Investigation on the Thin Film Nanocomposite Ceramic-Polymer to Patch Antenna

Neo Zhi Yieng[1], Noorlindawaty Md. Jizat[1], Sin Yew Keong[1], Lo Yew Chiang[1], Zubaida Yusoff[1], Mohd Faizal Jamlos[2]

[1]*Faculty of Engineering, Multimedia University, 63100 Cyberjaya, Selangor Darul Ehsan, Malaysia*

[2]*Advanced Communication Engineering Centre (ACE), School of Computer and Communication Engineering, Universiti Malaysia Perlis (UniMAP), 01000, Kangar, Perlis*

noorlindawaty.jizat@mmu.edu.my

***Abstract*—In this paper, an investigation of the high-permittivity ceramic-polymer composite antenna is performed using Barium Titanate, $BaTiO_3$ nanocomposite ceramic powder mixed with polymer composite of polydimethylsiloxane (PDMS). The ceramic-polymer composite, PDMS-$BaTiO_3$ thin film layer was formed through a spin coating process on the top and the bottom layer of the PDMS substrate for the antenna design in order to achieve an overall antenna size reduction. The proposed patch antennas using the ceramic-polymer composite were analysed at a resonant frequency of 2.45 GHz for WLAN applications regarding antenna performance on return loss, gain, bandwidth, radiation efficiency, and voltage standing wave ratio (VSWR). Two different experimental compositions of 15% and 25% PDMS-$BaTiO_3$ thin film substrate were prepared in the proposed design to create soft, hydrophobic, flexible, resistance against corrosion and lightweight antenna. Significantly, from theoretical analysis and simulation results, it was demonstrated that ferroelectric ceramic-polymer material leads up to 84 % size reduction without having to compromise other antenna performance parameters.**

***Index Terms*—Ferroelectric; Ceramic-Polymer; Barium Titanate (Batio3); Polydimethylsiloxane (Pdms); High Permittivity.**

I. Introduction

Microwave new material such as dielectric ceramics with high permittivity are needed for the next generation of microwave and millimeter wave communication due to extraordinary properties of the dielectric, size reduction, low-profile, light in weight, low manufacturing cost, easy fabrication and compatibility with flexible materials [1]. In addition, a combination of an amount of polymer that complements the ferroelectric material contributes to higher radiation efficiency and strong spontaneous electrical polarisation [2-3]. High dielectric permittivity, ε_r, in the ferroelectric ceramic material increase dielectric tenability which minimises the dielectric loss, thus provide a great solution for flexible antenna design using different techniques of fabrication [4-6].

In order to reduce antennas size, many techniques have been employed including the use of low-temperature co-fired ceramic (LTCC) substrates with sintering temperature below 1,000 °C, utilisation of polymer magneto-dielectric substrate and ceramic dielectric substrate [7-9]. In order to overcome the limitation of traditional high-temperature ceramic processing, spin coating with ceramic linking polymer technique is introduced. The nanoscience ceramic-polymer materials have been identified as new technology discovery with many revolutionary functions, especially towards the antenna evolution.

In this paper, investigation of thin film ferroelectric material Barium Titanate, $BaTiO_3$ ceramic nanocomposite powder mixed with polymer composite of PDMS, PDMS-$BaTiO_3$ to a conventional antenna design is performed. The proposed antenna design made it possible to reduce the dimension of the antenna without compromising the antenna performance of return loss, gain, voltage standing wave ratio (VSWR) and radiation efficiency with significant flexibility and weight reduction. Comparisons between existing antenna performances and proposed antenna design are presented in the subsequent part.

II. PDMS Antenna Design

PDMS with dielectric permittivity, $\varepsilon_r = 2.7$ and loss tangent of 0.04 is used as the substrate element with 2mm thickness. Elastomeric PDMS structures are typically fabricated using viscous liquid and a liquid cross-linking agent. The ferroelectric ceramic-polymer thin film possesses higher dielectric permittivity ε_r is utilised to reduce the proposed antenna size. In the proposed design, two compositions of Barium Titanate powder, nanopowder (cubic crystalline phase) with 100 nm particle size from Sigma Aldrich is added into PDMS with 15 % and 25 % ratio (with respective dielectric constant of 8 and 10.5)[4].

A. *Geometry and Antenna Design*

The design and detailed dimension structure of the PDMS-$BaTiO_3$ proposed antenna are illustrated in Figure 1(a), and the exploded cross-section substrate layers are depicted in Figure 1(b).

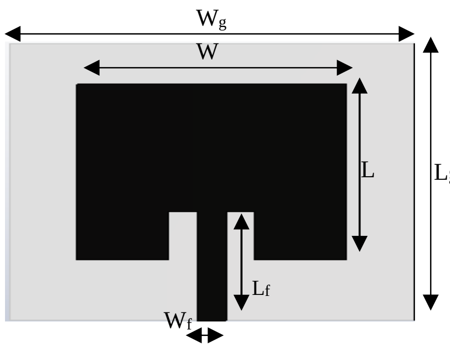
$$w = \frac{c}{2f_0}\sqrt{\frac{\varepsilon_r + 1}{2}} \quad (1)$$

$$l = \frac{c}{2f_0\sqrt{\varepsilon_r}} - 2\Delta l \quad (2)$$

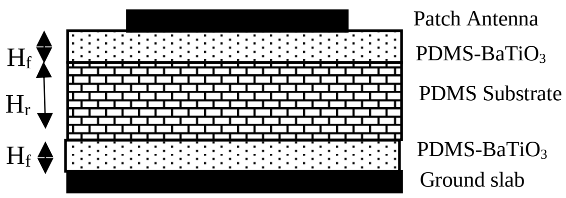
where: w = width
l = length
f_0 = operating frequency
c = speed of light in vacuum
ε_r = permittivity
Δl=length extension

As can be seen from the Figure 1, in the second and fourth layer, a thin film of PDMS-$BaTiO_3$ is composed while the third layer comprised of PDMS substrate. A mathematical model determined the width dimension and optimised according to Equation (1) and the actual length dimension of the patch determined by solving Equation (2) obtained from [10-11].

The detailed dimensions of the thin film PDMS-$BaTiO_3$ using 15 % and 25 % ratio are tabulated in Table 1. The substrate is fabricated using multilayer PDMS-$BaTiO_3$ thin layer with the antenna size of 0.12 λ_o x 0.14 λ_o using spin coating technique. The element of radiating element patch antenna and the ground plane is the copper metalised with a thickness of 0.035mm.



(a)



(b)

Figure 1: Antenna geometry (a) Detailed dimension (b) Cross-sectional

Table 1
Dimensions of the Proposed Antenna

Design variable (unit dimension in mm)	L	W	L_f	W_f	H_r	H_f	W_g	L_g
PDMS-$BaTiO_3$ (15 %)	18	20	13	2	2	1	30	33
PDMS-$BaTiO_3$ (25%)	16	18	12	2	2	1	27	29

B. Fabrication of Thin Film Substrate Using Spin Coating

In order to validate the design, the fabrication of the thin film substrate is performed. The pure PDMS used is Sylgard-184, containing the viscous liquid and a curing agent manufactured by Dow Corning. The first layer of pure PDMS was produced by the ratio of 10 (prepolymer):1 (curing agent). The first layer of PDMS was produced by having 2.4 grams of PDMS with curing agent, which is a ratio of 10:1, and it was added into the petri dish with degassing process and 24 hours of curing. The pure PDMS was mixed well and processed by a slow circular movement continuously until the substrate thickness achieves 2 mm thickness. After curing, the ceramic-polymer mixture of 15 % and 25 % $BaTiO_3$ powder were added to the existing PDMS solutions to produce two different concentrations of ceramic polymer, PDMS-$BaTiO_3$.

$$v\% = \frac{C_M/C_P}{\frac{C_M}{C_P} + \frac{P_M}{P_P}} \times 100\% \quad (3)$$

where: C_M= mass of the ceramic ($BaTiO_3$)
C_P = density of the ceramic ($BaTiO_3$)
P_M= mass and density of PDMS
P_p = density of PDMS

In order to prepare for 15 % PDMS-$BaTiO_3$ mixture, 0.35 grams of $BaTiO_3$ powder was added into the PDMS, whereas for a 25 % PDMS-$BaTiO_3$ mixture, 0.63 grams of $BaTiO_3$ powder was added into the pure PDMS composition. The percentage of ceramic powder mixed with PDMS is on a volume-based ratio, as defined in Equation (3) [4].

The vigorous stirring was performed for about 15 – 20 minutes before the mixture was poured into the petri dish which consists of the pure PDMS substrate. Spin coating was performed to have an even distribution, and the high-speed spin step is programmed to spread the fluid uniformly. Thin film settings for the spin coating were set to be in speed of 500 rpm in 10 seconds. The mixture was left for the air bubbles to reside in the desiccators.

Drying step was utilised to eliminate excess solvents on the top part of the thin film PDMS-$BaTiO_3$ and the same process repeated for the bottom layer. Subsequently, once the PDMS-$BaTiO_3$ mixture was ready, the surface of the PDMS layer was attached to the bottom layer of the subsequent substrate layer. The PDMS-$BaTiO_3$ mixture was again spin-coated by slow circular movement continuously to produce a bottom thin film layer, which can be seen in Figure 2.

(a) (b)

(c) (d)

Figure 2: PDMS-$BaTiO_3$ mixture (a) PDMS preparation (b) composition mixture (c) before spin coating (b) after spin coating

III. RESULTS AND DISCUSSION

The simulation of the antenna performance is executed using Computer Simulation Technology (CST) and tabulated in Table 2. The results obtained indicate that the higher percentage of PDMS-$BaTiO_3$ (25 %) which has higher dielectric constant showed better return loss -24 dB, VSWR of 1.6, a gain of 3.50, the directivity of 4.43 and enhanced antenna efficiency of 82.5 % in comparison to the 15 % PDMS-$BaTiO_3$ composition material.

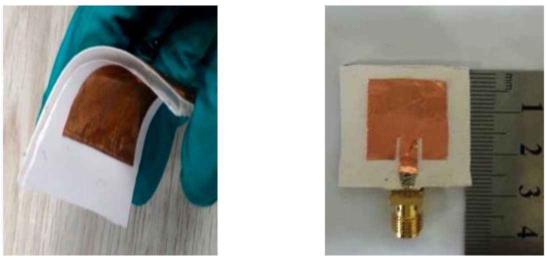
Table 2
Proposed antenna simulation performance with different compositions

Antenna Performance	PDMS-$BaTiO_3$ composition 15%	20%
S_{11} (dB)	-15.4	-24
VSWR	1.4	1.6
Gain	3.08	3.5
Directivity (dB)	4.33	4.4
Efficiency (%)	78	82.5

The final composite substrate with 25 % composition was therefore optimised and fabricated, where the resulted thin film PDMS-$BaTiO_3$ produce a reduced size substrate, with a soft, flexible and smooth surface as illustrated in Figure 3. The copper was used as the radiating antenna patch and the ground plane layer which is kept metalised as the full ground plane. The dielectric constant (ε_r) has a significant impact on antenna design, where the advanced technology of high permittivity substrate has allowed a considerable reduction of physical dimensions of the proposed antenna up to 84 % size reduction.

The proposed antenna performance between the simulation and the measurement results were plotted in Figure 4 and 5. S_{11}-parameter indicates the relationship between the input port and output port in an electrical system, in terms of power reflected from the antenna known as reflection coefficient, Γ or return loss. As shown from the Figure 4 and the detailed results tabulated Table 2, the antenna performance with 15 % PDMS-$BaTiO_3$ and 25 % PDMS-$BaTiO_3$ yield slightly different values of the return loss, S_{11} which are -15dB and -24dB respectively.

The S_{11} values of the antenna fabricated with 25 % PDMS-$BaTiO_3$ between the simulated and the measured are slightly varied due to the frequency shifting that might be contributed during the fabrication. However, the measured S_{11} value of -25.5dB is very promising since at operating frequency, the return loss parameter's minimum requirement is -10dB.



(a) (b)

Figure 3: Patch Antenna (a) Flexible PDMS $BaTiO_3$ substrate (b) Fabricated proposed antenna

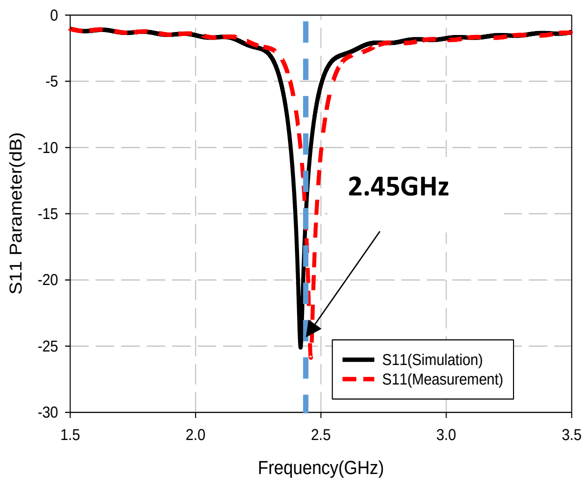
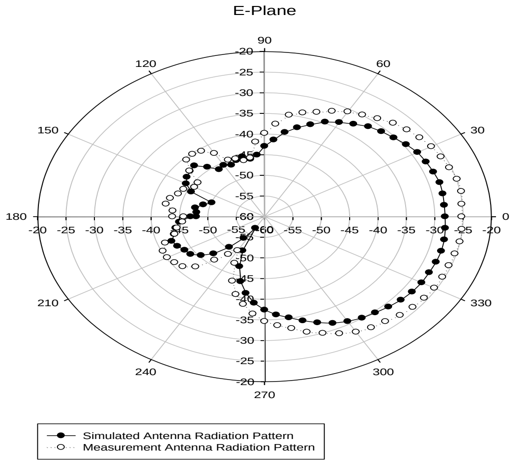
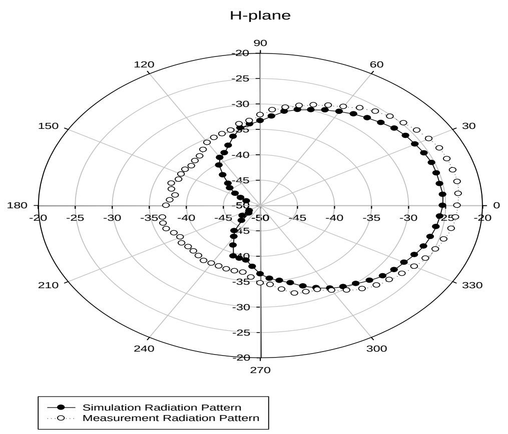


Figure 4: Simulation and measurement of return loss, S_{11} proposed antenna



(a)



(b)

Figure 5: Simulated and measured radiation patterns (a) E-Plane (b) H-plane

The proposed antenna radiation characteristics magnitude of the far zone field strength versus position around the antenna was also studied. Figure 5 plots the simulated and measured radiation pattern of the proposed antenna in the two principal planes, E(y-z) and H(x-z) plane at 2.45 GHz. The 3-dB half power beam width (HPBW) in the y-z plane and x-z-plane beamwidth of measured PDMS-$BaTiO_3$ thin film antenna is 108° and 79°, respectively.

Table 3
Antenna Performance Comparison from Previous Literatures

Ref.	Freq.	S_{11} (dB)	Size, W×L (mm)	Size Reduction (%)	BW (%)	Gain (dB)	Effic.,(%)
[12]		-39	32×30	70	14	6.1	
[13]		-16	27×26	66	4.7	1.0	
[14]	2.45	-10	29×29	75	5.2		
[15]	GHz	-37	43×42	84		4.65	68.7
This work		-24	16×18		3.3	3.74	82.5

From Table 3, it can be seen that the performance of the proposed antenna of PDMS-$BaTiO_3$ is comparable with the result obtained in those reported in the previous work and fulfil WLAN operating bandwidth (20 MHz) and significantly up till 84 % of size reduction in comparisons to the literature [10-13]. The high relative dielectric constant of the PDMS-$BaTiO_3$ made it possible to reduce the dimensions of the antenna without compromising the performance of the proposed antenna.

IV. CONCLUSION

This project investigated the effect of nanocomposite PDMS-$BaTiO_3$ towards antenna size reduction, when the antenna is fabricated using 25 % thin film layer of ceramic-polymer PDMS-$BaTiO_3$ ferroelectric material. The high permittivity of the PDMS-$BaTiO_3$ substrate leads to a significant size reduction up to 84 % at the same time contributes to a promising antenna performance in terms of the reflection coefficient, bandwidth, VSWR, radiation characteristics and significantly towards the efficiency. Moreover, the proposed substrate contains the water and dust resistance capability, with small geometries to meet the demands of modern electronic devices operating at WLAN frequency, 2.45 GHz. This new dielectric substrate can be extended for use in many other types of applications including tunable functionality antenna.

REFERENCES

[1] A. Nathan, and B. R. Chalamala, "Special Issue on Flexible Electronics Technology, Part 1: Systems and Applications," *Proceedings of the IEEE*, vol. 93, no. 7, pp. 1235–1238, 2005.

[2] V. K. Thakur, and R. K. Gupta, "Recent Progress on Ferroelectric Polymer-Based Nanocomposites for High Energy Density Capacitors: Synthesis, Dielectric Properties, and Future Aspects," *Chem. Rev*, vol. 116, no. 7, pp. 4260–4317, 2016.

[3] C. P. Lin, "Development of a Flexible SU-8/PDMS-Based Antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, 2011.

[4] A. A. Babar, "Performance of High-Permittivity Ceramic-Polymer Composite as a Substrate for UHF RFID Tag Antennas," *International Journal of Antennas and Propagation*, ID 905409, pp. 1-8, 2012.

[5] M. S. M. Isa, A. N. L. Azmi, A. A. M. Isa, M. S. I. M. Zin, S. Saat, Z. Zakaria, I.M. Ibrahim, M. Abu, A. Ahmad, "Textile Dual Band Circular Ring Patch Antenna under Bending Condition," *Journal of Telecommunication, Electronic and Computer Engineering*, vol. 9, no. 3, pp. 37–43, July – September. 2017.

[6] B.S. Yew, F.H. Wee, S. Bahri, M. Muhamad, "Simulation Analysis and Electromagnetic Dosimetry of Patch Antenna on Hugo Voxel Model," *Journal of Telecommunication, Electronic and Computer Engineering*, vol. 9, no. 1–4, pp. 37–40. 2017.

[7] C. L. Huang, W. R. Yang and S. H. Huang, "Miniaturization of ring resonator bandpass filters using dielectric ceramic substrates," *Microwave and Optical Technology Letters*, vol. 55, pp. 660–663, 2013.

[8] N. Abdullah, N. M. Jizat, SKA Rahim, M. I. Sabran, M. Zaman, "Investigation on graphene based multilayer thin film patch antenna," *2016 IEEE 10th European Conference on Antennas and Propagation* (EuCAP), pp. 1–5, 2016.

[9] A. S. M. Alqadami, M. F. Jamlos, P. J. Soh, M. R. Kamarudin, "Polymer (PDMS-Fe3O4) magneto-dielectric substrate for a MIMO antenna array," *Applied Physics A*, vol. 122, no. 9, 2016.

[10] N. M. Jizat, S. N. Mohamad, and M. I. Ishak, "Resonator graphene microfluidic antenna (RGMA) for blood glucose detection," *AIP Conference Proceedings* 1885, 020126, 2017.

[11] C. Balanis, *Antenna Theory Analysis and Design*, Wiley, 1997.

[12] F. H. Wee and F. Malek, "Design and Development of Ferroelectric Material for Microstrip Patch Array Antenna," *World Academy of Science, Engineering and Technology*, vol. 62, pp. 290–293, 2012.

[13] J. H. Yoon, "Fabrication and measurement of modified spiral-patch antenna for use as a triple-band (2.4GHz/5GHz) antenna," *Microwave and Optical Technology Letters*, pp. 1275–1279, 2006.

[14] S. A. Kumar, T. Shanmuganantham and G. Sasikala, "Design and development of implantable CPW fed monopole U slot antenna at 2.45 GHz ISM band for biomedical applications," *Microwave and Opt. Technology Letters* 57, pp. 1604–1608, 2015.

[15] I. Anaekwe and J. S. Marciano, "The Effect of Curvature Adaptation on 2.4GHz Rectangular Patch Antennas," *IEEE 2013 Tencon – Spring*, 2013.