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Antenna array bandwidth enhancement using polymeric nanocomposite substrate

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Abstract A 4 × 2 array antenna is developed using a new nanocomposite polymeric magneto-dielectric substrate. The permittivity and permeability factors have been accounted in designing the proposed array antenna at the frequency of 2.6 GHz. A pure polydimethylsiloxane (P-PDMS) ($\varepsilon_r = 2.7$) solution is mixed with ferrite III oxide ($\mu_r = 1.2$) to generate this new nanocomposite polymeric magneto-dielectric (NPMD) substrate. The NPMD surface is then hardened and located in between two P-PDMS layers. The 4 × 2 radiating elements are immersed to the top of P-PDMS layer, while SMA coaxial feeder is fed from underneath the ground layer. This sealing technique enabled the proposed antenna to be waterproof and flexible. This combination contributes to bandwidth enhancement of 52.65 %, size miniaturization of 176 × 156 mm^2 and high gain of 10.8 dB. The measured results show a good agreement with simulations.

1 Introduction

Patch microstrip antennas are commonly constructed using dielectric substrates. One of the main factors to obtain a good antenna performance is the dielectric permittivity of the substrate. It describes the amount of electric field or flux which is generated per unit charge in the medium [1]. Low permittivity yields more electric flux in a medium due to the polarization effects as illustrated in Fig. 1 [2].

Another contributing factor is the permeability which can be described as the amount of magnetic flux created within the medium when external magnetic fields are applied. By including ferrite which is a magnetic material in the microstrip antenna substrate, additional control on radiation pattern can be obtained, besides bandwidth enhancement and size reduction [3–6].

The increasingly demanding antenna requirements in recent years have triggered researchers to construct radiators which are flexible, light and robust. Among the advantages of using polydimethylsiloxane (PDMS)-based materials is that it is thermally stable, simple to fabricate and modified to feature different permittivity or permeability [7]. Jovanche et al. [8] presented a flexible patch PDMS antenna where copper-mesh structures were fully integrated inside the PDMS substrate.

On the other hand, a reconfigurable PDMS antenna for millimeter waves was introduced by Hage-Ali et al. [9]. A new, reliable and robust technological process for supporting transmission lines and microstrip antenna arrays was described.

Karilainen et al. [10] presented a miniaturized antenna using magneto-dielectric and dielectric substrates. To reduce antenna size, the characteristics of the magneto-dielectric material such as the strength of the magnetic response, natural magnetic inclusions and low losses characteristics are taken into account. The properties of the magneto-dielectric polymer nanocomposites are complementary for microwave device and RF applications as investigated by Morales et al. [11].

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While it is well known that a high dielectric permittivity can reduce antenna size, it indirectly decreases its bandwidth and radiation efficiency. Therefore, replacing a high permittivity substrate with magneto-dielectric material is one of the options to reduce antenna size while allowing bandwidth enhancement [12, 13, 14–17] .

This paper attempts to use this magneto-dielectric substrate to simultaneously increase gain, bandwidth and size compactness. The combination of pure PDMS (P-PDMS) with ferrite III oxide (Fe_3O_4) leads to the introduction of the new nanocomposite polymeric magneto-dielectric (NPMD) substrate. NPMD is then placed in between of another two layers of P-PDMS layers. The 4 × 2 radiating elements are placed on top of the P-PDMS layer, while a full ground layer is embedded in another layer of P-PDMS. It is found that the presence of the Fe_3O_4 magnetic material enhanced the bandwidth and gain of the proposed antenna up to 52.65 % and 10.8 dB, respectively.

This paper is organized as follows: In Sect. 2, the performance of a single patch made using P-PDMS, FR4 and NPMD substrates is analyzed. Next, Sect. 3 presents the 4 × 2 array made using NPMD substrate. The simulation and measurement results are discussed in Sect. 4 prior to the conclusion section.

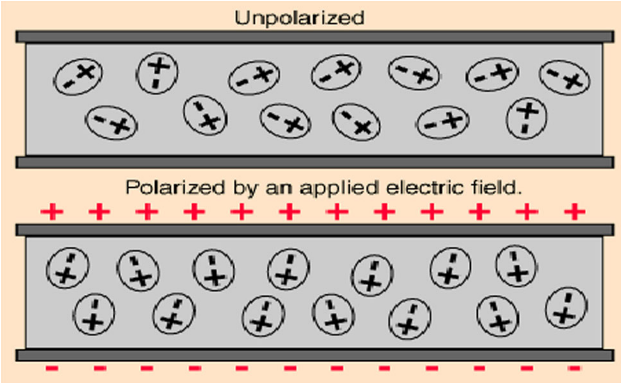


Fig. 1 Schematic diagram of unpolarized and polarized situations when applied electric field [2]

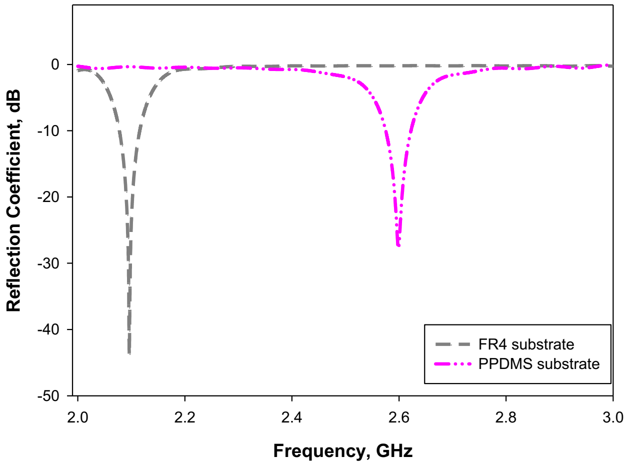
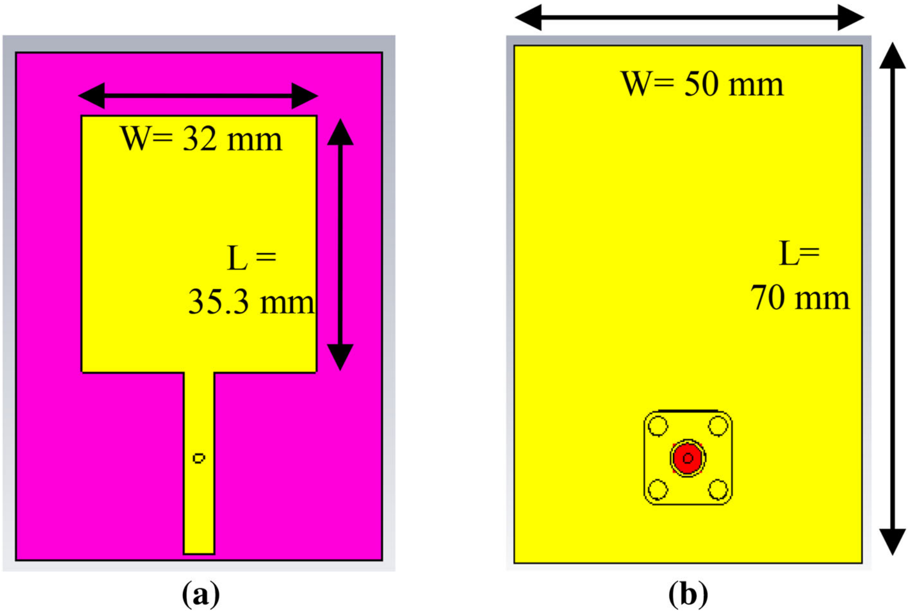


Fig. 3 Reflection coefficient of two similarly dimensioned P-PDMS and FR4 antennas

Fig. 2 Single-patch pure PDMS antenna. **a** *Front* view and **b** *back* view



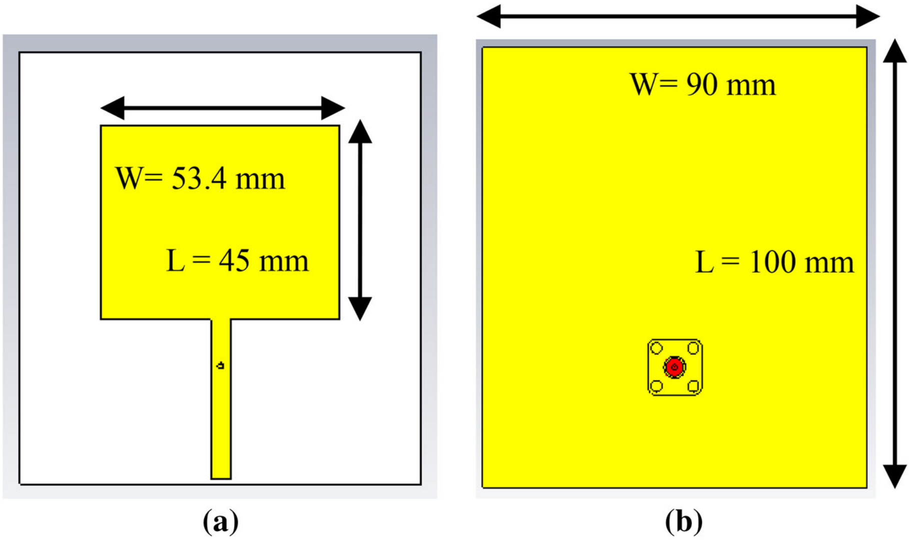


Fig. 4 Single-patch FR4 antenna. **a** *Front* and **b** *back* views

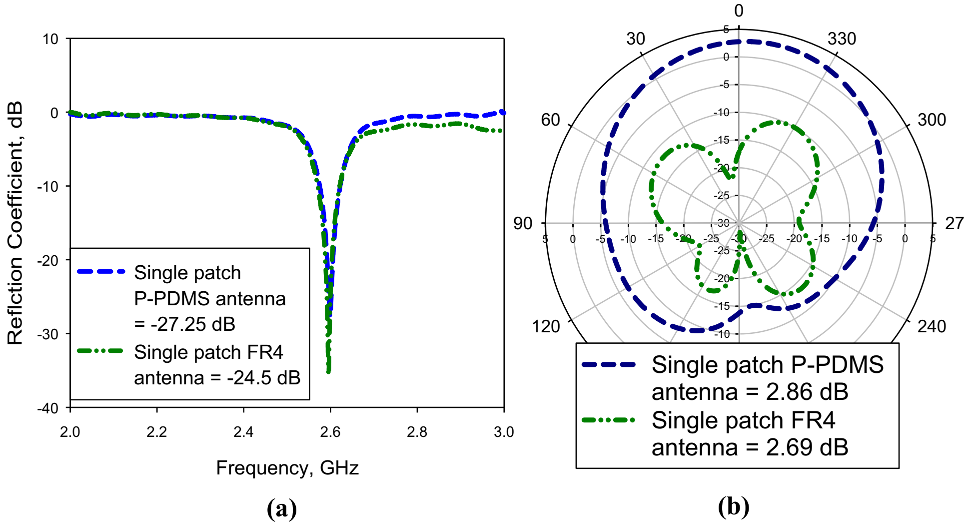


Fig. 5 Simulation results for single-patch P-PDMS and FR4 antennas. **a** Reflection coefficient and **b** polar radiation pattern

2 Substrate materials

First subsection in this section will compare P-PDMS and FR4 substrates. The effect of adding the magnetic materials on the antenna performance will be analyzed in the following subsection.

2.1 Permittivity comparison of P-PDMS with FR4 substrates for a single-patch antenna

Since permittivity is one of the main factors as to ensure the amount of electric flux that exists in the substrate, this section investigates two antennas using two different substrates: P-PDMS ($\varepsilon_r = 2.7$) and FR4 ($\varepsilon_r = 4.7$). The thicknesses for both substrates are 1.6 mm. The single-patch P-PDMS antenna is shown in Fig. 2.

A single-patch P-PDMS antenna is designed with an optimal size of 50 mm for the width and 70 mm for the length. An SMA coaxial probe is fed from the bottom of the ground layer as shown in Fig. 2b. Optimization was performed, and it was found that 32 × 35.5 mm is the best dimension patch for single-patch P-PDMS antenna as shown in Fig. 2a.

In Figs. 3, 4, replacement of P-PDMS with FR4 has shifted frequency downwards, while remaining the same dimension. This occurred because higher permittivity reduces the electric flux inside the substrate due to the polarization factor [1]. Therefore, a single-patch FR4 antenna needs to be re-optimized to function at 2.6 GHz.

Figure 4a shows the optimized single-patch FR4 antenna with larger dimensions of 53.4 mm × 45 mm compared to P-PDMS. The ground plane dimensions widen as well as can be seen in Fig. 4b.

Figure 5a clearly records that a single-patch P-PDMS antenna produced better S_{11} compared to a single-patch FR4 antenna. The same pattern goes to gain's parameter as depicted in Fig. 5b.

2.2 Adding magnetic material into pure PDMS (P-PDMS) antenna

As previously mentioned, magneto-dielectric material is capable of enhancing bandwidth while reducing the size of the antenna. The combined use of magnetic field and electrical field can further enhance bandwidth as well as miniaturize the antenna size [11, 12, 18, 19]. Fe_3O_4 has been chosen as it is relatively lower loss compared to other magnetic materials [11].

The combination P-PDMS–Fe_3O_4 produced a new substrate known as the nanocomposite polymeric magneto-dielectric (NPMD) substrate. The NPMD layer is located in the middle of P-PDMS layers as photograph in Fig. 6. The SMA coaxial probe is fed from the bottom layer where the substrate thickness is 4.2 mm. Figure 7 depicts the single-patch NPMD antenna.

Figure 8 shows the reflection coefficient, S_{11} for the three designed patch antennas, whereas the gain is shown in Fig. 9. The single-patch NPMD antenna outperforms the results compared to the single-patch P-PDMS and FR4 antennas as tabulated in Table 1.

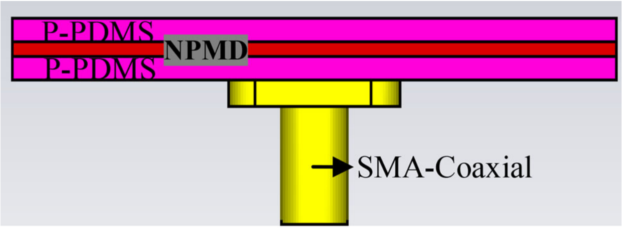


Fig. 6 NPMD (*dark color*) is located in the middle of P-PDMS antenna

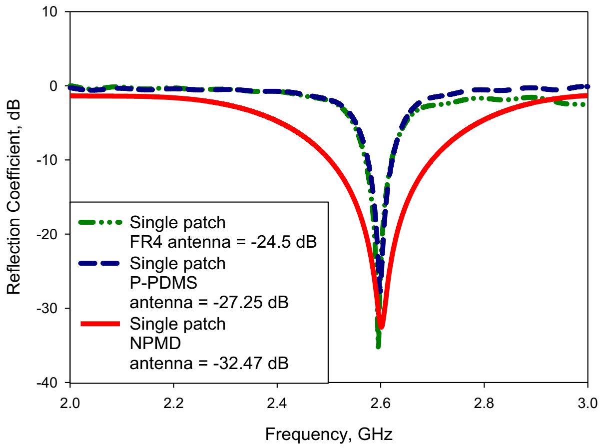
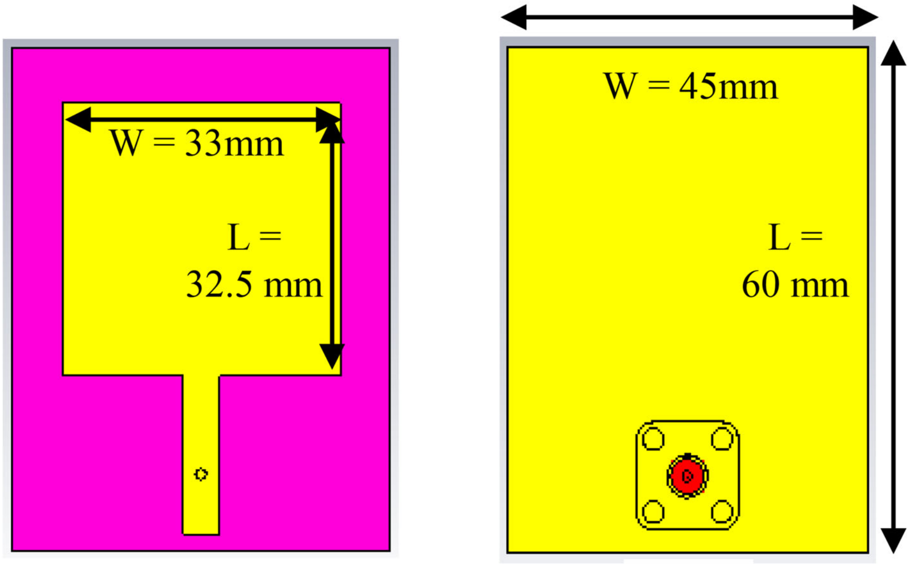


Fig. 8 Simulation results for single-patch FR4 antenna

Fig. 7 Single NPMD patch antenna. **a** *Front* view and **b** *back* views



(a) **(b)**

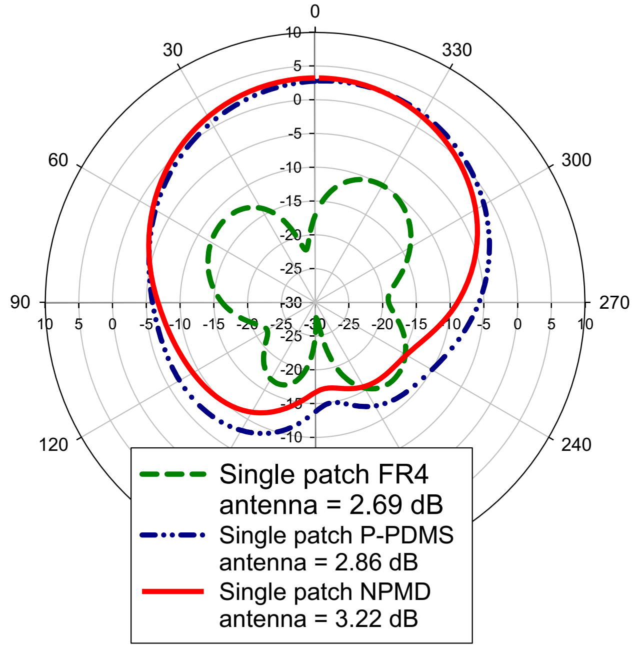


Fig. 9 Polar radiation pattern for single-patch FR4 antenna (*green line*), single-patch P-PDMS antenna (*blue line*) and single-patch NPMD (*red line*)

3 Array configuration

In Sect. 2, the authors proved that combination of P-PDMS with Fe$_3$O$_4$ has the advantages of wider bandwidth, size miniaturization and gain enhancement. For further enhancement, 4 × 2 array antenna is designed with optimized size of 176 × 156 mm^2, as shown in Fig. 10a. The antenna is designed with full ground plane at the reverse side (refer to Fig. 10b).

Figure 11 demonstrates the fabrication steps of proposed array antenna. Firstly, copper clad have been cut accurately to the dimension required as can be seen in Fig. 11a, b. Figure 11c shows the liquid is ready for the first layer of P-PDMS substrate. After the layer turn to sticky semisolid, the radiating patches are aligned properly as shown in Fig. 11d. The NPMD liquid yields new eye-catching brown color as depicted in Fig. 11e. The next step is pouring P-PDMS layer on top of solid NPMD layer as can be seen in Fig. 11f. Finally, ground layer is covered by P-PDMS layer to ensure this proposed antenna is fully sealed, and Fig. 11g, h shows the complete 4 × 2 array antenna prototype. The SMA coaxial feeder is fixed at the bottom of

Table 1 Comparison results between P-PDMS, FR4 and NPMD antenna

Single-patch antenna at operating frequency of 2.6 GHz				
Substrate	Size antenna (W × L) mm	Size patch (W × L) mm	Reflection coefficient S11 (dB)	Gain (dB)
P-PDMS	50 × 70	32 × 35.3	−27.25	2.86
FR4	90 × 100	53.4 × 45	−24.50	2.69
NPMD	45 × 60	33 × 32.5	−32.47	3.22

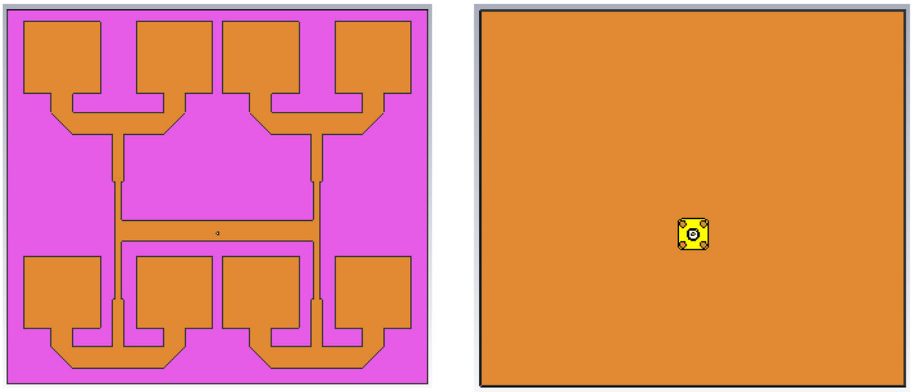
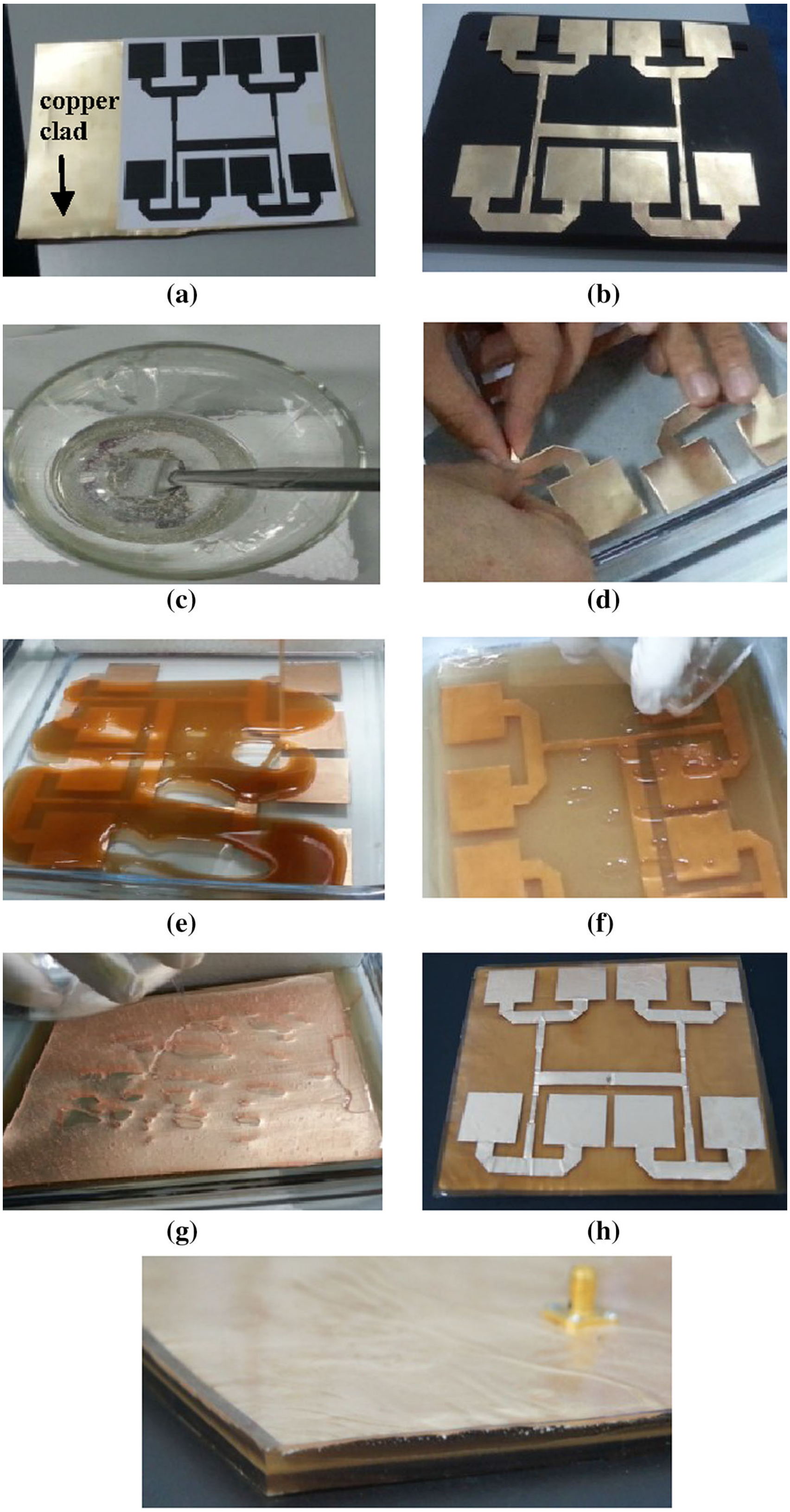

(a) **(b)**

Fig. 10 The 4 × 2 array antenna. **a** *Front* and **b** *back* views



(a) (b) (c) (d) (e) (f) (g) (h) (i)

Fig. 11 Fabrication steps **a** Copper clad sheet before cutting, **b** cutting the copper clad according to the dimension of the radiating elements, **c** a liquid P-PDMS substrate, **d** the overall copper clad is placed on the P-PDMS layer, **e** NPMD substrate still in liquid condition, **f** fourth layer of P-PDMS substrate, **g** final layer of P-PDMS substrate after placement of the ground layer, **h** a complete prototype of 4 × 2 array antenna and **i** SMA connector inserted via the ground plane to the radiating elements

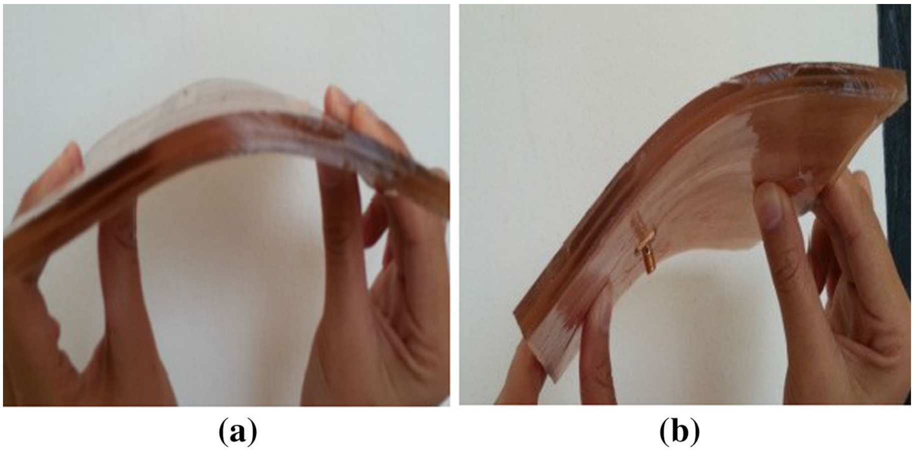

(a) (b)

Fig. 12 The 4 × 2 array antenna can be bent and flexible. **a** *Front* view and **b** *back* view

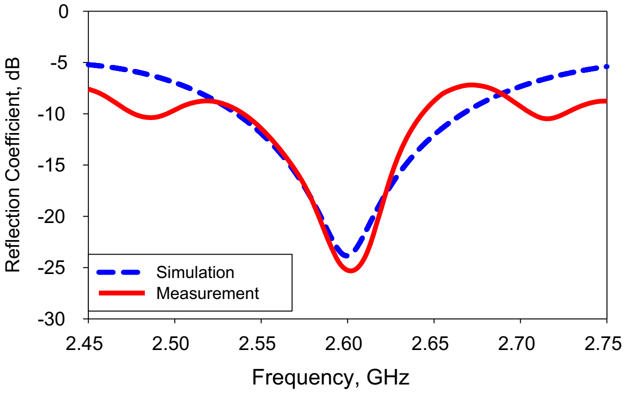


Fig. 13 The measurement (*red line*) and simulation (*blue line*) results of reflection coefficient

the antenna and penetrates into P-PDMS layer to touch the ground plane as shown in Fig. 11i.

The fabricated antenna has outstanding mechanical properties in terms of bending and flexibility as illustrated in Fig. 12. The radiating element and ground plane are fully immersed inside the P-PDMS substrate which could make it as a water resistance antenna.

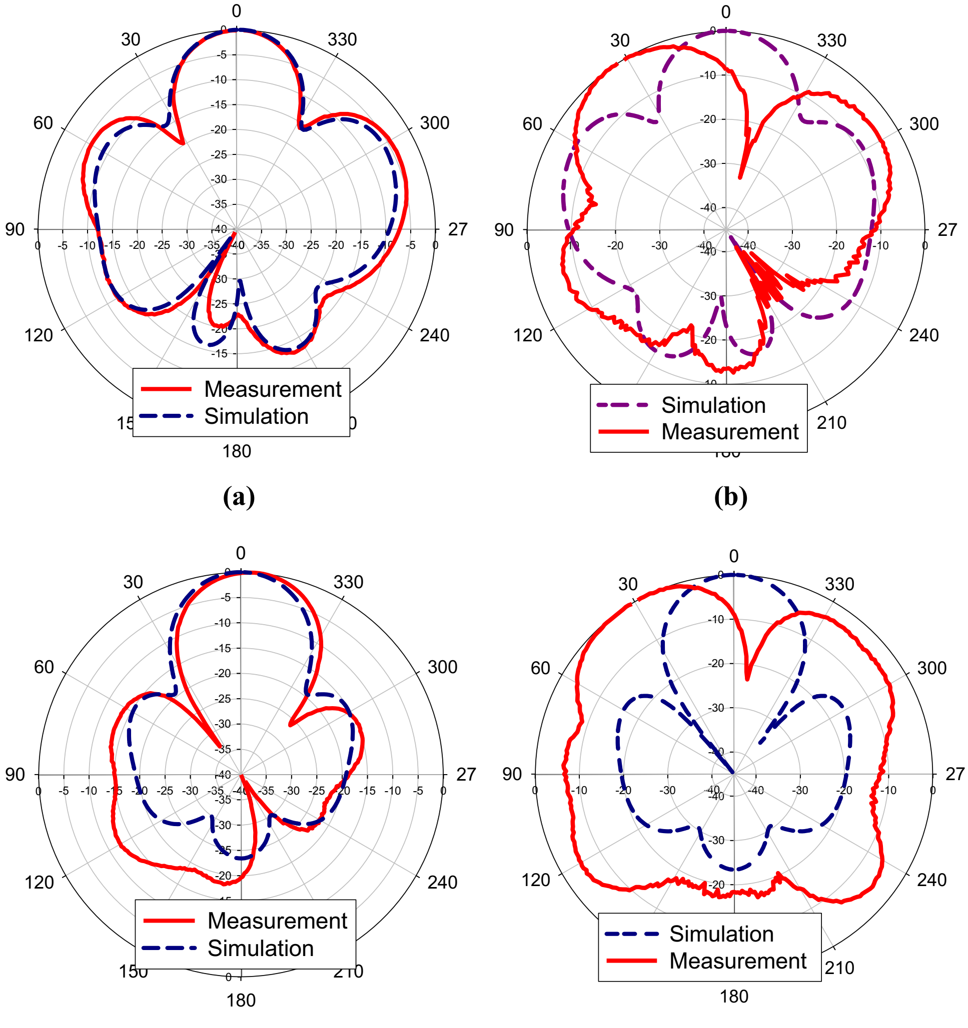
4 Results and discussion

A lower permittivity is required for the antenna to attain a wider bandwidth and high radiation efficiency [6]. Combination of P-PDMS with Fe_3O_4 created strong electrical magnetic fields. NPMD produced a magnetic medium within the substrate and yields a great impedance bandwidth with permeability of 1.2. By adding NPMD layer, the antenna size is minimized due to the fact that effective wavelength is declined as in Eq. (1) [20].

$$\lambda_{\text{eff}} = \frac{\lambda_{\text{air}}}{\sqrt{\varepsilon_r \mu_r}} \tag{1}$$

Measurement and simulation reflection coefficient are compared in Fig. 13. It shows that both results are comparable with measurement result stated at −23.92 dB, while simulation result is −23.85 dB. The bandwidth is recorded at 52.65 %. The simulation and measurement pattern results at 2.6 GHz are presented in E- and H- planes shown in Fig. 14. Good agreement between measurements and simulations is achieved.

Fig. 14 Polar radiation pattern of proposed antenna for **a** and E-co plane, **b** E-cross plane, **c** H-co plane and **d** H-cross plane



(a) (b)

(c) (d)

5 Conclusion

This paper presented a new substrate based on the combination of P-PDMS and NPMD. The combination of P-PDMS (electrical medium) with NPMD (magnetic medium) is capable of miniaturizing the antenna size, increases bandwidth and improves overall antenna's performance. The bandwidth is enhanced at 52.65 %, size miniaturization of 176 × 156 mm^2 and high gain obtained at 10.8 dB. Moreover, the 4 × 2 array antenna which is fully covered by P-PDMS and NPMD substrates leads to the water and dust resistance capability. Besides the excellent agreements, simulation and measurement results show a good performance in terms of reflection coefficient, gain and radiation pattern. This new dielectric substrate can be extended for use in many other types of applications, which requires size compactness and wide bandwidths such as the fifth-generation wireless systems (5G).

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