes the development of antennas in 24 GHz ISM band using a low-cost FR408HR substrate. This work paves the way for the development of low-cost, short-range automotive and other industrial radar sensors.

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