Noncollimating MmW Polyethylene Lens Mitigating Dual-Source Offset From a Tx/Rx WiGig Module

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Abstract—The design of a micromachined polyethylene lens for WiGig modules is described and its electromagnetic characteristics are measured. The lens is electromagnetically fed by linearly polarized Tx and Rx patch antennas integrated in an existing ball-grid-array (BGA) organic module. Antennas are separated from each other by a distance of 4.45 mm (0.89 λ0 at 60 GHz). The goal of the lens is to increase the gain of each antenna while lowering the beam de-ping effect due to their offset position regarding the focal point of the lens. A geometrical optics/physical optics (GO/PO) hybrid method is applied to the design and analysis of the lens shape for noncollimating purpose. Using a lens height of 30 mm for both Tx and Rx antennas, a 13-dBi minimum realized gain from 54 to 66 GHz is obtained. Compared to an elliptical lens providing an equivalent real gain over the same bandwidth, the de-ping angle from the boresight direction is reduced from 15° to 4°. Full-wave simulations are verified by measurements.

Index Terms—Antenna-in-package (AiP), antenna gain, 60-GHz WiGig standard, lens antennas, millimeter-wave (MmW) antennas.

I. INTRODUCTION

Along with the rapid growth of the mobile devices market [1], the consumer demand for high data rate communications is increasing continuously year-over-year. In light of this, the worldwide broadband available in the unlicensed 60 GHz band recently opened the way for high data rate technologies in wireless personal area network (WPAN). Recently, the IEEE WLAN 802.11ad amendment has been adopted by the industry under the WiGig brand name and integrated in the WiFi alliance [2]. This standard will extend the existing capabilities and current use cases of the IEEE WLAN 802.11a/b/g/n, also enabling new usages like kiosk file downloading, wireless HDMI, wireless docking, etc.

Such applications require inexpensive and low-power millimeter-wave (MmW) transceivers to address mass-market products. In the past years, this challenge was overcome thanks to the advances in both silicon-based CMOS [3] and BiCMOS [4] technologies.

Today, the next step is to integrate the front-end circuit with the antenna in a cost-effective way. The antenna performance depends on the targeted use case. For a line-of-sight (LoS) transmission over a short distance (e.g., < 3 m), a 5–6-dBi antenna gain is required.

The antenna-in-package (AiP) is the preferred approach by industries to meet both these specifications and low-cost integration goals. In the past years, several packaging technologies were envisioned. Various high-performance demonstrators were built in high-temperature cofired ceramics (HTCC) [5], low temperature cofired ceramics (LTCC) [6], and high density interconnect (HDI) [7] technologies using low-loss organic substrates. In those studies, antenna gain ranges from 3 to 7 dBi with a single element antenna. In addition, it should be noted that all these modules and most of the existing industrial modules operate with two independent and physically spaced Tx and Rx antennas [7]–[10].

If we consider a point-to-point transmission over a longer distance (e.g., > 10 m), the gain of the antennas should be higher than 10 dBi. In order to achieve a reliable and easy-to-install module, we also might relax the constraints on the Tx and Rx antennas alignment using a wider than 10° beamwidth.

To meet all the aforementioned specifications in a cost-effective way, we propose to leverage an existing short-range WiGig organic module by adding a dielectric shaped lens on top of it. The most difficult challenge to overcome is to mitigate the offset of the Tx/Rx antennas from the center of the module and, therefore, the focal point of the lens.

Several research groups already designed dielectric lenses at 60 GHz using various materials such as teflon [11], polyethylene [12], alumina [13], and quartz [14]. Recently, our research team demonstrated the possibility to reach interesting performance with a three dimensional (3-D) printed plastic lens [15] placed over a WiGig module [7] with built-in separated Tx and Rx antennas as sources. However, as both Tx and Rx antennas were positioned slightly away from the focal point of the lens (0.15 λ0 at 60 GHz), the pointing direction of the main radiated beam was 15° offset from the boresight direction.

In this communication, we propose a micromachined polyethylene shaped lens to mitigate this effect. In Section II, we first briefly present the source antenna and then the design procedure of the noncollimating lens. In Section III, PO analysis, full-wave simulations, and measurements of the lens placed over the WiGig module are presented. Finally, this communication ends with a short conclusion.

II. DESIGN OF THE LENS ANTENNA

A. 60-GHz: HDI Organic Module

The WiGig module used to feed the lens was designed in the MmW high-density-integration (HDI) technology developed by STMicroelectronics. This technology uses low-cost HDI organic substrates, which demonstrated suitable performance at MmW [7]. The module is made of three substrates (one core and two preprep) stacked...
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Fig. 1. Picture of the 60 GHz BGA (bottom view left side and top view right side).

Fig. 2. Schematic view of the lens placed above the BGA module.

B. Lens Antenna Design

As previously explained, in order to achieve a 10-m point-to-point transmission distance, the realized gain of the involved antennas should be higher than 10 dBi. In order to increase the gain of the BGA module, an axial symmetric lens (z-axis) was selected to be placed on top of it (Fig. 2).

A polyethylene low-loss material was chosen for the lens, which is also a relatively easy material to machine by milling. The complex permittivity of the used polyethylene was measured around 60 GHz using an open Fabry–Perot resonator [16]: values of $\varepsilon_r = 2.3$ and $\tan(\delta) = 0.0005$ were found. The lens was designed and analyzed using a classical hybrid geometrical optics/physical optics (GO/PO) approach integrated into the ILASH software tool developed by Lima et al. [17] at the central frequency (60 GHz). The GO/PO method requires the knowledge of the Tx and Rx antenna radiation pattern inside the lens material. These were obtained at 60 GHz using the full-wave HFSS software, considering the BGA module radiating into an unbounded polyethylene medium [Fig. 3(a)]. In this simulation, the BGA module was placed over a 1.25-mm thick ABS plastic slab ($\lambda_0/4$ at 60 GHz) and absorbing radiation conditions were set on the sides and bottom face of the slab. For both Tx and Rx antennas, the obtained radiation pattern was nonsymmetrical both in the E- and H-planes, mainly due to the metallic parts surrounding the antennas (dc lines, ground plane, etc.).

Traditionally, when the lens goal is to maximize its aperture efficiency (highest gain for a given lens aperture), a synthesized ellipse shape is normally used [18]. The synthesized ellipse is an extended hemispherical lens with an extension length $L$ that forces most of the rays to exit the lens parallel to each other when the feed antenna is placed at the center of the lens base (the focal point), see [Fig. 3(b)]. In this case, the elliptical lens was designed with $R = 7.5$ mm and $L = 9.05$ mm to ensure about 15 dBi gain when fed at the focal point by the radiation patterns of the antennas of the BGA module. This allows some margin to accommodate the feeding related losses across the band and ensures angular range coverage around boresight with a gain higher than 10 dBi.

However, the integrated Rx and Tx patches of the BGA are separated from each other in the H-plane by a distance $\Delta d = 4.45$ mm. This means that the Tx and Rx lens feeds cannot be placed simultaneously at the focal point of the lens, being offset at the base of the lens by $y = \Delta d/2 = 2.225$ mm. This offset induces a strong depointing effect of the main radiated beam away from the axis of the lens (z-axis), as can be seen in [Fig. 3(c)]. Therefore, although the maximum gain of the lens is 15 dBi, it is shifted to $\theta = 5^\circ$ while gain falls to 5.7 dBi at $\theta = 0^\circ$ where Tx and Rx beams intersect the lens axis. It can be shown that the angular depointing can be reduced by increasing the lens size compared to $\Delta d$. However, in the case of the elliptical lens, up-scaling its size increases concomitantly the directivity so the resulting beam narrowing maintains the problem of low gain at $\theta = 0^\circ$.

Therefore, an alternative type of lens is required, which allows increasing its size without significant gain penalty at $\theta = 0^\circ$. This communication proposes a newly shaped axial symmetric lens where the aperture efficiency is traded by less beam depointing. The proposed lens transforms the feed radiation pattern $U(\eta)$ inside the lens into a wider output power pattern $G(\theta)$ despite the larger lens size. The shaped lens design is based on a GO formulation that was previously developed in [19] for a different target.

The lens profile is represented by the $r(\eta)$ function (Fig. 4). It can be determined from the following set of differential equations:

$$\frac{\partial \theta}{\partial \eta} = \frac{T(\eta) U(\eta) \sin(\eta)}{K G(\theta) \sin(\theta)}$$

$$\frac{\partial r}{\partial \eta} = \frac{r(\eta) \sin(\theta - \eta)}{\sqrt{\varepsilon_r - \cos(\theta - \eta)}}$$

where $\eta$ is the independent variable, $T(\eta)$ represents the power Fresnel transmission coefficient across the lens surface, and $K$ is the power balance normalization constant [19].

The above formulation assumes $\phi$-independent feed radiation pattern $U(\eta)$ and target power pattern $G(\theta)$. For this step, an axial symmetric radiation pattern of the feed $U(\eta)$ was generated as an average of the components in the main planes of both Tx and Rx patches. The obtained $U(\eta)$ radiation pattern is presented in the black dashed curve of [Fig. 3(a)]. The target radiation pattern was defined as an axial symmetric Gaussian beam

$$G(\theta) = \exp\left[-\left(\theta/\theta_0\right)^2\right]$$
Fig. 3. (a) Normalized simulated radiation patterns at 60 GHz of the Rx and Tx antennas of the BGA module in an unbounded medium of polyethylene. (b) Elliptical lens profile and associated ray tracing. (c) Simulated copolarized gain in the H-plane ($xz$ plane) of the synthesized elliptical lens with the Tx and Rx feeds placed $x = \Delta d/2 = 2.225$ mm away from the focal point of the lens (see Fig. 2 for $\Delta d = 4.45$ mm).

Fig. 4. Shaped lens profile [resulting from the evaluation of (1) and (2)] and associated ray tracing.

Fig. 5. Total gains at 60 GHz of the lens-assembly in the H-plane.

where $\theta_0$ is the Gaussian width. The $\theta_0$ value was adjusted to $25^\circ$ to ensure a gain higher than 10 dBi.

The lens material is the same as the one used for the elliptical lens. The differential equations (1) and (2) were integrated numerically from the initial values $\eta = 0^\circ$ ($\theta = 0^\circ$) up to the $\eta = 90^\circ$ edge of the lens. The initial value of $r(\eta = 0^\circ) = F$ is a scaling factor that does not change the shape of the lens. However, the larger is this value, the larger is the size of the lens, reducing the depointing error. Inherent to the design, increasing the size also improves the lens radiation pattern compliance with the target $G(\theta)$. Parameter $F$ was optimized to 30 mm as a compromise between overall size and beam depointing. The resulting profile of the lens is represented in Fig. 4. In order to allow fixing the lens to the probe-fed measurement equipment, a cylindrical extension was added around its base (Fig. 4), which does not affect its performance.

The ray tracing for the centered feed that is added to Fig. 4 shows a major difference between this lens and the synthesized ellipse lens: the rays no longer exit the lens parallel to each other. This means lesser focusing capability (i.e., lower aperture efficiency), but conversely lower beam tilting dependence with the off-axis displacement of the feed at the base of the lens. This can be seen in the radiation patterns (Fig. 5) calculated at 60 GHz with ILASH and the full-wave HFSS tool for $y = \Delta d/2 = 2.225$ mm feed offset. The maximum gain is 15.3 dBi while the gain along the axis of the lens is 14.9 dBi, which is
above the required threshold of 10 dBi. Both simulation methods show quite similar results with minor discrepancies. The effect of the multiple total internal reflections is seen on the sidelobe level [20]. In some cases, total internal reflection can generate a surface wave propagating along the curvature of the lens, which increases the overall directivity. Only a full-wave simulator is able to take this effect into account.

It is interesting to compare the dependence of the boresight gain ($\theta = 0^\circ$) for both lens types as a function of the $y$-axis feed displacement (Fig. 6). As expected, the shaped lens is much more immune to the off-axis feed offset while ensuring the required gain above 10 dBi at $\theta = 0^\circ$, at least up to 0.5\lambda_0 offset. As previously referred, changing the size of the shaped lens has little influence on its maximum gain unlike the elliptical lens. However, reducing its size does affect beam depointing. For instance, if $F = 15 \text{ mm}$, half of the current value, the on-axis gain for the same $y = \Delta d/2 = 2.225 \text{ mm}$ feed offset is about 9 dBi while the maximum gain remains close to 16 dBi.

Fig. 6. Gain along the axis of the lens ($\theta = 0^\circ$) versus the feed displacement $\Delta d/2$ away from the center of the base of the lens for both the synthesized ellipse and the shaped lens at 60 GHz.

Fig. 7. Fabricated BGA module (left) and lens (right) prototype.

Fig. 8. Simulated and measured reflection coefficient of the lens antennas version 1 (Tx-v1 & Rx-v1). Simulated reflection coefficient of the lens antenna version 2 (Tx-v2).

Fig. 9. Measured and simulated (HFSS) total realized peak and boresight gains of the lens antennas (Tx & Rx-v1) and of the Tx-v1 antenna radiating in air.

Fig. 10. (a) Simulated (HFSS) copolarized (Tx-v1 and Tx-v2) and cross-polarized (Tx-v1) realized gains of the antennas of the lens assembly at 60 GHz in the H plane ($\varphi = 90^\circ$). Measured data are also presented for Tx-v1. (b) Simulated (HFSS) copolarized (Rx-v1 and Rx-v2) and cross-polarized (Rx-v1) realized gains of the antennas of the lens assembly at 60 GHz in the H plane ($\varphi = 90^\circ$). Measured data are also presented for Rx-v1.
III. MEASUREMENTS

The lens-assembly was measured using our 3-D radiation pattern measurement setup. The BGA module was inserted in the base cavity of the lens and the Tx and Rx antennas were fed using a microelectronic probe [20], [21]. Fig. 7 presents the manufactured BGA and the lens prototype.

In Fig. 8, the simulated and measured reflection coefficient of the lens antenna is presented both for Tx and Rx feeds (v1 curves). Because of the nonsymmetrical metallic environment and via arrangement surrounding the RF antenna access (die to BGA connection), despite some discrepancies with simulation due to the fabrication tolerances, the measured reflection coefficient is below $-4 \, \text{dB}$ in the frequency band, 50–67 GHz. As explained before, this is not due to the lens but rather to the manufacturing process of this novel organic stack-up for the BGA module. There is no fundamental limit precluding a better impedance match. In order to demonstrate it, we indeed carried out an optimization of the BGA module (called v2) with improved matching. In Fig. 8, the simulated reflection coefficient of the lens antenna (BGA v2) is presented for Tx feed. To achieve this improved matching, the patch antennas of the BGA module have been squared (they were initially rectangular) and the length of the respective coupling slots has been increased; also the series stubs have been also adjusted.

Fig. 9 shows the measured and HFSS simulated total realized gain of the shaped lens in the peak and boresight directions both for the Tx and Rx feeds. The figure shows also the total realized gain of the BGA Tx antenna without the lens for comparison purpose. The gain of the lens is higher than 13 dB from 54 GHz to 66 GHz, whereas the gain of the Tx antenna of the BGA module in free space is higher than 3.2 dB. This represents an improvement from 6 to 10 dB across this frequency band.

Figs. 10 and 11 show the radiation patterns of the lens in the H- and E-planes at 60 GHz both for the Tx and Rx feeds, BGA module v1 and v2. Indeed, simulated radiation patterns from BGA module v2 with lens demonstrate that the mitigation of the depointing effect is still valid with improved matching. For the fabricated BGA module v1, measurement (dots) and simulation (plain lines) results are in good agreement, confirming the expected H-plane beam depointing and a reasonably symmetrical behaviour. The maximum realized copolarized gain is 13.9 dB at 60 GHz for the Tx feed and 13.2 dB at 60 GHz for the Rx feed. In the H-plane, the beamwidth at the absolute copolarization gain level of 10 dB is $28^\circ$. Cross-polarization within this angular interval never exceeds $-9 \, \text{dB}$. In the E-plane, the beamwidth at the absolute copolarization gain level of 10 dB is $20^\circ$. Cross-polarization within this angular interval never exceeds $-6.4 \, \text{dB}$.

IV. CONCLUSION

In this communication, we described an innovative cost-effective solution to leverage an existing WiGig module with built-in separate Tx and Rx linearly polarized patch antennas by adding a shaped lens to address moderate range ($>10 \, \text{m}$) point-to-point LoS communications. The main challenge was to mitigate the strong beam depointing effect presented by canonical lenses, like the ellipsoidal lens, caused by the Tx/Rx feed offset from the focal point of the lens, while ensuring a gain higher than 10 dB in a given angular region around boresight ($\theta = 0^\circ$). We achieved this objective by designing an appropriately shaped lens. The design procedure was depicted along with its performance when the lens was integrated with the BGA module. Simulations and measurements confirmed a depointing reduction from $15^\circ$ in the ellipsoidal lens to $4^\circ$ in the shaped lens, while offering up to 10 dB improvement of the boresight gain over the independent BGA module. Although the main tradeoff of the proposed solution is the larger size of the lens when compared to a classical ellipsoidal lens, the 30-mm height of the shaped lens stays within acceptable size limits.

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REFERENCES


**QUERIES**

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To meet all the aforementioned specifications in a cost-effective way, we propose to leverage an existing short-range WiGig organic module by adding a dielectric shaped lens on top of it. The most difficult challenge to overcome is to mitigate the offset of the Tx/Rx antennas from the center of the module and, therefore, the focal point of the lens.

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A. 60-GHz: HDI Organic Module

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up with four metal layers distributed between the prepreg and the core substrates and also on top of each prepreg. The HDI technology enables minimum track space and width of 50 μm which is of paramount importance at mmWave frequencies.

In Fig. 1, the top and bottom pictures of the module are presented. This 12 × 12 × 0.5 mm³ ball-grid-array (BGA) module integrates two identical antennas: 1) Tx and 2) Rx linearly polarized aperture-coupled patch antennas. They mainly radiate in the direction opposite to the front-end circuit since this antenna-topology exhibits a high front-to-back ratio. Therefore, the parasitic influence of the radiation of the antennas over the main PCB after the final assembly is minimized.

Measurements of the Tx and Rx antennas were already performed and presented in [7]. They both exhibit a realized gain higher than 6 dBi and a −4-dB worst reflection coefficient in the 57–66 GHz band.

This matching could be indeed enhanced by optimizing the manufacturing process and the antenna’s topology, but it will have no other effect whatsoever on the lens shape and its effectiveness to mitigate the beam depointing, which are the main goals of this communication. However, we already performed additional simulations for this matching optimization, as it will be described later.

B. Lens Antenna Design

As previously explained, in order to achieve a 10-m point-to-point transmission distance, the realized gain of the involved antennas should be higher than 10 dBi. In order to increase the gain of the BGA module, an axial symmetric lens (z-axis) was selected to be placed on top of it (Fig. 2).

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The lens profile is represented by the r(η) function (Fig. 4). It can be determined from the following set of differential equations:

\[
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\frac{\partial \theta}{\partial \eta} &= \frac{T(\eta) U(\eta) \sin(\eta)}{K G(\theta) \sin(\theta)} \\
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where η is the independent variable, T(η) represents the power Fresnel transmission coefficient across the lens surface, and K is the power balance normalization constant [19].

The above formulation assumes φ-independent feed radiation pattern U(η) and target power pattern G(θ). For this step, an axial symmetric radiation pattern of the feed U(η) was generated as an average of the cocomponents in the main planes of both Tx and Rx patches. The obtained U(η) radiation pattern is presented in the black dashed curve of [Fig. 3(a)]. The target radiation pattern was defined as an axial symmetric Gaussian beam

\[
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(b) Elliptical lens profile and associated ray tracing. (c) Simulated copolarized gain in the H-plane ($xz$ plane) of the synthesized elliptical lens with the Tx and Rx feeds placed $x = \Delta d/2 = 2.225$ mm away from the focal point of the lens (see Fig. 2 for $\Delta d = 4.45$ mm).

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Fig. 5. Total gains at 60 GHz of the lens-assembly in the H-plane.

where $\theta_0$ is the Gaussian width. The $\theta_0$ value was adjusted to 25° to ensure a gain higher than 10 dBi.

The lens material is the same as the one used for the elliptical lens. The differential equations (1) and (2) were integrated numerically from the initial values $\eta = 0°$ ($\theta = 0°$) up to the $\eta = 90°$ edge of the lens. The initial value of $r(\eta = 0°) = F$ is a scaling factor that does not change the shape of the lens. However, the larger is this value, the larger is the size of the lens, reducing the depointing error. Inherent to the design, increasing the size also improves the lens radiation pattern compliance with the target $G(\theta)$. Parameter $F$ was optimized to 30 mm as a compromise between overall size and beam depointing. The resulting profile of the lens is represented in Fig. 4. In order to allow fixing the lens to the probe-fed measurement equipment, a cylindrical extension was added around its base (Fig. 4), which does not affect its performance.

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above the required threshold of 10 dBi. Both simulation methods show quite similar results with minor discrepancies. The effect of the multiple total internal reflections is seen on the sidelobe level [20]. In some cases, total internal reflection can generate a surface wave propagating along the curvature of the lens, which increases the overall directivity. Only a full-wave simulator is able to take this effect into account.

It is interesting to compare the dependence of the boresight gain \(\theta = 0^\circ\) for both lens types as a function of the y-axis feed displacement (Fig. 6). As expected, the shaped lens is much more immune to the off-axis feed offset while ensuring the required gain above 10 dBi at \(\theta = 0^\circ\), at least up to 0.5\(\lambda_0\) offset. As previously referred, changing the size of the shaped lens has little influence on its maximum gain unlike the elliptical lens. However, reducing its size does affect beam depointing. For instance, if \(F = 15\) mm, half of the current value, the on-axis gain for the same \(y = \Delta d/2 = 2.225\) mm feed offset is about 9 dBi while the maximum gain remains close to 16 dBi.

Fig. 6. Gain along the axis of the lens \((\theta = 0^\circ)\) versus the feed displacement \(\Delta d/2\) away from the center of the base of the lens for both the synthesized ellipse and the shaped lens at 60 GHz.

Fig. 7. Fabricated BGA module (left) and lens (right) prototype.

Fig. 8. Simulated and measured reflection coefficient of the lens antennas version 1 (Tx-v1 & Rx-v1). Simulated reflection coefficient of the lens antenna version 2 (Tx-v2).

Fig. 9. Measured and simulated (HFSS) total realized peak and boresight gains of the lens antennas (Tx & Rx v1) and of the Tx-v1 antenna radiating in air.

Fig. 10. (a) Simulated (HFSS) copolarized (Tx-v1 and Tx-v2) and cross-polarized (Tx-v1) realized gains of the antennas of the lens assembly at 60 GHz in the H plane \((\varphi = 90^\circ)\). Measured data are also presented for Tx-v1. (b) Simulated (HFSS) copolarized (Rx-v1 and Rx-v2) and cross-polarized (Rx-v1) realized gains of the antennas of the lens assembly at 60 GHz in the H plane \((\varphi = 90^\circ)\). Measured data are also presented for Rx-v1.
In this communication, we described an innovative cost-effective solution to leverage an existing WiGig module with built-in separate Tx and Rx linearly polarized patch antennas by adding a shaped lens to address moderate range (>10 m) point-to-point LoS communications. The main challenge was to mitigate the beam depointing effect presented by canonical lenses, like the elliptical lens, caused by the Tx/Rx feed offset from the focal point of the lens, while ensuring a gain higher than 10 dB in a given angular region around boresight (θ = 0°). We achieved this objective by designing an appropriately shaped lens. The design procedure was validated along with its performance when the lens was integrated with the BGA module. Simulations and measurements confirmed a depointing reduction from 6 to 10 dB across this frequency band.

In this section, we report measurements confirming the expected H-plane beam depointing and a cross-polarization gain level of 10 dBi. In the E-plane, the beamwidth at the absolute copolarization gain level at 60 GHz for the Tx feed and 13.2 dB at 60 GHz for the Rx feed. In the H-plane, the beamwidth at the absolute copolarization gain level at 60 GHz is 28°. Cross-polarization within this angular interval never exceeds −9 dB. In the E-plane, the beamwidth at the absolute copolarization gain level of 10 dB is 20°. Cross-polarization within this angular interval never exceeds −6.4 dB.

IV. Conclusion

In this communication, we described an innovative cost-effective solution to leverage an existing WiGig module with built-in separate Tx and Rx linearly polarized patch antennas by adding a shaped lens to address moderate range (>10 m) point-to-point LoS communications. The main challenge was to mitigate the beam depointing effect presented by canonical lenses, like the elliptical lens, caused by the Tx/Rx feed offset from the focal point of the lens, while ensuring a gain higher than 10 dB in a given angular region around boresight (θ = 0°). We achieved this objective by designing an appropriately shaped lens. The design procedure was validated along with its performance when the lens was integrated with the BGA module. Simulations and measurements confirmed a depointing reduction from 6 to 10 dB across this frequency band.

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REFERENCES


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