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Bandwidth enhancement using Polymeric Grid Array Antenna for millimeter-wave application

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Abstract A new grid array antenna designed on a polymeric polydimethylsiloxane (PDMS) substrate is presented. A good relative permittivity of the PDMS substrate increases the antenna bandwidth. The PDMS surface is also hardened to protect the proposed grid array antenna's radiating element. A SMA coaxial connector is used to feed the 36 × 35 mm^2 antenna from its bottom. A bandwidth enhancement of 72.1% is obtained compared to conventional antenna. Besides, its efficiency is increased up to 70%. The simulated and measured results agreed well and the proposed antenna is validated to suit millimeter-wave applications.

1 Introduction

Millimeter-wave technology is one of the important aspects of the fifth-generation (5G) wireless communication systems. It generally promises communication with high speed and capacity [1, 2] besides being applied in automotive radar systems [3]. One of the potential antenna topologies for such application is the planar antenna due to its low profile and potentially low cost [4].

Microstrip grid array antenna is initially proposed by Kraus et al. in 1964 as a linearly polarized traveling-wave antenna. In the 1990s, this grid array antenna became more popular due to its low profile, ease of fabrication and high gain [5–15]. Hildebrand and McNamara presented the performance of the microstrip grid array antenna using the integral equation technique in 1993 [7].

In early 1990s through 2000s, Nakano and his colleagues investigated a variety of grid array antennas [8–14]. For example, a double-layer grid array antenna capable of simultaneously radiating vertically and horizontally polarized beams was proposed [8]. Next, the radiation characteristics of a grid array antenna and combined two grid array antennas into a cross-mesh array antenna were then studied in [11]. Further, study on cross-mesh array antenna with four feeding terminals was presented in [12, 13].

A grid array antenna for millimeter-wave applications was proposed in [16]. It was observed that the substrate choice influences the performance of the microstrip grid array antenna. Therefore, polydimethylsiloxane (PDMS) substrate is selected in this paper.

PDMS is one of the more popular types of polymer besides others such as polyetherimide (PEI) and polyethylene terephthalate (PET). PDMS is a silicon-based substrate with low permittivity, low loss, low cost, ease of fabrication and flexibility [17]. Besides, it also colorless and water resistant, which enables the embedding of the radiating patch inside the proposed PDMS substrate [18].

A millimeter-wave patch array antenna printed on PDMS at 60 GHz was proposed in [19]. Meanwhile, a PDMS antenna was introduced for millimeter-wave applications by Moulder et al. [20]. To the best of the authors' knowledge, the combined microstrip grid array antenna

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with the PDMS substrate for millimeter-wave application is presented here is for the first time. The proposed antenna operates from 26 to 28 GHz.

First, the design procedure in ensuring proper operation of the grid array antenna is first presented. This is followed by the design and fabrication process of the PDMS antenna. This includes the process of substrate molding and hardening from its initial liquid form to the embedding of the grid array into the PDMS substrate. Next, the simulated and measured results are compared and discussed in Sect. 3 prior to the conclusion in Sect. 4.

2 Antenna design

2.1 Polydimethylsiloxane (PDMS) as substrate

As per explained previously, the correct substrate selection is a determinant for a good grid array antenna performance. PDMS has been selected as the substrate, which is fabricated using the Silgard-184 silicone elastomer kit shown in Fig. 1. The PDMS is initially in a liquid form and hardens upon a heating process. Without any curing agent or heating element, this process will take longer. Thus, a curing agent is used and mixed at a ratio 10 (PDMS) to one (curing agent). Next, this PDMS mixture is hardened inside an oven at a temperature of 90 °C for one to 2 h. Figure 2 summarizes the PDMS substrate fabrication process, while a completed substrate is shown in Fig. 3.

One of the unique features of PDMS is that its electric permittivity can be tuned higher or lower by using additives while it is still in liquid form [18]. Due to the broad bandwidth and high radiation efficiency requirements, a low PDMS permittivity has been selected for measurement as shown in Fig. 3. The PDMS permittivity measured using Agilent 85070E Dielectric Probe Kit is shown in Fig. 4, indicating $\varepsilon_r = 2.7$ at 28 GHz. On the other hand, higher-permittivity PDMS substrates can be applied for the design of electronic circuits [21].

2.2 Polymeric Grid Array Antenna

In this section, the fabrication process of Polymeric Grid Array Antenna (PGAA) is described. The PGAA antenna is

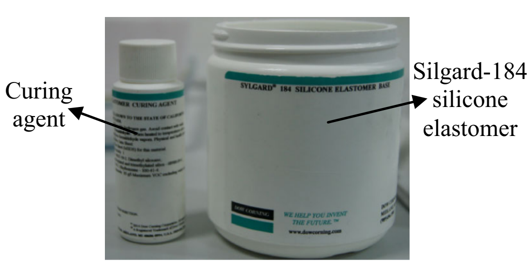

Fig. 1 Sample of Silgard-184 silicone elastomer and curing agent

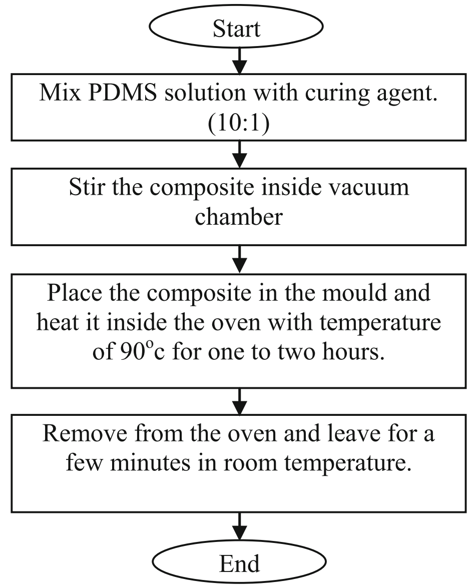

Fig. 2 Flowchart of the fabrication process for PDMS substrate

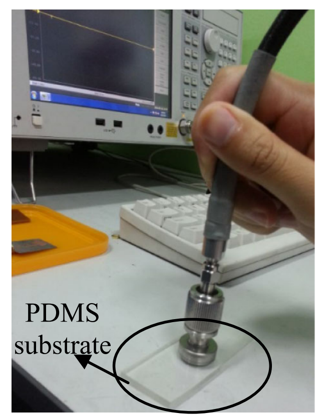

Fig. 3 Sample of PDMS substrate during permittivity measurement

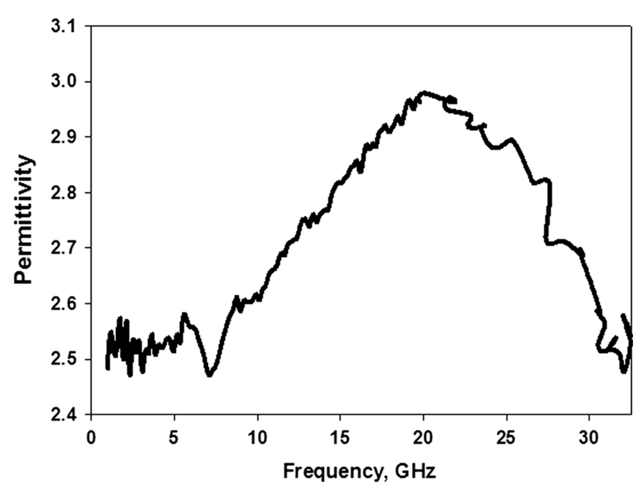

Fig. 4 Result of the PDMS permittivity measurement

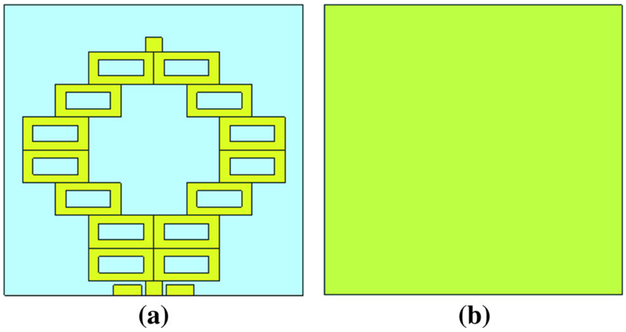

Fig. 5 Simulated Polymeric Grid Array Antenna structure. **a** Front view and **b** back view

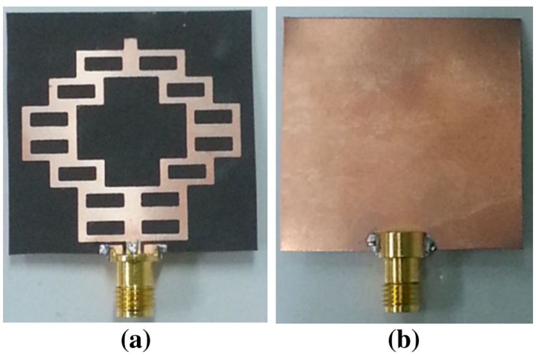

Fig. 6 Fabricated Grid Array Antenna structure. **a** Front view and **b** back view

initially designed using CST Microwave Studio software on a Rogers RT5880 substrate ($\varepsilon_r = 2.2$; $\tan\delta = 0.0009$) and optimized in terms of gain, reflection coefficient (S_{11}) and radiation patterns.

The final optimized PGAA with full ground plane is dimensioned at 36 × 35 mm^2 and is shown in Fig. 5a, b. The radiator of this structure is then embedded into the PDMS substrate as shown in Fig. 6a, b to ensure good water isolation and improved robustness [18].

The antenna fabrication process is summarized in Fig. 7. First, the PDMS liquid is prepared as illustrated in Fig. 7a. Upon the layer turning into a semi-solid form, the radiating patch shown in Fig. 6 is aligned onto this layer, see Fig. 7b. After several minutes, the last layer of PDMS substrate is added to ensure that the radiating patch is strongly connected with the first PDMS layer. Finally, the radiating patch is covered using another PDMS layer as shown in Fig. 7c. The PDMS layer is hardened before being removed from the mold as shown in Fig. 7d. Figure 7e, f shows the completed PGAA prototype. The SMA coaxial feeder is fixed at the side of the antenna as shown in Fig. 7g.

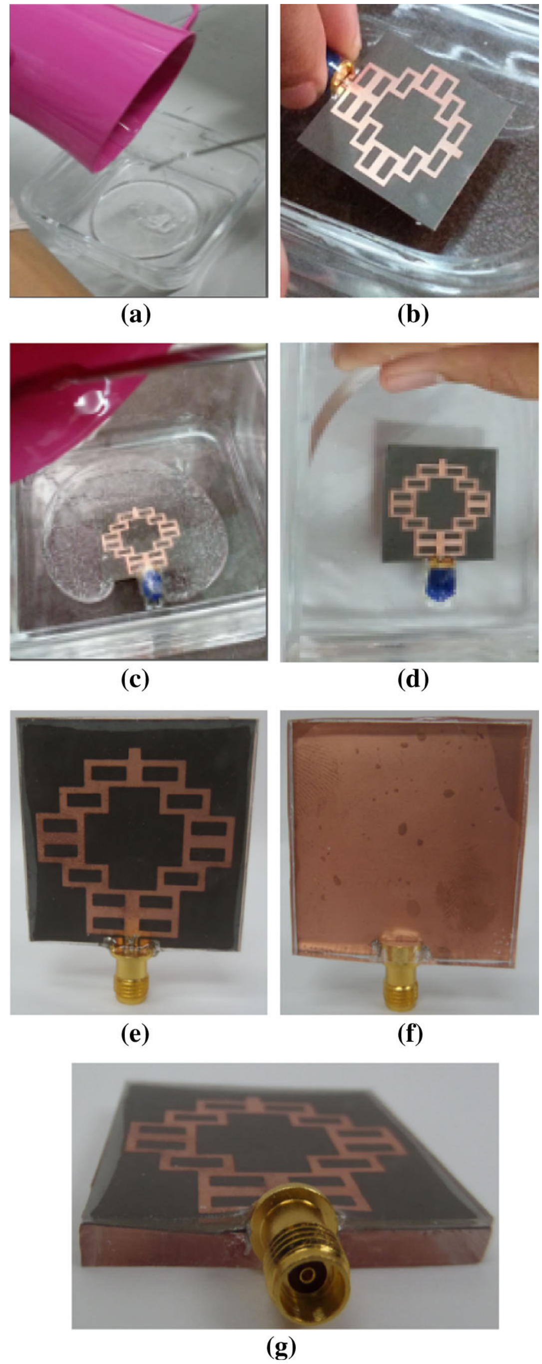

Fig. 7 Fabrication steps **a** a PDMS first layer is poured into the mold, **b** the radiating patch is placed onto the PDMS layer, **c** the addition of a final layer of PDMS substrate, **d** removing the proposed antenna from the mold and the completed PGAA prototype for **e** front view and **f** for back view; **g** addition of the SMA connector

3 Experimental results and discussion

The Polymeric Grid Array Antenna is designed using 14 rectangular loops grid cells. Each grid cell consists of a short, *s*, and a long, *l*, side pairs as illustrated in Fig. 8. The

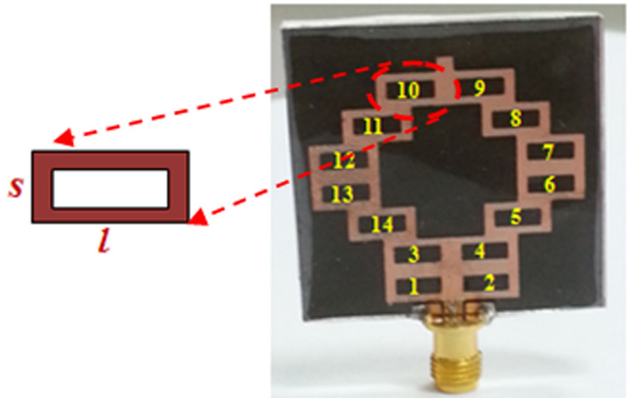

Fig. 8 Sample grid cell of Polymeric Grid Array Antenna

Fig. 9 Measurement of the PGAA prototype in an anechoic chamber

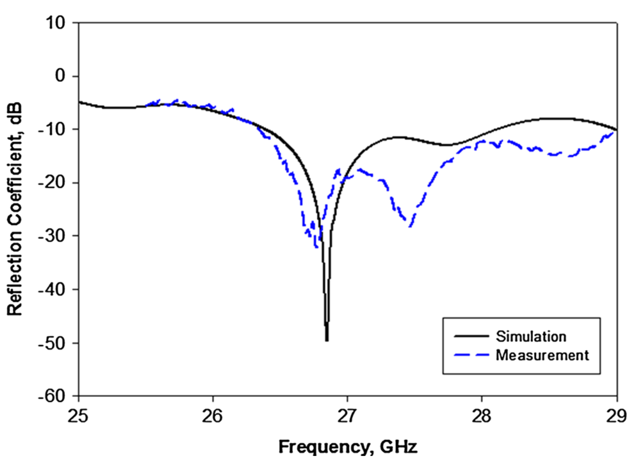

Fig. 10 Simulated (*solid line*) and measured (*dotted line*) reflection coefficients

short side, s, functions as the radiator and transmission line, whereas the long side, l, acts as a transmission line.

The fabricated antenna is measured in anechoic chamber as shown in Fig. 9. The optimal reflection coefficient, S_{11}, is −49.74 dB at 26.8 GHz, see Fig. 10. The bandwidth is 1721 MHz and is improved by 72.1% compared to a conventional antenna array presented in [4].

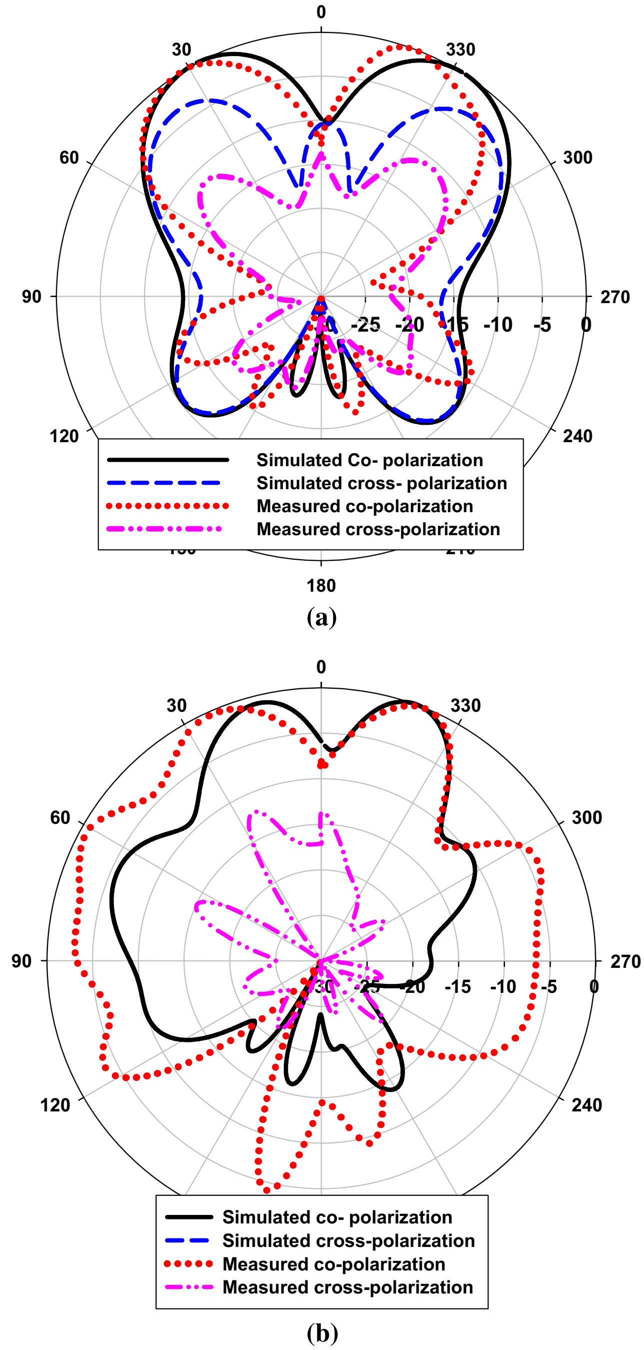

Fig. 11 Polar radiation patterns of the proposed antenna; in the azimuth plane **a** co- and cross-polarization, and elevation plane for **b** co- and cross-polarization

The simulated and measured radiation patterns shown in Fig. 11 indicated good agreements in both planes. A maximum gain of 13.52 dB is achieved. For the elevation plane as in Fig. 11b, the simulated cross-polarization is not in scale because their value is too small and this proves that the proposed antenna is in linear polarization.

4 Conclusion

This paper presents a Polymeric Grid Array Antenna for millimeter-wave application. The proposed antenna consists of 14 optimized rectangular loops with 25 radiating elements. The grid cells are formed by a short and a long side of the grid. The simulated S_{11} is -49.74 dB at 26.8 GHz. Besides, improved water resistance and robustness, up to 72.1% bandwidth enhancement is observed using the PDMS polymeric substrate compared to a conventional antenna. The optimized antenna fed using a coaxial cable obtained a maximum gain of 13.52 dB. Due to the enhanced gain, bandwidth and low profile feature, the proposed antenna can be potentially applied in 5G wireless communication systems.

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