Liquid Crystal Polymer: Potential Bio-Compatible Substrate for Antenna Application

B. Biswas[1], A. Karmakar[2] and V. Adhikar[3]

Abstract – **This work describes the capability of Liquid Crystal Polymer (LCP) as an attractive choice for antenna usages targeting several bio-medical applications. One lower frequency application details about the development of a conformal, wideband, fractal implemented miniaturized antenna for wireless capsule endoscopy purpose over 2450 MHz Industrial, Scientific and Medical (ISM: 2400-2480 MHz) band. Whereas, another application outlines the developmental activity targeting high gain 100 GHz planar antenna array for medical imaging with appreciable resolution. Both of the works have been explained in detail with design, modelling and fabrication issues. Substrate has also been modelled for high-frequency application.**

Keywords – **LCP, Flexible, Antenna, WCE, Medical imaging.**

I. Introduction

Liquid Crystal Polymer (LCP) has become attractive choice since its introduction to RF (Radio Frequency) world about two decades ago, as a substrate and packaging material due to its unique electrical and mechanical characteristics. One of its most promising qualities is its flexibility, which enables the evolving of conformal electronics to RF and microwave world. Numerous innovations are possible with conformal electronics, including bio-medical engineering field. Sensors, wireless communication devices and antennas can be fabricated on LCP for use in personal health monitoring systems. Being a bio-compatible material it is safe for use inside the human body, showing no toxic characteristics at all [1]. Apart from this, it offers low loss and dielectric stability from DC to 110 GHz, making it suitable to almost every consumer, and military applications [2]. And, this organic polymer is practically appealing for antenna system since the material naturally prohibits the excitation of surface wave because of its low permittivity value. Most of the recent research work is focused on novel antenna design on LCP. The ultra-thin, light weight, paper-like plastic can incorporate variety of electronic components, yet it moulds to any desired shape and appears to perform well in the extreme environment conditions and intense radiation [1, 3]. Even few researches are investigating novel 3D meta-material ideas utilizing LCP to develop flexible lenses and dramatically improve the power efficiency of conventional RF modules [3]. Recent research shows that, LCP substrate is gaining much popularity in the neuroprosthetic implantable medical devices too, because of its extremely low moisture absorption rate(less than 0.04%, compared to PTFE and borosilicate glass) compared to polymide and parylene-C [4]-[6].

This work emphasizes on the development of miniaturized antenna upon LCP substrate catering various bio-medical applications. Fractal engineering and array concept in developing terahertz frequency range antenna have been demonstrated here for miniaturization as well as to enhance the efficacy of the device. Two different extreme frequency regimes (2.45 GHz and 100 GHz) have been chosen here to prove the super-wideband characteristic of LCP, providing solution for long pending medical problems, like-wireless methods for traditional painful endoscopy system, high resolution medical imaging to detect malignant tissues of human body, etc. The following sections start with the modelling of the substrate and then subsequently the antenna development work is summarized.

II. LCP Substrate and its Dielectric Behaviour

In this work, we have chosen standard M/s Rogers made ULTRALAM-3850 HT LCP substrate of 4-mil thickness, properties of which is summarized in Table I. As, the current work is based on planar configuration of RF/microwave/sub-millimetre wave circuits, hence three kinds of losses are mainly encountered, namely - conductor loss, dielectric loss and radiation loss. Out of these three, the second category is a strong function of substrate's property and frequency of operation [7].

TABLE I
PROPERTIES OF ULTRALAM-3850 HT LCP SUBSTRATE

Properties	Values
Dielectric constant	3.14
Dissipation factor	0.0020
Volume resistivity	1×10^{12} MΩ-cm
Surface resistivity	1×10^{10} MΩ-cm
Dielectric breakdown strength	3500 V/mil
Thermal conductivity	0.0 W/m/K
Moisture absorption	< 0.04%
Density	1.4 gm/c.c

The permittivity and resistivity together form a factor called, 'Dielectric Relaxation Frequency' given by [7]:

$$f_c = \frac{1}{2\pi R_{LCP}\, C_{LCP}} = \frac{1}{2\pi \rho_{LCP}\, \epsilon_{LCP}}, \quad (1)$$

Article history: Received August 12, 2020; Accepted June 25, 2021

[1]B. Biswas is with the CSIR-CSIO, Chandigarh, India, E-mail: balaka.biswas@gmail.com
[2]A. Karmakar is with the SCL, Mohali, India, E-mail:ayanns@gmail.com
[3]V. Adhikar is with COMSOL Multiphysics Software Ltd., India, E-mail: vaibhavadhikar09@gmail.com

where, R_{LCP} and C_{LCP} are the resistance and the capacitance of the substrate and ρ_{LCP} and ϵ_{LCP} are the resistivity and permittivity of the substrate, respectively. This relation shows the effect of the resistivity on the cut-off frequency (f_c), which basically tells the rate at which how a dielectric material is polarized and depolarized with the application and withdrawal of alternating field. The same phenomenon can be understood with the help of a 'leaky capacitor' concept applied in transmission line model. Fig. 1 shows the equivalent model. The product of 'R_{LCP}' and 'C_{LCP}' gives an idea of time-constant ($T_{LCP}= R_{LCP} * C_{LCP}$). As the T_{LCP} increases more time is required to charge the C_{LCP} externally with the electric field and similar discussion is true during discharge phenomenon.

The conductor loss is expressed in terms of 'R_f' and the substrate loss is denoted by 'G_{sub}'. As the LCP is offering very high resistivity, the substrate behaves as pure capacitance almost, so the contribution of conductance with respect to capacitance becomes very low.

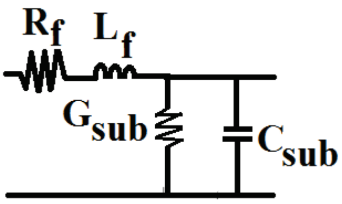


Fig. 1. Equivalent circuit of the transmission line

III. Antenna Design Methodologies

A. Antenna for Wireless Capsule Endoscopy (WCE)

WCE is an emerging technology in medical field since 2001, for diagnosis of diseases within the gastrointestinal (GI) tract [8-10]. Both traditional painful endoscopy and colonoscopy methods can be replaced by this single unique procedure. The capsule endoscopy system comprises of two small cameras, a wireless IC transceiver, LEDs, battery, optical domes and an antenna. Antenna performs the bio-telemetry function in this whole system. Designing antenna for such a system is bit tiresome, because of smaller capsule dimension and dispersive nature of human body tissue. For high resolution data transmission, wide bandwidth is indispensible for such antenna system. In this work, the flexibility feature of LCP substrate is used to realize a conformal 2.45 GHz centred antenna. It is proposed to be placed outside the capsule wall, mainly aiming to save the inner space of capsule for other electronic components. To achieve the miniaturization and wideband profile both in single antenna structure, Minkowski fractal geometry is implemented. Maximum gain and radiation efficiency are obtained with the placement of antenna at the outer wall of capsule. Standard dimension (26×11 mm^2) of the capsule is considered for the entire simulation work. Here, the antenna is fed by 50 Ω CPW type transmission line, architecture of which is shown in Fig. 2. Optimized dimension of this proposed antenna is summarized in Table II. A second iterated fractal is applied to get better wideband characteristics, which is clear from Fig. 3. Further iterations have not been tried out because of practical fabrication limitations.

While traversing through the gastro-intestinal tract of the human body through peristalsis, the endoscopy capsule experiences various tissues outside it with different electrical characteristics. This may affect in the detuning of the WCE antenna during its actual operation. To study this practical scenario, a cubical phantom with an approximate side of λ_0 is considered. Considering the electrical properties of various bio-logical tissues at 2.45 GHz [11], the FEM simulation was carried out, resulting in detuning effect of antenna resonance frequency, as shown in Fig. 4.

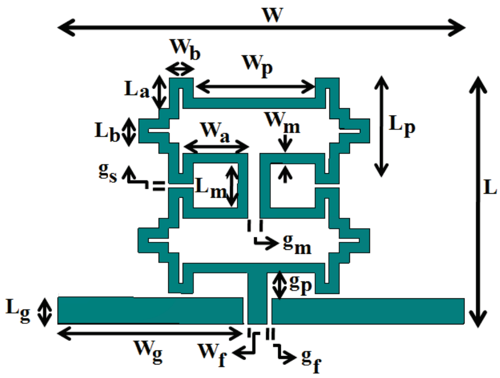


Fig. 2. Architecture of proposed antenna

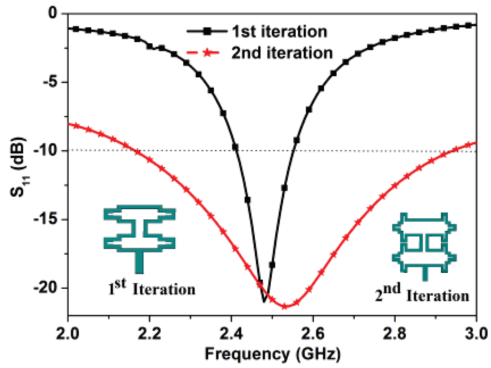


Fig. 3. ArchEffect of fractal iterations on the reflection coefficient S_{11}

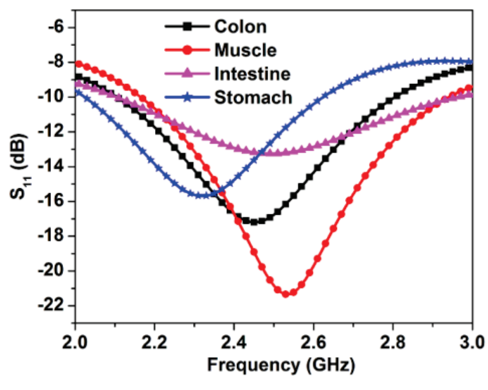


Fig. 4. Effect of various human phantoms on the reflection coefficient of antenna

Within the GI tract, the orientation of the capsule is random in nature. The effect of this randomised orientation can be theoretically studied to some extend with an assumption of 45° orientation in three different planes (XY, YZ and ZX). Fig. 5 shows the simulation results, which expresses the unfaltering effect of resonance characteristics with this direction changing.

Far-field simulated radiation pattern of the proposed antenna considering both in the presence of battery and without battery are provided in Fig. 6. E-plane pattern is almost like figure of eight whereas H-plane pattern exhibits almost Omni-directional behaviour. Essentially, the SAR (Specific Absorption Rate) value of the antenna was also calculated with respect to 1g-average standard. To meet the C95.1-2005 IEEE standard guided regulation [12], the allowed transmitted power is 3.2 mW for a muscle phantom.

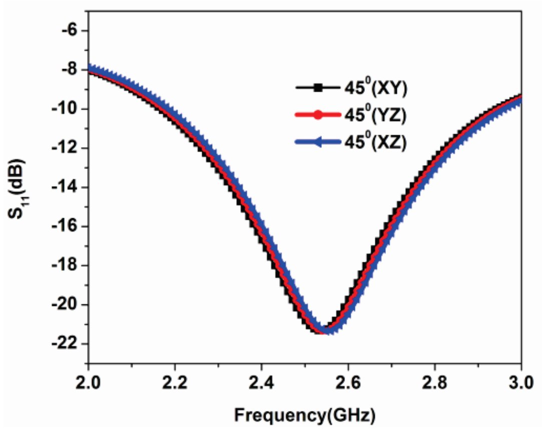
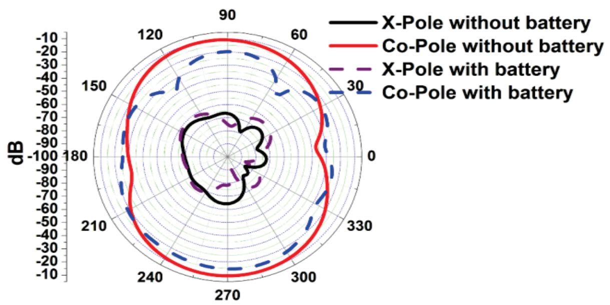
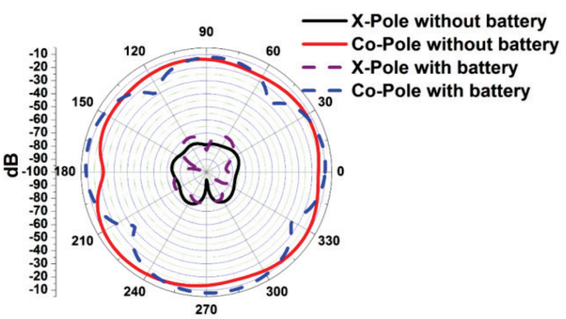


Fig. 5. Effect on the antenna resonance characteristics with the different orientation of the capsule within the GI tract



(a)



(b)

Fig. 6. Radiation pattern characteristic of the proposed antenna with and without battery: (a) E-plane, (b) H-Plane at 2.45 GHz

TABLE II
OPTIMIZED DIMENSION OF THE CAPSULE ANTENNA

Parameter	Values (mm)
W	20
L	13
W_g	9
L_g	1.3
W_f	1
g_f	0.2
g_p	1.2
g_m	0.6
g_s	0.2
W_b	1.2
W_p	6
L_a	1.5
L_b	1.2
L_m	2.2
W_a	2.2
W_m	0.5
L_p	5.2

B. Antenna for Medical Imaging

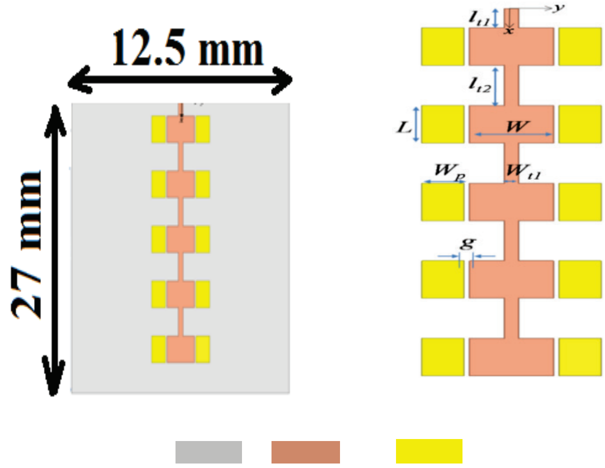
In modern day medical diagnosis, imaging plays a key role to diagnose the health of various internal tissues of human body in a non-invasive manner. This process can produce a very high resolution image if the operating frequency is targeted as high as 100 GHz or more. But, this high end technique demands miniaturized high-gain antenna with super-wideband characteristics, preferably fabricated on non-toxic substrate [13]. LCP is a suitable candidate for such application. Additionally, 'flexibility' feature of LCP substrate makes it an attractive choice for realizing conformal antenna for bio-medical usage.

Present work proposes design and development of a parasitic-element loaded rectangular microstrip antenna array (RMAA) with very high gain on 4-mil (±12.5%) thick LCP substrate for 100 GHz application. High peak gain of around 19 dBi has been achieved with the planar configuration having five elements connected in cascade with series feeding. Each of these elements excites two parasitic patches placed on both sides of the non-radiating edges of the primary patches. Proposed rectangular microstrip antenna array comprises series-fed five patch elements, each having length 'L' and width 'W' and loaded with parasitic patch elements of length and width 'L' and 'Wp' on both sides of main radiating elements.

Fig. 7 shows the schematic of the antenna. Dimensions of the patch are given by Eqn. (2) and (3), [13]:

$$W= \frac{c}{2f_r}\sqrt{\frac{2}{1+\varepsilon_r}}, \qquad (2)$$

$$L=\frac{c}{2\sqrt{\varepsilon_{eff}}\,f_r}-2\Delta L. \qquad (3)$$

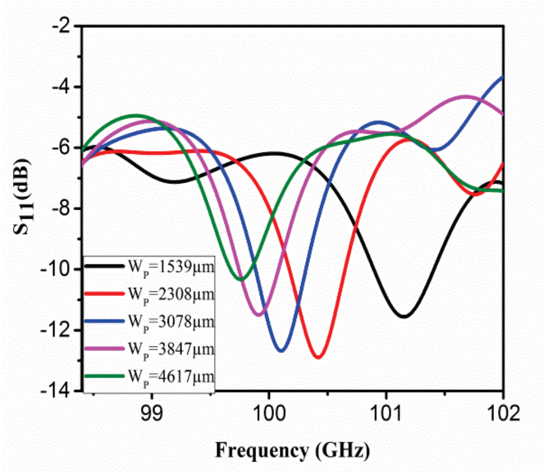


(a) (b)

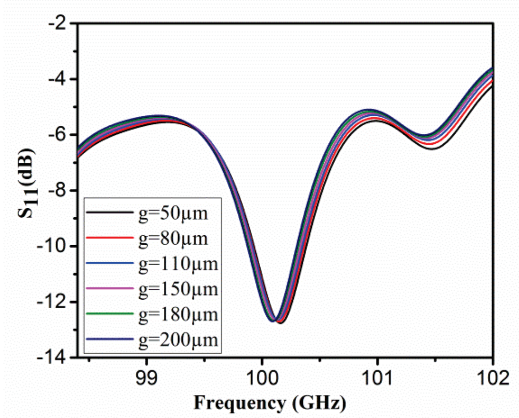
Fig. 7. (a) Top view and (b) dimension of the proposed 100 GHz antenna

where ε_{eff} is effective dielectric constant and ΔL is extended length on both sides of the radiating patch due to the fringing field [14]. Segments of the transmission-line in between the patches are responsible for phase matching. The dimension of these transmission lines i.e. length 'l_{t1}' and 'l_{t2}' and width 'W_{t1}' are computed from [15].

Whole design exercise is accomplished for the centre frequency of $f_r = 100$ GHz. The present design maintains simplicity, flexibility and exhibits much increased gain of 19.2 dBi. Implementing parasitic patches at the non-radiating edges of main patch array effectively enhances the aperture size of the array structure which in turn increases the gain of antenna. Introduction of these patches inherently alters the capacitive loading phenomenon. The gap between the main antenna and parasitic patch decides the amount of field coupling. To ensure strong coupling and optimal excitation of the parasitic patch element, its gap (g) from the main radiating element should be as less as possible [16]. Systematic parametric studies have been carried out to get an optimum value of gap 'g' and width of parasitic patch 'Wp', and is indicated in the S_{11} plot of Fig. 8. As can be noted from the plot of Fig. 8(a), for a gap dimension of 50 to 100 µm, there is hardly any difference in resonant frequency, but a slight change is observed in refection coefficient curve. Actually flux linkage phenomenon is not captured clearly with the results. But, when the width of parasitic patches 'Wp' changes, it changes the impedance of antenna and current vector also. The dimension of all design parameters have been optimized and summarized in Table III.



(a)



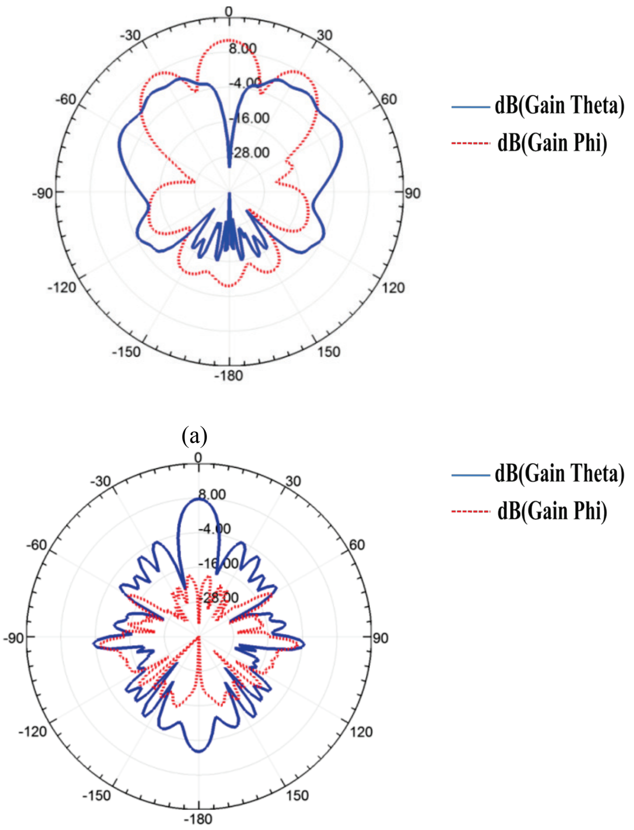
(b)

Fig. 8. Parametric radiation of reflection coefficient of antenna with design parameter: (a) Width wise, (b) Gap wise

Simulated far field radiation pattern of the antenna is shown in Fig. 9. H-plane indicates the broad side profile at the broadside direction and X-pol level is 38 dB below than Co-pol. E-plane pattern is like a flower with multi-shape petals. Peak simulated gain is obtained as 19.2 dBi.

TABLE III
OPTIMIZED DIMENSION OF RMAA

Variables	Without parasitic elements (µm)	With parasitic elements (µm)
L	2489	2489
W	3078	3078
l_{t1}	1293	1293
l_{t2}	2685	2685
w_{t1}	690	500
w_p	-	1539
g	-	200
h	100	100



(a)

(b)

Fig. 9. Far field simulated radiation pattern:
(a) E-plane, (b) H-plane plots

IV. ANTENNA FABRICATION AND TESTING

A. WCE Antenna

The proposed antenna was fabricated on 4 mil thick Liquid Crystal Polymer substrate. Standard wet etching chemistry has been used to pattern the metal layer (18 µm of copper) in the front side and in the backside it is removed fully. After fabrication antenna is wrapped over the capsule structure and then 0.1 mm thick spray coating of PEEK ($\varepsilon = 3.2$, $\tan\delta = 0.01$) layer was applied followed by assembly of suitable RF-connector (Fig. 10). Measurement is done by R&S make ZVA-40 Vector Network Analyzer and a cylindrical glass beaker to form a phantom. The liquid was made by mixing 26.7% (by volume) diethylene glycol butyl ether (DGBE: C8H18O3) with 73.2% de-ionized (DI) water and 0.04 % salt (NaCl). The salted aqueous solution was made with solid contents of 5 gm/L. Assuming the phantom environment around the WCE antenna, 3D EM simulations was carried out (Fig. 11). Fig. 12 demonstrates the experimental setup for measuring the return loss behaviour of such antenna module in the lab.

Fig. 13 shows the simulated and measured reflection coefficient of the capsule antenna inside the phantom liquid. Both results resemble well to each other, only little difference is attributed due to fabrication tolerances and human errors associated in preparation of phantom liquid.

Fig. 10. Fabricated antenna wrapped outside the capsule

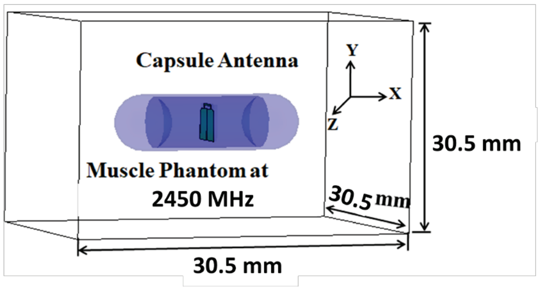


Fig. 11. Simulation environment of the EM analysis for WCE antenna

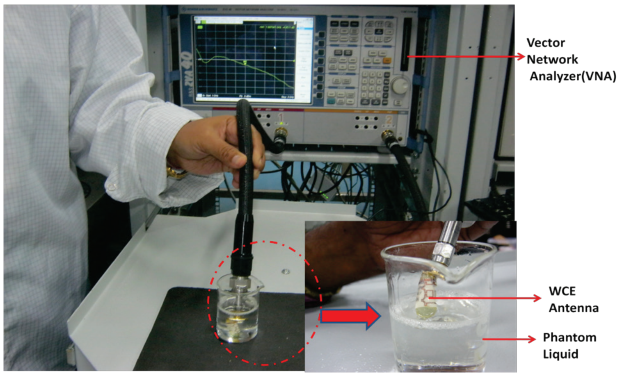


Fig. 12. Experimental setup for measuring the return loss of the WCE antenna dipped into liquid phantom

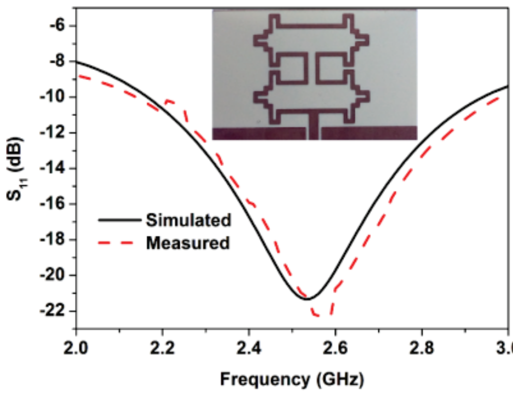
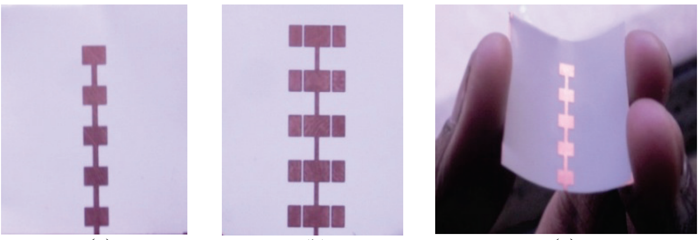


Fig. 13. Simulated and measured reflection coefficient of proposed conformal antenna

B. Medical Imaging Antenna

Two prototype structures have been fabricated on 4 mil thick Liquid Crystal Polymer ($\varepsilon_r = 2.9$, $\tan\delta = 0.002$) substrate. Fig. 14 shows the fabricated prototypes (front view), explaining the flexibility of substrate. Standard wet etching chemistry has been used to pattern the metal layer (18 µm of copper). The backside of the substrate is fully metalized to realize the common ground plane. Currently the testing process of these antennas is under progress.



(a) (b) (c)

Fig. 14. Fabricated prototypes of the (a) antenna array (b) array with parasitic patches (c) illustration of the conformal shaped antenna

V. CONCLUSION

The whole work is focused to explore the capability of LCP substrate throughout the entire gamete of EM spectrum for bio-medical applications in context with development of miniaturized antenna. Substrate has been modelled for its high frequency practical uses. Two different case studies have been done at 2.45 GHz and 100 GHz targeting practical bio-medical antenna usage. Flexibility, non-toxic characteristics, light weight, robustness in harsh environment and above all easy to make circuit capability make this substrate as an attractive candidate for bio application in very near future. Table IV shows a comparative study consisting of potentiality of LCP substrate in comparison to other bio-compatible substrates for RF/microwave, applications especially in antenna field. It can be inferred that, LCP has a very wide frequency range of operation along with its bio-compatibility nature. No additional coating is required for it.

TABLE IV
COMPARISON OF RECENTLY REPORTED ANTENNA STRUCTURES FOR BIO-MEDICAL APPLICATIONS OVER VARIOUS SUBSTRATES

Reference number	**Type of bio-compatible substrate for RF/ Microwave application**	**Frequency of operation**	**Max. gain of antenna reported**
[17]	Aerogel Poly	11.7 GHz	8 dBi
[18]	Alumina (Al_2O_3) and metallic coating is silver-palladium alloy	2.45 GHz	..
[19]	Alumina	915 MHz	-27 dBi
[20]	Teflon PTFE	9.16 to 17.74 GHz	2.54 dBi
This work	LCP (Liquid Crystal Polymer)	2.45 GHz and 100 GHz	-30 dBi@2.45 GHz and + 19.3 dBi@100 GHz

ACKNOWLEDGEMENT

Authors are very much grateful to Director-SCL, Chandigarh for his generous support to access various resources of SCL from time to time during this project. They are also thankful to Dr. Amitava Das, Principal Scientist of CSIO-Chandigarh for his meaningful guidance during whole activity.

REFERENCES

[1] N. Kingsley, "Liquid Crystal Polymer: Enabling Next-Generation Conformal and Multilayer Electronics", *Microwave Journal*, pp. 188-200, May 2008.

[2] D.C. Thompson, O. Tantot, H. Jallageas, G.E. Ponchak, M.M. Tentzeris, and J. Papapolymerou, "Characterization of Liquid Crystal Polymer (LCP) Material and Transmission Lines on LCP Substrates from 30 to 110 GHz", *IEEE Trans. Microwave Theory and Techn.*, vol. 52, no. 4, pp. 1343-1352, April 2004.

[3] Georgia Tech Report. Available: https://phys.org/news/2006-08-georgia-tech-liquid-crystal-polymer.html

[4] S.W. Lee, K.S. Min, J. Jeong, J. Kim and S.J. Kim, "Monolithic Encapsulation of Implantable Neuroprosthetic Devices using Liquid Crystal Polymers", *IEEE Transactions on Biomedical Engineering*, vol. 58, no. 8, pp. 2255-2263, August 2011.

[5] D.J. Edell and B. Farrell, "Implantable Devices Having a Liquid Crystal Polymer Substrate", U.S. Patent 6 643 552, 2003.

[6] K. Jayaraj and B. Farrell, "Liquid Crystal Polymers and Their Role in Electronic Packaging", *Adv. Microelectron.*, vol. 25, pp. 15-18, 1998.

[7] A. Karmakar and K. Singh, *Si-RF Technology*, 1st Edition, Singapore: Springer Publication, 2019.

[8] A.M. Buchner, "The Role of Chromoendoscopy in Evaluating Colorectal Dysplasia", *Gastroenterol. Hepatol.*, vol. 13, no.6, pp. 336-347, 2017.

[9] M. Guardiola, M. Ceresa, J. Romeu, G. Fernandez-Esparrach, M.A. Gonzalez-Ballester, and O. Camara, "Microwave Endoscopy for Colorectal Cancer Prevention", *Int. J. CARS.*, vol. 12, no. 1, pp. 21, 2017.

[10] M. Guardiola, et. al., "Dielectric Properties of Colon Polyps, Cancer, and Normal Mucosa: Ex Vivo Measurements from 0.5 to 20 GHz", *Med. Phys.*, vol. 45, no. 8, pp. 3768-3782, 2018.

[11] S. Salahuddin, *Acquisition of Dielectric Properties of Tissues in the Microwave Range*, Ph. thesis, NUI Galway; doi: http://hdl.handle.net/10379/15559

[12] "IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields. 3 KHz to 300 GHz", IEEE standard C95.1-2005, 2005.

[13] E. Pickwell and V.P. Wallace, "Biomedical Applications of Terahertz Technology", *J. Phys. D: Appl. Phys.*, vol. 39, no. 17, Article no. R301, 2006.

[14] C.A. Balanis, *Antenna Theory Analysis and Design*, John Wiley & Sons, Inc., Third edition, 2005.

[15] M.S. Rabbani and H. Gi-Shiraz, "Improvement of Microstrip Antenna's Gain, Bandwidth and Fabrication Tolerance at Terahertz Frequency Bands", *Proc. Wideband Multi-Band Antennas and Arrays for Civil, Security and Military Applications Conf.*, 2015.

[16] G. Kumar and K.P. Ray, *Broadband Microstrip Antenna*, Artech House Publisher Inc., pp. 113-114, 2003.

[17] M. Habib Ullah, W. N.L. Mahadi, and T.A. Latef, "Aerogel, Poly(butylene succinate) Biomaterial Substrate for RF and Microwave Applications", *Sci Rep* 5, Article number 12868, 2015, doi: 10.1038/srep12868

[18] S. Seran, T. Karacolak, and J.P. Donohoe, "A Small Implantable Dual Band Biocompatible Antenna for Medical Wireless Telemetry Applications", *2013 USNC-URSI Radio Science Meeting (Joint with AP-S Symposium)*, p. 212, 2013, doi: 10.1109/USNC-URSI.2013.6715518

[19] K. Zhang, C. Liu, X. Liu, H. Guo, and X. Yang, "Miniaturized Circularly Polarized Implantable Antena for ISM-band Bio-medical Devices", vol. 2017, Article ID 9750257, doi: 10.1155/2017/9750257

[20] M. Abu, et al., "Miniaturized Implantable Ultra-Wideband Antenna with Bio-Compatible Substrate Material", *Applied Mechanics and Materials*, vol. 850, Trans. Tech. Publications, Ltd., Aug. 2016, pp. 71-76, doi: 10.4028/www.scientific.net/amm.850.71