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PAPER

3D Printed EM Lens Focusing Antenna Design for Location-Based Services in 5G/6G Systems: Complexity Reduction and Performance Improvement

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ABSTRACT

To achieve better antenna performance and eventually radio localization in fifth and/or sixth generation (5G/6G) wireless systems, it requires massive antenna array-based radio frequency (RF) front ends, resulting in increased overall hardware and computational complexity. In this paper, we propose an electromagnetic (EM) lens focusing antenna, which is capable of providing improved antenna parameters with less complexity as compared to traditional without lens antenna. The proposed EM lens antenna array, where an EM lens, fabricated by a 3D printer, is combined with a microstrip patch antenna array, has an ability to focus the incoming signal on a small area/subset of the antenna array, after passing through the lens, as a function of the angle of arrival (AoA). Resultantly, with the same signal energy as without a lens, we have to process a subset of the antenna array, which eventually contributes to reducing the complexity of the overall RF front end. Furthermore, the performance of the antenna parameters is enhanced significantly. The measured results, i.e., gain and 3 dB beamwidth, are 15.4 dB and 31.5°, respectively, in the case when a single 4.2 GHz frequency patch antenna is combined with an EM lens, which are much improved as compared to the traditional without lens antenna. The improved antenna parameters and AoA-based focusing ability of the proposed 3D-printed lens antenna show that the location-based services for 5G and 6G systems can be achieved in a better way with less complexity.

KEYWORDS

lens antenna, 3D printed lens, smart devices, 5G/6G technology, wireless communication, location-based services

1 INTRODUCTION

Recently the communication technologies, particularly the cellular communication systems, have witnessed dramatic advancements in their infrastructure and

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eventually provided the enhanced quality of services to their users. From first-generation (1G) analog communication infrastructure to the latest fifth-generation (5G) digital infrastructure of communication systems, each generation of communication systems provides higher bandwidth and data rates with multifold services. Starting from 2019, 5G cellular systems are under commercial deployment stage, aiming to provide users with multiple advanced features, including new services, improved data rates in 10s of gigabits per second (Gbps), reduced latency, improved user experiences, and host novel opportunities for industries [1]. The groundbreaking technologies such as massive multiple-input-multiple-output (MIMO) or massive antenna array (MAA) proposed for 5G and 6G wireless communication systems intend to revolutionize the ways of communication and connectivity among people with enhanced performance and reliability [2]. The use of an MAA-based radio frequency front end (RFFE) at a cellular base station (BS) can augment the data rates in Gbps and can serve a huge number of people to get connected wherever they go. However, the MAA-based RFFEs have brought some interesting challenges regarding increased hardware and signal processing complexity, which appear as a hurdle to serving the people at an affordable cost, particularly in low-and middle-income countries. The use of the massive MIMO technique at a BS requires a massive number of hardware (RF chains) and computational complexity in processing large volumes of data signals [3, 4]. Furthermore, most of the related literature is focused on data transmission aspects of the massive MIMO system, not the radio localization and eventually providing the location-based services [5, 6, 7]. In general, the performance of the localization methods is directly proportional to the number of antenna elements deployed in the RFFE. Thus, the MAA-enabled RFFE appears to be a good solution for location-based services as well if its challenges are addressed properly.

The vision of this work is to enable a paradigm shift in designing large-scale antenna arrays deployed in massive MIMO-type technology-based RFFE of cellular communication systems. In this paper, we propose an electromagnetic (EM) lens focusing antenna, which is capable of providing improved antenna parameters with less complexity as compared to traditional without lens antenna. In this regard, the proposed EM lens antenna technique has a unique property of focusing the incoming signal, passing through the lens, on a small area/subset of a large antenna array as a function of angle-of-arrival (AoA). As a result, it will require a few numbers of hardware (RF chains) to process a signal with the same signal energy as without an EM lens case. Moreover, due to a small subset of antennas processing in beam focusing/beam steering, the computational complexity can also be dramatically simplified without employing any sophisticated signal processing algorithms. Eventually, due to the illuminated subset of the antenna as a function of the AoA, precise radio localization-based services can be provided with reduced hardware and computational complexity as compared to the traditional without EM lens MAA systems. We design the lens antenna at 4.2 GHz (mid-range band of 5G technology) and 10 GHz (radar X band) frequencies using polylactic acid (PLA) substrate for the lens and three different types of substrates for the microstrip patch antenna (MPA), including RT Duroid 5880, RO 4350b, and FR4. The designed lens antenna was fabricated and tested in an anechoic chamber for the results validation.

The paper is further organized as follows. Section 2 provides a comprehensive literature review of the related work. The proposed methodology is described in section 3, followed by results and discussion in section 4. Finally, the paper is concluded in section 5.

2 RELATED WORK

The radio localization is a widespread concept in wireless systems where the aim is to locate the source of the received RF signal using one of the many available techniques, including angle of arrival (AoA) or direction of arrival (DoA) estimation, received signal strength indicator (RSSI), and time of arrival (ToA) estimation and its variant time difference of arrival (TDoA) [8]. Among these techniques, the AoA estimation technique, having applications such as in radar, sonar, the internet of things (IoT), and location-based services (LBS) in cellular systems, is a technique in which the angle of the received signal is estimated using an antenna array followed by one of the AoA estimation algorithms such as multiple signal classification (MUSIC), Root MUSIC, Capon's Method, and estimation of signal parameter via rotational invariance technique (ESPRIT) [9, 10]. Generally, the performance of the AoA estimation-based localization is directly proportional to the number of antenna elements deployed in the array. Thus, large antenna arrays can enhance the performance of the antenna parameters, and eventually the localization results can also be improved. However, the large antenna arrays, i.e., massive MIMO techniques, introduce hardware complexity [11]. Besides this, the associated computational cost also increases, particularly when a location-finding algorithm is applied [5, 12, 13, 14].

The authors in [7] propose a technique of cavity-backed MIMO elements to enhance the antenna performance, which is feasible for low-sized antenna arrays. Similarly, a low-cost multi-beam antenna scheme for massive MIMO has been reported in [15]. Moreover, to overcome the cross-user correlation in large antenna systems, a method L-shape array has been suggested in [16]. Furthermore, a few other novel techniques have been proposed, such as in [17, 18, 19, 20, 21], to tackle the challenges of large antenna array systems. However, most of the proposed methods in the literature either address the hardware or computational complexities separately and particularly in the data transmission perspective, not the location-based services as we propose in this paper. By extending our preliminary work, such as reported in [14, 22], in this paper, we propose to combine a 3D printed EM lens with a dielectric substrate-based antenna for improving the antenna performance and reducing the complexity. As mentioned in the below section, we describe in detail the process of designing, fabrication, and measuring the EM lens-assisted antenna, which can be used for location-based services in 5G/6G cellular systems.

3 PROPOSED METHODOLOGY

The proposed EM lens antenna design consists of a dielectric substrate-based EM lens combined with a dielectric substrate-based MPA array at the bottom of the lens, as shown in Figure 1. In this way, the signal coming from a particular direction (i.e., θ) would be focused on a particular subset of the antenna array after passing through the lens which will eventually provide the same signal energy as without the lens, Resultantly, it would increase the antenna performance and reduce the hardware and computational complexity, as one would need to select and process a subset of the antenna array with corresponding RF chains and the computational complexity. Furthermore, the AoA-based focusing ability of the proposed EM lens antenna is the unique property of finding the source location with reduced signal processing complexity because as the direction of the source signal varies, the focused subset of the antenna array varies. Thus, the focused subset of antenna elements can be selected by employing an antenna selection algorithm as described in the below subsection and proceeding further to estimate the location/direction of the focused signal.

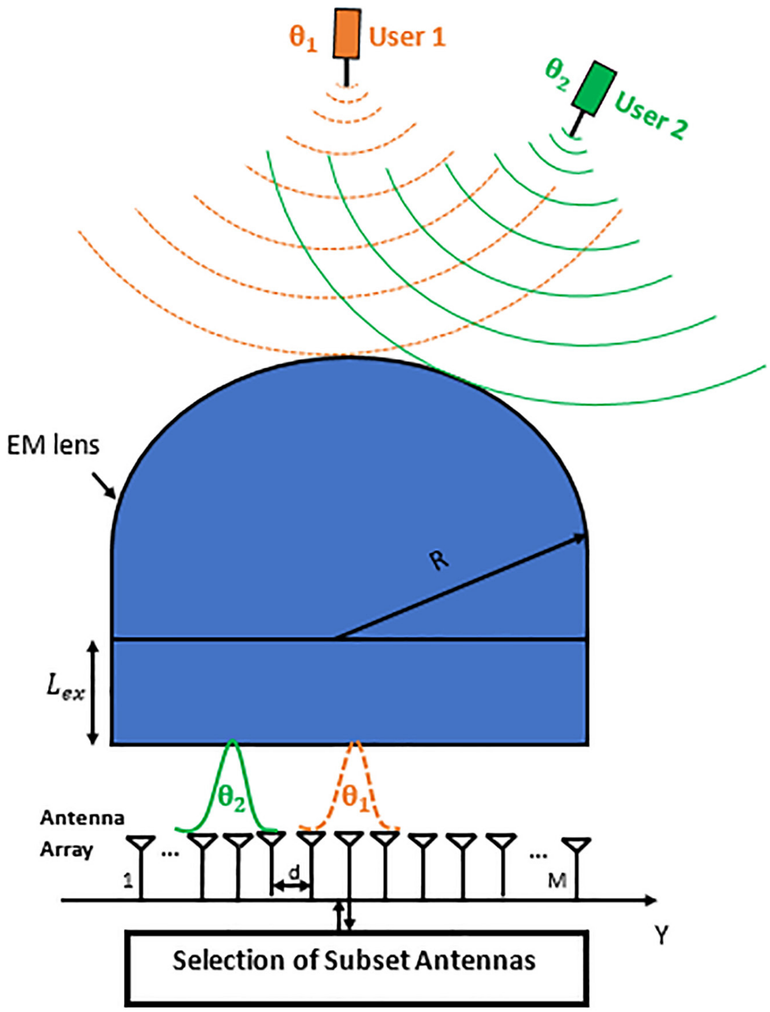

Fig. 1. Proposed 3D-printed EM lens focusing antenna setup

The design principle and geometric parameters of the quarter-wave transformer (QWT) fed microstrip patch antenna (MPA) are described in detail in [14] and summarized in Tables 1 and 2 below, where we consider three different types of substrates for the patch antenna, i.e., RT Duroid 5880, RO4350b, and FR4, and two frequencies, i.e., 4.2 GHz (for the 5G/6G systems) and 10 GHz (x-band radar), for the performance analysis point of view. Moreover, the design of the proposed EM lens and the antenna selection algorithm are described in the below subsections.

Table 1. Properties of substrates assumed for QWT-fed MPA (in millimeter unit)

Substrate	ε_r	h	t	$\tan\delta$
RT Duroid 5880	2.2	1.57	0.035	0.0004
RO4350b	3.66	1.52	0.035	0.0037
FR4	4.4	1.57	0.035	0.02

Table 2. The QWT-fed MPA design parameters (in millimeter units) at 4.2 GHz and 10 GHz frequencies

Substrate	L	W	l_{50}	w_{50}	l_{qw}	w_{qw}
4.2 GHz						
RT Duroid 5880	22	32	13	4.83	13	1.97
RO4350b	34.5	16.8	13	4.83	13	1.97
FR4	15.50	27.91	9.881	3.050	10.91	1.380
10 GHz						
RT Duroid 5880	8.55	11.8	5.05	1.28	5.05	1.20
RO4350b	6.35	12.3	3.5	3	4.65	0.80
FR4	5.95	11.2	4.21	3.21	4.4	0.55

3.1 3D printed EM lens design

In this paper, we design a PLA substrate-based extended hemispherical (EHS) lens as shown in Figure 1, where R and L_{ex} representing the radius and extension length, respectively, are the lens geometric parameters that actually control the focusing and eventually the performance of the lens antenna. The PLA filament/substrate, having a dielectric constant (ε_r) of around 2.7, is readily available and can be used to print the desired lens using a simple 3D printer machine. Generally, the lens radius can be chosen in the range $R_l = 2\lambda_0$ to $25\lambda_0$, where λ_0 is the wavelength at the desired frequency (f_0), given by $\lambda_0 = c/f_0$, where c is the speed of light constant. Moreover, L_{ex}, can be calculated by using the expression, as reported in [23], such as, $L_{ex} = R\left(\frac{\sqrt{\varepsilon_r}+1}{\sqrt{\varepsilon_r}-1}-1\right)$, where ε_r is the dielectric constant of the lens material.

In this way, the design of the simulated PLA substrate-based EHS lens, as described in our paper [14], was exported to 3D-CAD design software, where the design was adjusted according to our lab's 3D printer configurations. The lens geometric parameters were optimized as $R = 2\lambda_0 = 60\ mm$ at $f_0 = 10$ GHz, diameter (D) = $2R = 120\ mm$, and $L_{ex} = 49.4\ mm$. Additionally, in order to fabricate the lens accurately, we fixed the speed of the 3D printer, nozzle temperature, and bed temperature as 50 mm/second, 200 $C°$, and 40 $C°$, respectively. In this manner, the supplied design took almost 1 week in fabricating the desired lens. The 3D-printed lens is illustrated in Figure 2a. Furthermore, the QWT-fed patch MPAs were designed at 4.2 GHz and 10 GHz frequencies using three different dielectric substrates, PCB sheets, as mentioned above. The design parameters of the QWT-fed MPAs are summarized in Table 2, whereas L, W, l_{qw}, w_{qw}, l_{50} *and* w_{50} represent, respectively, the patch length, patch width, quarter-wave strip length, width, 50-ohm line length, and width. The simulated MPAs, simulated in the 3D EM simulator, were fabricated using a CNC machine as shown in Figure 2b–d. Later, the fabricated patch antenna was integrated with the printed lens at the bottom center of the lens. The lens antenna was later tested and measured in the anechoic chamber in order to observe the desired antenna parameters. In this manner, in below subsection, we describe an antenna selection algorithm in order to select the illuminated antenna subset for further processing.

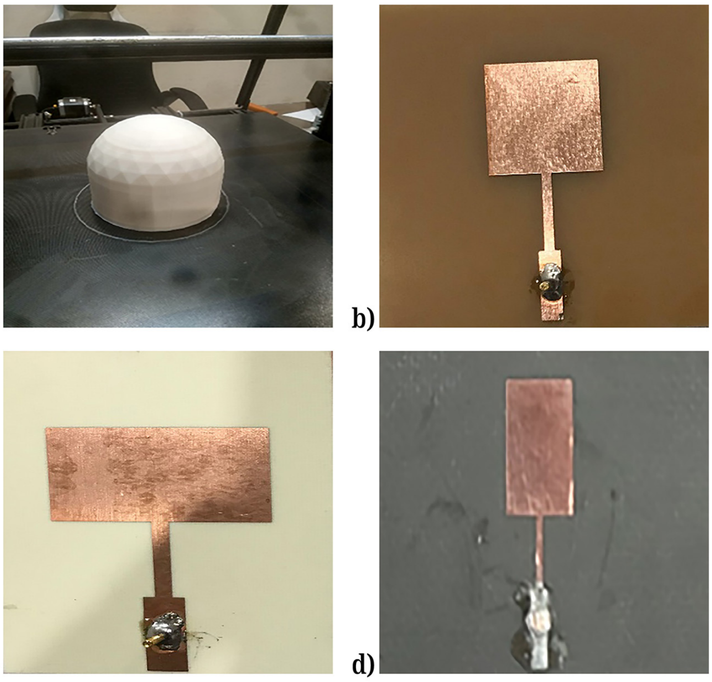

Fig. 2. The fabricated a) 3D printed lens, and b)–d) single patch antennas at 4.2 GHz frequency

3.2 Focused-antenna selection algorithm

To process the excited antenna from the array, we need to employ an antenna selection (AS) strategy. We propose to use the RF coupler [11] based AS technique in which we connect each pair of antennas with a four-port RF coupler. The excited input ports will generate sum (Σ) and difference (Δ) patterns on the output ports which can be used to estimate the direction (θ) of the received signal from the expression as mentioned in [24, 25]. For this, the Σ pattern from the port m_{Σ}^{*} is passed through an integrator and comparator to check if the received Σ signal satisfies the preset threshold (T_v) voltage of selecting the antenna pair. If it satisfies the T_v value then the corresponding sum (m_{Σ}^{*}) and difference (m_{Δ}^{*}) ports for kth user terminal are selected for further processing using RF switches. However, it will keep swapping across maximum *M/2* couplers for the entire array. Thus, we summarize the AS algorithm as follows.

Algorithm: AS using RF Coupler

1: Initialize two sets, one for the unselected antennas $\hat{U} = \{1,2,\ldots,M\}$ and one for selected antennas $\hat{S} = \{\varnothing\}$
2: while $(Card(\hat{S}) \leq S)$
3: If $\left(P_{m_{\Sigma}} \geq T_v \; AND \; m \in \hat{U}\right)$ ***then***
4: Perform: $m_{\Sigma}^{*} = m$
$m_{\Delta}^{*} = m_{\Sigma}^{*} + 1$
5: Extract: $j_k = \left\{m_{\Sigma}^{*}, m_{\Delta}^{*}\right\}$ antenna elements
6: Update: $\hat{S} = \hat{S} \cup \left\{j_k\right\}$ AND
$\hat{U} = \hat{U} / \left\{j_k\right\}$.
End
End

Here, P_{m_Σ} represent the total power of the Σ-port. Thus, the proposed method selects and processes the focused antenna elements with low complexity and improved antenna parameters as compared to the conventional digital signal processing techniques as discussed in the below results section.

4 RESULTS AND DISCUSSION

In this section, we provide and discuss the obtained measured results of the various lens focusing antennas at operating frequencies of 4.2 GHz and 10 GHz using three different dielectric substrates for MPA, i.e., RT Duroid 5880, RO4350b, and FR4. The 3D-printed PLA substrate-based EHS lens and each substrate-based patch antenna was combined in such a manner that patch antenna were integrated at the bottom center of the lens. In this way, the lens antenna was tested and measured in an anechoic chamber, as shown in Figure 3, for the desired performance. The measured results of the lens have been also compared with the traditional antennas without the lens. We discuss the measured results for both 4.2 GHz and 10 GHz frequencies below.

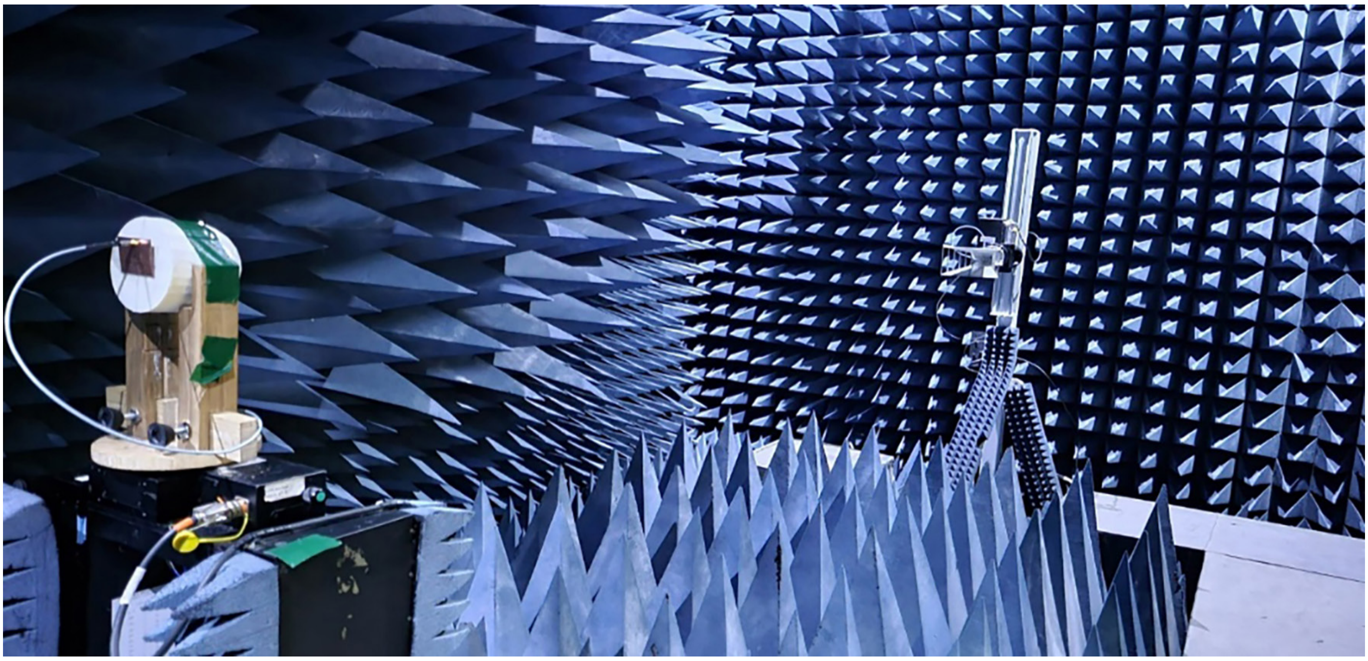

Fig. 3. The fabricated lens focusing antenna under test in an anechoic chamber

The fabricated single MPAs with lens (WL) and without lens (WoL) were characterized on a vector network analyzer (VNA) and tested in receiving mode in an anechoic chamber. The overall measured results are summarized in Table 3 for both 4.2 GHz and 10 GHz frequencies using three different types of dielectric substrates for MPA. First, we discuss the measured results of the RT Duroid 5880 substrate-based MPA integrated with a lens. The measured reflection coefficient (S11) WL and WoL case for 4.2 GHz and 10 GHz frequencies are illustrated in Figure 4a and in Figure 4b respectively, when a single MPA was combined at the bottom-center of the lens. It can be observed that the measured S11 is around –10 dB at 4.2 GHz resonate frequency in the case of both WL and WoL. However, the measured S11 for the 10 GHz frequency antenna in the case of both WL and WoL resonate around 11.4 GHz, which is little shifted from the desired 10 GHz frequency due to fabrication error. Hence, the radiation pattern was measured at 11.4 GHz instead of 10 GHz. Moreover, the position of the single MPA was varied with step size of the $d_s = \lambda_0/2$ to the left and right side of the bottom-center of the lens in order to assess the beam steering/focusing ability of the lens antenna as a function of the AoD/AoA of the signal. The S11 in such cases is also shown in Figure 4a–b.

Later, the proposed lens antenna was tested at the desired frequencies i.e., 4.2 GHz and 11.4 GHz, in an anechoic chamber in receiving mode, as shown in Figure 3, to measure the radiation patterns and the far-field antenna parameters. The 2D-rectangular radiation patterns (normalized to 0 dB) of the same structures at the desired frequencies are shown in Figure 5a and b. It can be remarked that the radiation pattern of the MPA with lens is much more directional and narrower as compared to the traditional MPA without a lens case, as expected. Additionally, the measured far-field antenna parameters, i.e., gain (G_a) in dBi, direction of main lobe (D_l) in degrees, 3 dB beamwidth/half power beamwidth (HPBW) in degrees (BW), and side lobe level (S_l) in dB, as demonstrated in Table 3, show that the antenna parameters in case WL are much improved as compared to the WoL case scenarios. This was also proved in simulation experiments reported in our paper in [14], and the same simulated results are summarized in Table 4. Furthermore, the measured radiation pattern as a function of the MPA position (i.e., $d_s = \pm\lambda_0/2$ towards the left and right sides from the bottom-center of the lens) is also illustrated in Figure 5a and b, which shows that as the AoA of the incoming signal varies, the focused antenna element (position) varies (the maximum signal received on). This proves the lens's focusing ability (i.e., on a subset of the antenna array) as a function of the AoA. The measured antenna parameters in such cases are also demonstrated in Table 3.

In addition to these results of the RT Duroid 5880 substrate-based MPA integrated with a lens, we also performed a few experiments by using the RO 4350b and FR4 substrates-based single MPA combined with a lens. Both substrates-based MPAs were resonating around both desired frequencies, i.e., 4.1 GHz and 9.8 GHz. The measured results with and without a lens using RO 4350b and FR4 substrates are provided in Table 3, where it can be noticed that the results obtained WL are much improved as compared to WoL particularly in the case of RO 4350b, which is a low-loss substrate compared to FR4. For instance, for a single MPA with a lens at a 4.2 GHz resonate frequency, the measured gain and 3 dB beamwidth for RO 4350b (and FR4), respectively, are 15.4 dB (11.9 dB) and 31.25° (31°), which are improved as compared to without lens case i.e., 2.82 dB (–1.22 dB), and 73.56° (71.67°). While in the case of 10 GHz frequency, the RT Duroid 5880 substrate-based patch antenna integrated with the lens outperforms than the other considered substrate-based patch antennas by providing, for instance, $G_a = 15.13$ dBi and $BW = 12°$.

Furthermore, all the above-demonstrated measured results are in somehow good agreement with the simulated results, which show that the proposed lens antenna provides improved performance and reduces the overall hardware and computational cost. Resultantly, the proposed lens antenna structure can be deployed in the RF front end of the 5G/6G cellular systems to achieve location-enabled services with low complexity and improved performance.

Table 3. Measured antenna parameters of the single MPA with lens (WL) and without lens (WoL) at 4.2 GHz and 10 GHz frequencies using different substrates for MPA

MPA Substrate	4.2 GHz					10 GHz				
	S11 (dB)	G_a (dBi)	D_l	BW (deg)	S_l (dB)	S11 (dB)	G_a (dBi)	D_l	BW (deg)	S_l (dB)
RT Duroid 5880 (WoL)	−18.41	5.459	−4°	66°	−16.7	−10.52	5.447	12°	70°	−7.0
RT Duroid 5880 (WL)	−8.22	12.84	−6°	34°	−18.5	−8.5	11.76	−2°	12°	−3.2
RT Duroid 5880 (WL) at $d_s = -\lambda_0/2$	−8.22	9.489	−16°	38°	−19.8	−9.7	12.71	−12°	12°	−3.8
RT Duroid 5880 (WL) at $d_s = -2\lambda_0/2$	−8.22	9.310	−32°	36°	−19.6	−7.8	12.33	−26°	14°	−3.9
RT Duroid 5880 (WL) at $d_s = +\lambda_0/2$	−8.22	11.55	2°	36°	−16.9	−9.7	15.13	10°	12°	−3.4
RT Duroid 5880 (WL) at $d_s = +2\lambda_0/2$	−8.22	8.90	4°	30°	−11.9	−7.8	14.19	22°	12°	−3.4
RO 4350b (WoL)	−25.6	2.82	1.3°	73.56°	−9.2	−17.7	2.57	1.3°	32.44°	−12.9
RO 4350b (WL)	−25	15.4	5.9°	31.25°	−28.7	−17	12.3	4.13°	19.53°	−42.4
FR4 (WoL)	−9.7	−1.22	0.8°	71.67°	−14.3	−10.98	0.33	1°	22.4°	−10.4
FR4 (WL)	−9.5	11.9	4°	31°	−27.4	−10.2	12	3.9°	16.22°	−45.8

Table 4. Simulated antenna parameters of the single MPA with lens (WL) and without lens (WoL) at 4.2 GHz and 10 GHz frequencies using different substrates for MPA

MPA Substrate	4.2 GHz					10 GHz				
	S11 (dB)	G_a (dBi)	D_l	BW (deg)	S_l (dB)	S11 (dB)	G_a (dBi)	D_l	BW (deg)	S_l (dB)
RT Duroid 5880 (WoL)	−33.12	7.04	0.0	67.7°	0.0	−33.33	7.67	0.0	71.4°	−17.7
RT Duroid 5880 (WL)	−22.51	21.5	0.0	10.2°	−19.5	−46.74	21.5	0.0	6.2°	−22.7
RO 4350b (WoL)	−48.98	5.95	0.0	83.8°	0.0	−45.64	6.65	0.0	78.3°	0.0
RO 4350b (WL)	−13	20.7	0.0	11.3°	−20.1	−44.53	17.5	3.0	11.4°	−10.1
FR4 (WoL)	−27.68	4.152	0.0	78.6°	0	−42.51	5.21	0.0	86.5°	0.0
FR4 (WL)	−23.43	16.7	0.0	9.5°	−16.6	−42.86	16.6	3.0	11.2°	−7.4

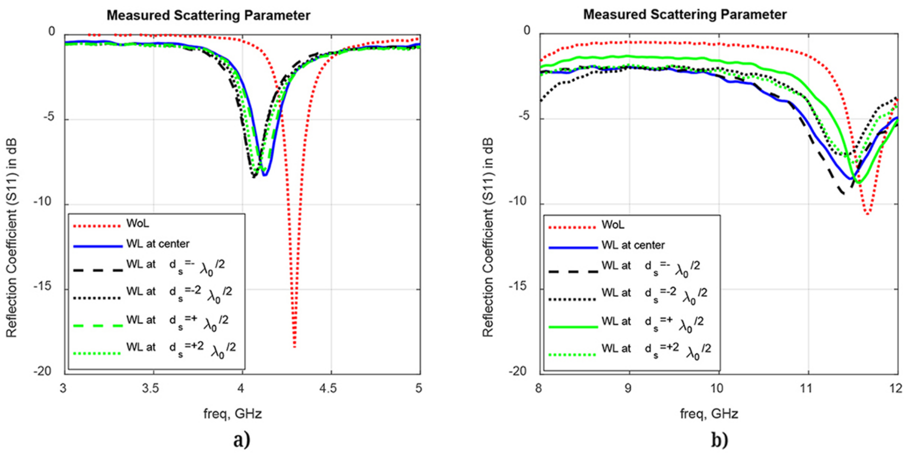

Fig. 4. Measured reflection coefficient (S11) as a function of frequency of a) 4.2 GHz, and b) 10 GHz, WL and WoL using single RT Duroid 5880 substrate-based MPA

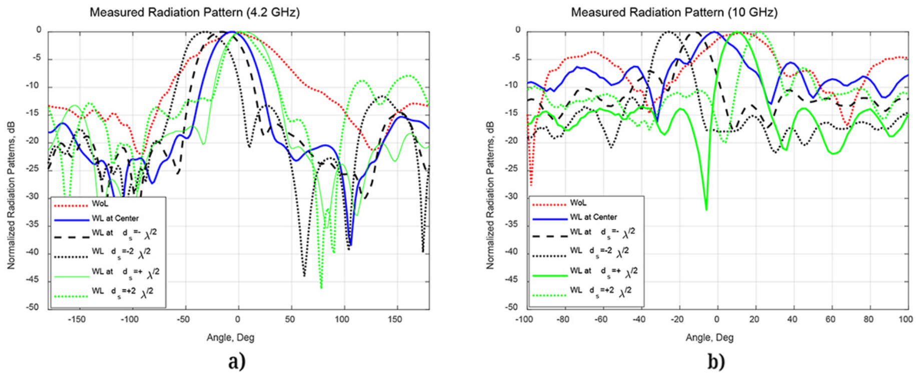

Fig. 5. Measured radiation pattern at frequency of a) 4.2 GHz and b) 10 GHz, WL and WoL using single RT Duroid 5880 substrate-based MPA

5 CONCLUSION

To perform the location-based services in 5G/6G cellular systems with low complexity, in terms of the number of hardware and computation processing efforts, and improved performance, in this paper, we proposed a 3D-printed EM lens focusing antenna array concept. The proposed lens antenna has a property to focus the received signal as a function of the AoA on a subset of the antenna array with the same signal power as in the case without the lens. Hence, it facilitates the location-finding task. In this regard, the proposed PLA substrate-based lens was very carefully first designed with desired geometric parameters, simulated, and then fabricated precisely in a whole solid state using a simple 3D printer machine. Later, the lens was combined with the three different types of substrate-based patch antenna fabricated at 4.2 GHz and 10 GHz frequencies to analyze thoroughly the lens antenna structure's performance. The proposed lens antenna and the traditional without-lens patch antenna were tested and measured in anechoic chamber. From the measured results, it has been analyzed that the proposed lens antenna having low complexity outperforms the conventional without lens antenna at both frequencies of operation. Moreover, by shifting the position of the patch antenna beneath the lens i.e., $d_s = \pm\lambda_0/2$, the beam steering/focusing ability of the lens antenna as a function of the AoA, it has been analyzed. Thus, the proposed lens-focusing antenna has potential to be used in massive antenna array-based location-finding technologies such as 5G/6G cellular systems.

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