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PAPER

Cost-Effective Electromagnetic Lens-Assisted Microstrip Patch Antenna Design for Location-Based Services in 5G/6G Technology Radio Frequency Front End

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ABSTRACT

Microstrip patch antennas (MPAs) are popular in wireless communication systems due to their compact size and easy-to-design properties. However, the performance of such antennas sometimes becomes limited, especially when used in location-based services that require either sophisticated antenna arrays-based radio frequency front-end (RFFE) design or complex signal processing techniques. This paper introduces the concept of an electromagnetic (EM) lens-assisted MPA where a polylactic acid (PLA) substrate-based EM lens is combined with a conventional MPA. Because the EM lens has focused ability, the EM lens-assisted MPA provides improved overall antenna performance. In this paper, we design and simulate the EM lens-assisted MPA and analyze the performance at different frequencies, i.e., 4.2 GHz and 10 GHz, and dielectric substrates for the MPA, i.e., FR4, RO4350b, and RT Duroid 5880. The obtained results show that the EM lens-assisted MPA, particularly the RT Duroid substrate-based MPA integrated with the EM lens, outperforms the traditional MPA without the EM lens. Furthermore, the proposed lens antenna can steer the beam as a function of the MPA position with less complexity and improved performance. Thus, the proposed EM lens antenna in this paper has the potential to revolutionize the RFFE design to be used for location-enabled services, especially in fifth/sixth generation (5G/6G) technology.

KEYWORDS

smart devices, 5G/6G technology, wireless communication, electromagnetic lens antenna, RF front end, location finding

1 INTRODUCTION

The communication systems have witnessed tremendous advancements over the years, enabling faster data rates, broader coverage, and seamless connectivity. Over the past few years, there has been significant progress in the development of

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fifth-generation (5G) technology, driven by the exponential growth of cellular traffic. The surge in demand for faster data rates and greater bandwidth necessitates innovative solutions. One such solution is multiple-input multiple-output (MIMO), which optimizes spectral efficiency and channel capacity by exploiting the multipath property without altering the input power [1, 2, 3, 4]. By implementing MIMO, higher data rates can be achieved, effectively addressing the challenges posed by increasing mobile traffic. However, traditional radio frequency front-end (RFFE) solutions face challenges in providing accurate and reliable wireless services. Moreover, the increasing demand to enrich the effectiveness of wireless communication and radar systems has resulted in the development of microwave antennas with highly directive beams [5]. In this regard, three main structures have been put forth conventionally, including reflectors [6, 7, 8], radiating elements array setup [9, 10] or cavities such as Fabry-Perot (FP) [11, 12], and lenses [13, 14, 15].

The Institute of Electrical and Electronics Engineers (IEEE) defines an antenna as "a means for radiating or receiving radio waves" [16]. In the realm of wireless communication, microstrip patch antennas (MPAs), also called patch or printed antennas, have emerged as a significant alternative to traditional antennas due to their attributes of wide bandwidth and compact size. These antennas are constructed with a metal patch positioned above a ground plane, separated by a dielectric material. The ease of design and straightforward fabrication process have led to their widespread adoption in various wireless applications, making them a prominent choice in modern research and development [17, 18, 19, 20]. However, the performance of such antennas sometimes becomes inadequate, especially when used in location-based services that require either sophisticated antenna arrays-based RFFE design or complex signal processing techniques [21]. Another way to improve the performance of a patch antenna is to combine an electromagnetic (EM) lens with it (called an EM lens-assisted MPA) as proposed in this paper. Because the EM lens can focus the signal as a function of the position of the antenna/(s) integrated with the lens [22, 23, 24], not only can the antenna parameters be improved, but the location-based services can be achieved with less complexity as compared to traditional beam-steering or direction-finding methods such as mentioned in [25, 26, 27, 28, 29].

By extending our preliminary work in [30], in this paper, we describe the design principles of the EM lens-assisted patch antenna in detail and analyze its performance by varying the frequencies of operations and dielectric substrates of the MPA. Moreover, we demonstrate the significance of the proposed lens antenna in beam steering (enabling location-based services) as a function of the position of the MPA integrated with the lens.

This paper is further organized as follows: Section 2 explains the proposed methodology adopted, which includes the design of an EM lens integrated with an MPA. The results obtained in the simulation setup and the design parameters assumed are described in Section 3. Finally, we conclude the paper in Section 4.

2 PROPOSED METHODOLOGY

The EM lens-assisted MPA design, where the EM lens is integrated with an MPA, is a groundbreaking technique that utilizes EM principles to manipulate and focus radio frequency (RF) signals in cellular communication systems with highly directional and narrow beams. The signal focusing ability of the EM lens patch antenna is a function of the angle of arrival (AoA)/angle of departure (AoD) of the signal so that as the AoA of the signal varies, the focusing area varies. This property in the RF front-end design is beneficial for improving signal propagation, reducing interference, and enhancing spatial resolution, particularly in massive or large-scale MIMO technology-based systems that are facing increased hardware and software complexities. Moreover, by controlling the direction and intensity of RF signals, EM lens technology may provide more precise and accurate location-based services within cellular networks with less hardware and computational complexity. This innovation has the potential to revolutionize the efficiency, accuracy, and reliability of location-based applications, benefitting both network operators and end users. As further advancements are made, EM lens-assisted massive MIMO technology is expected to shape the future of cellular communication systems.

To design the EM lens-assisted patch antenna, first, we design a simple patch antenna below in subsection 2.1 and then integrate it with the EM lens in subsection 2.2.

2.1 Patch antenna design

In designing and fabricating an MPA, the printed circuit board (PCB) sheet, consisting of a dielectric substrate and copper layers, and feeding technique play a vital role. A vast literature is available regarding patch antenna design principles such as those mentioned in [1, 16, 19]. In this paper, we use a quarter-wave transformer (QWT)-matched patch antenna design by considering different dielectric substrates, for instance, FR4, RO4350b, and RT Duroid 5880, at operational frequencies (f_o) of 4.2 GHz (5G technology band) and 10 GHz (radar X-band). The geometric parameters for designing the proposed patch antenna, shown in Figure 1, can be calculated as follows [19, 32]:

$$\text{Patch width (W)} = \frac{C}{2f_0\sqrt{\frac{2}{\varepsilon_r + 1}}}, \quad (1)$$

$$\text{Effective dielectric } (\varepsilon_{eff}) = \frac{(\varepsilon_r + 1)}{2}\frac{(\varepsilon_r - 1)}{2}\left[1 + 12\frac{\text{h}}{\text{W}}\right]^{\frac{-1}{2}}, \quad (2)$$

$$\text{Effective length } (L_{eff}) = \frac{C}{2fo\sqrt{\varepsilon_{eff}}}, \quad (3)$$

$$\text{Extension length } (\Delta\text{L}) = \frac{0.412\text{h}\,(\varepsilon_{eff} + 0.3)\left(\frac{\text{W}}{\text{h}} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{\text{W}}{\text{h}} + 0.8\right)}, \quad (4)$$

$$\text{Actual length of the patch } (L) = L_{eff} - 2\Delta L, \quad (5)$$

Where, $c = 3 \times 10^8\ m/sec$, ε_r, and h represent the speed of light, dielectric substrate constant, and the height of the dielectric substrate, respectively.

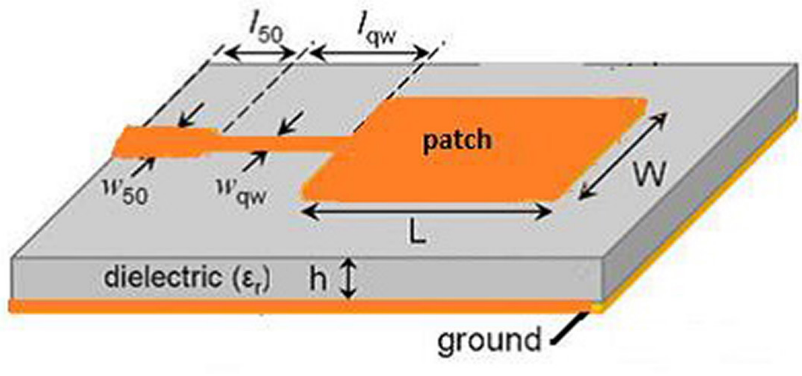

Fig. 1. Typical design of a QWT matched patch antenna

As mentioned earlier, in this paper, we design QWT-fed patch antennas at frequencies of 4.2 GHz and 10 GHz using FR4, RO4350b, and RT Duroid 5880 substrates. The substrate properties (i.e., dielectric constant (ε_r), substrate height (h), copper thickness (t), and tangent or substrate loss (tan δ)) of three considered substrates and the corresponding QWT-matched patch antenna design parameters (in millimeter units) at both frequencies are summarized in Table 1 and Table 2, respectively. Whereas the variables L, W, l_{50}, w_{50}, l_{qw}, and w_{qw} represent the length of the patch, width of the patch, length of the 50-ohm transmission line, width of the 50-ohm transmission, length of the QWT matching section, and width of the QWT matching section.

Table 1. Properties of substrates assumed

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

Table 2. The QWT matched MPA design parameters (in millimeter units) without a lens at 4.2 GHz and 10 GHz frequencies

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

2.2 Electromagnetic lens design and its integration with patch antenna

To advance the performance of the conventional patch antenna, we introduce the concept of an EM lens-enabled patch antenna where an EM lens is combined with a traditional patch antenna. For effective lens antenna design, it is important to choose the right lens geometry (i.e., spherical/Luneburg, extended hemispherical, elliptic, etc.) and lens material (i.e., Teflon, resolute, polyethylene, silicon, PLA, quartz, etc.) [15, 29]. In this section, we design the extended hemispherical (EHS) lens, as shown in Figure 2, where R_l and L_{ex} are lens geometric parameters representing the lens radius and extension length, respectively. By varying these lens design parameters, the focusing ability of the lens can be controlled, and so can the antenna parameters. Moreover, by changing the spatial position of the MPA, integrated with the lens, the beam can be driven in different directions.

In this paper, we design a polylactic acid (PLA) substrate-based EHS lens, where ε_r of the PLA is 3.54 and the tan δ is 0.011. The PLA is a readily available filament material that can be used to print the lens using a 3D printer. The R_l and ε_r values for the proposed EHS lens can be assumed from the range of $R_l = 2\lambda_0$ to $25\lambda_0$, and $\varepsilon_r = 1.1$ to 13, respectively, where λ_0 is the wavelength of the desired signal, given by $\lambda_0 = c/f_0$. While, L_{ex}, depending on the lens filament selected and the required grade of focusing degree, it can be calculated as [31].

$$L_{ex} = R_l\left(\frac{\sqrt{\varepsilon_r}+1}{\sqrt{\varepsilon_r}-1}-1\right). \tag{6}$$

We have simulated PLA material-based EM lenses and combined them with each of the above-designed patch antennas using an EM simulator. The geometric design parameters of the PLA-based EM lens at frequencies of interest are summarized in Table 3, where $R_l = 5\lambda_0$ and L_{ex} is calculated using expression (6). While results observed of the proposed lens antenna are described in detail in the below section. However, in order to attain the desired results and to lessen the simulation time, a manual optimization in design parameters of the lens and/or patch antenna is generally required.

Table 3. Design parameters of the PLA-based EM lens (in millimeter units) at frequencies of interest

Frequency (GHz)	R_l	L_{ex}
4.2	357	286
10	150	120

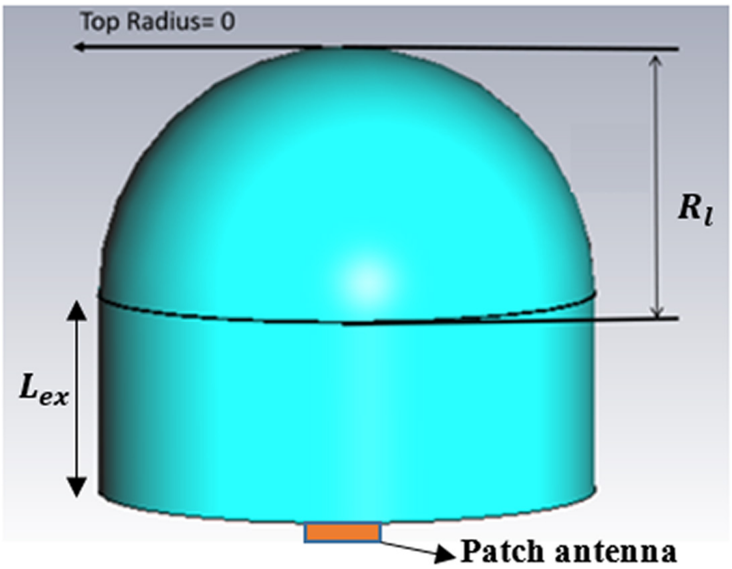

Fig. 2. Proposed EHS lens combined with a patch antenna

3 RESULTS AND DISCUSSION

We discuss, in this section, the obtained results of the various simulated EM lens-assisted patch antennas at frequencies of 4.2 GHz and 10 GHz using three different dielectric substrates for patch antennas, i.e., FR4, RO4350b, and RT Duroid 5880. The obtained results have also been compared with the traditional patch antennas without the lens. We discuss the results obtained for the 4.2 GHz frequency below, which are followed by 10 GHz frequency results.

The simulated 4.2 GHz EM lens-assisted MPA design values using three different dielectric substrates are provided above in Tables 2 and 3. The simulated designs, where the patch antenna is positioned at the bottom-center of the lens, provided the return loss (RL/S11), displayed in Figure 3 (a–c), as –23.4364 dB, –13 dB, and –22.51 dB for the FR4, RO4350b, and RT Duroid 5880, respectively. The obtained return loss of the lens antenna in each case is less than the acceptable –10 dB value and in good agreement to without the lens antenna. Moreover, the 2D radiation pattern of each designed lens antenna is illustrated in Figure 4 (a–c), which reflects that the beam is quite narrow and directional. Furthermore, the obtained antenna performance parameters, i.e., return loss (RL), antenna gain (G_a), main lobe direction (D_l), 3dB-beam width (BW) in degrees unit, and the side lobe level (S_l), are provided in Table 4 with the lens (WL) and without the lens (WoL). It is observed that all the considered lens-assisted MPAs provide better antenna performance parameters as compared to the patch antennas without lenses. Particularly, the BW of each lens antenna is much narrower, showing the high directional beam due to the focusing ability of the proposed EM lens. Moreover, the lens antenna designed using the RT Duroid substrate-based patch antenna provides overall better results over other substrates due to the low substrate loss.

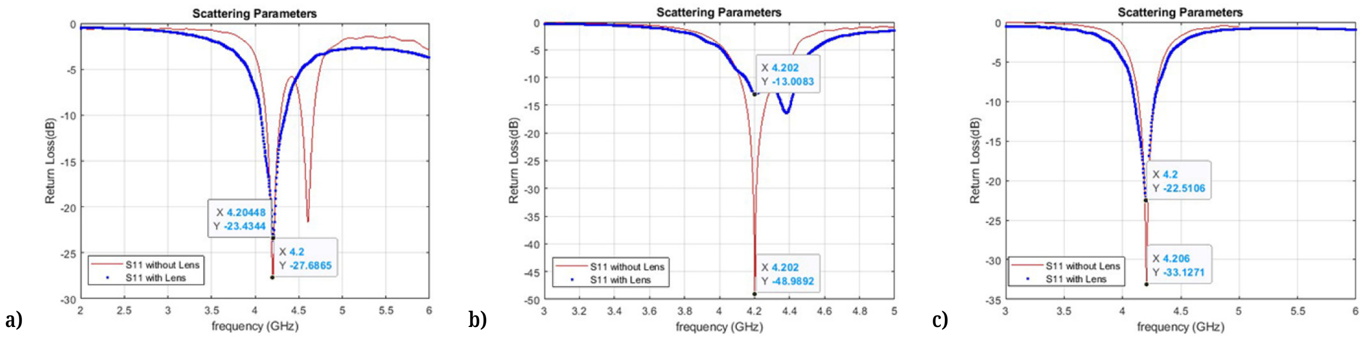

Fig. 3. The obtained return loss (S11) at frequency 4.2 GHz with and without a lens antenna using a) FR4, b) RO4350b, and c) RT Duroid 5880 substrate

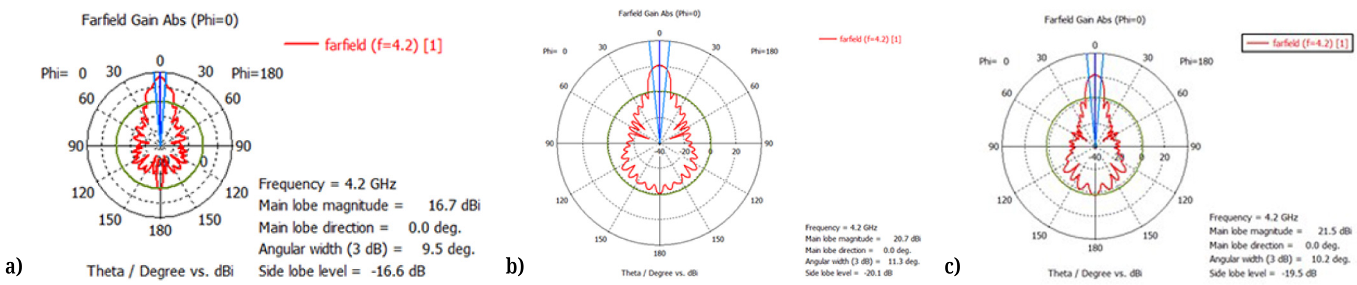

Fig. 4. The proposed 4.2 GHz lens antenna's obtained 2D radiation pattern using a) FR4, b) RO4350b, and c) RT Duroid 5880 substrates

Table 4. Obtained Antenna Parameters WL and WoL at 4.2 GHz frequency

Substrate	*RL* (*dB*)	G_a (*dBi*)	D_l	*BW* (*deg*)	S_l (*dB*)
FR4 (WoL)	–27.68	4.152	0.0	78.6	0
FR4 (WL)	–23.43	16.7	0.0	9.5	–16.6
RO4350b (WoL)	–48.98	5.95	0.0	83.8	0.0
RO4350b (WL)	–13	20.7	0.0	11.3	–20.1
RT Duroid 5880 (WoL)	–33.12	7.04	0.0	67.7	0.0
RT Duroid 5880 (WL)	–22.51	21.5	0.0	10.2	–19.5

In this way, the simulated EM lens-assisted patch antenna at a 10 GHz frequency provided the RL, illustrated in Figure 5 (a–c), as –42.86 dB, –44.53 dB, and –46.74 dB for the FR4, RO4350b, and RT Duroid 5880, respectively. The obtained return loss in each case is less than the acceptable –10 dB value and in good agreement with the traditional without-lens antenna. The 2D radiation pattern of each designed lens antenna is displayed in Figure 6 (a–c), which reflects that the beam is quite narrow and directional. Moreover, the observed antenna parameters with a lens and without a lens are given in Table 5. Here, the observed antenna performance parameters of the projected lens antennas are better than those of the traditional ones without the lens antennas. The lens antenna designed at a frequency of 10 GHz using a low-loss RT Duroid 5880 substrate-based patch antenna provides overall better results, followed by the RO4350b and FR4 substrates, respectively.

Table 5. Obtained antenna parameters WL and WoL at 10 GHz frequency

Substrate	*RL* (*dB*)	G_a (*dBi*)	D_l	*BW* (*deg*)	S_l (*dB*)
FR4 (WoL)	–42.51	5.21	0.0	86.5	0.0
FR4 (WL)	–42.86	16.6	3.0	11.2	–7.4
RO4350b (WoL)	–45.64	6.65	0.0	78.3	0.0
RO4350b (WL)	–44.53	17.5	3.0	11.4	–10.1
RT Duroid 5880 (WoL)	–33.33	7.67	0.0	71.4	–17.7
RT Duroid 5880 (WL)	–46.74	21.5	0.0	6.2	–22.7

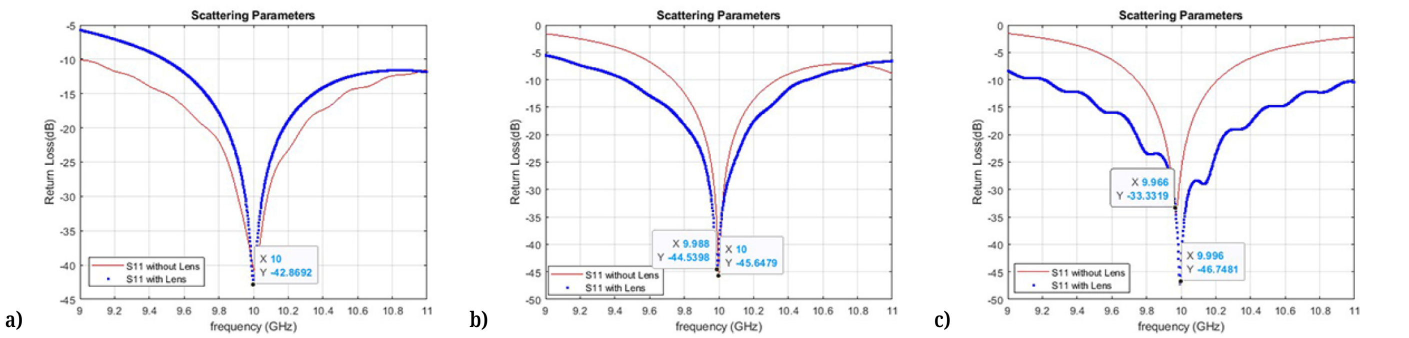

Fig. 5. The obtained return loss (S11) at 10 GHz frequency with and without the lens antenna using a) FR4, b) RO4350b, and c) RT Duroid 5880 substrate

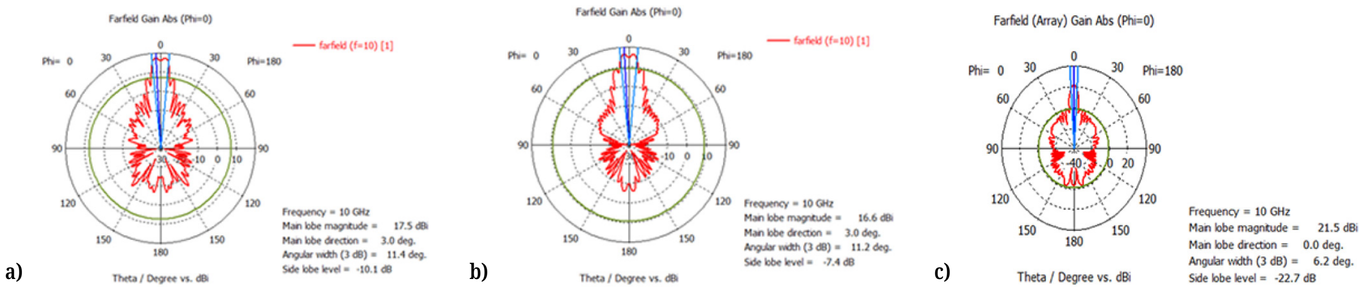

Fig. 6. The proposed 10 GHz lens antenna's obtained 2D radiation pattern using a) FR4, b) RO4350b, and c) RT Duroid 5880 substrate

Additionally, to investigate the beam steering capability of the anticipated lens antenna design in different directions as a function of the location of the MPA beneath the lens, we have designed a 10 GHz linear array of 1 × 2 size of the RT Duroid 5880 substrate-based patch antenna and shifted it from the lens bottom center point towards the left side and right side of the lens with a step size of $d_s = \lambda_0/2$ (position of antenna), as displayed in Figure 7a and 7b. As a result, the observed 2D radiation patterns in various directions as a function of the antenna position (d_s) are illustrated in Figure 7c and 7d. It can be observed that as the antenna element's position varies, the beam is steered accordingly in different directions with almost similar performance as discussed earlier and summarized below in Table 6. Moreover, it can be noticed that the beam steering ability of the low-loss substrate-based lens antenna (i.e., RT Duroid 5880) is synchronous as compared to the high-loss substrate-based lens antenna (i.e., FR4). Eventually, the proposed lens antenna seems suitable to be used in the RF front end of the 5G/6G cellular systems to provide location-enabled services with less complexity and better performance. However, the practical realization of the projected design, especially the EM lens, can be achieved by using professional 3D printing technology, which is beyond the scope of this work.

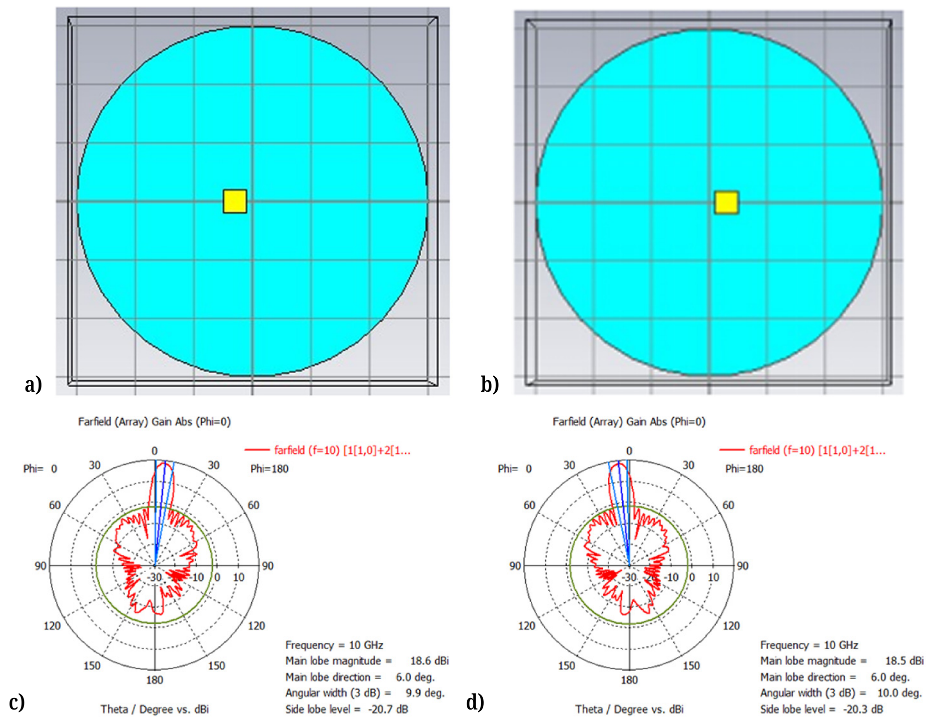

Fig. 7. At 10 GHz frequency and RT Duroid 5880 substrate, MPA array design with lens and shifting of array to a) left and b) right sides of the lens center; and observed simulated 2D radiation pattern (combined array) with c) left shift $d_s = -\lambda_0/2$, and d) right shift $d_s = +\lambda_0/2$

Table 6. Observed antenna performance parameters of 10 GHz MPA array (1 × 2) with lens as a function of shifting of array

Substrate	RL (dB)	G_a (dBi)	D_l (deg.)	BW (deg.)	S_l (dB)
FR4 at $d_s = -\lambda_0/2$ (left)	–27.60	14.3	1	*14.5*	–6.6
FR4 at $d_s = +\lambda_0/2$ (right)	–15.24	17.03	–7	*8.3*	–1.1
FR4 at $d_s = -2\lambda_0/2$ (left)	–20.85	17.02	9	*11.6*	–9
FR4 at $d_s = +2\lambda_0/2$ (right)	–15.23	17.29	–13	*7.4*	–1.1
RO4350b at $d_s = -\lambda_0/2$ (left)	–12.2	17.7	3	*10.2*	–15.4
RO4350b at $d_s = +\lambda 0/2$ (right)	–12.0	17.4	–3	*10.5*	–15.1
RO4350b at $d_s = -2\lambda_0/2$ (left)	–10.39	18.13	10	*14.1*	–15.7
RO4350b at $d_s = +2\lambda_0/2$ (right)	–11.2	17.6	–9.8	*14.5*	–15.8
RT Duroid 5880 at $d_s = -\lambda_0/2$ (left)	–16.16	18.6	6	*9.9*	–20.7
RT Duroid 5880 at $d_s = +\lambda_0/2$ (right)	–16.53	18.50	–6	*10*	–20.3
RT Duroid 5880 at $d_s = -2\lambda_0/2$ (left)	–16.13	17.61	11	*11.1*	–14.4
RT Duroid 5880 at $d_s = +2\lambda_0/2$ (right)	–16.27	17.56	–10.6	*11.3*	–15

4 CONCLUSION

In this paper, we analyzed the performance of the proposed PLA-based EM lens-assisted microstrip patch antenna designed at 4.2 GHz and 10 GHz frequencies using different dielectric substrates, i.e., FR4, RO4350b, and RT Duroid 5880-based patch antennas. Firstly, we simulated the simple QWT-fed MPAs at desired frequencies and the substrates using an EM simulator. Then each designed MPA was combined with a PLA material-based hemispherical EM lens. The lens-assisted MPA provided overall improved antenna parameters due to it focusing property. Furthermore, it was observed that due to lower substrate loss, the RT Duroid substrate-based MPA integrated with the lens provided better results as compared to the other substrates considered in the MPAs design. Secondly, it was observed that by varying the location of the MPA in the proposed lens antenna array setup, the beam was steered accordingly. Eventually, the proposed lens antenna seems appropriate to be used in the RF front end of the 5G/6G wireless communication systems to provide location-based services with less complexity and better performance.

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