FLEXIBLE ORGANIC POLYMER MATRIX COMPOSITE ANTENNA FOR WIRELESS LOCAL AREA NETWORK APPLICATION

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ABSTRACT

The growing demand for flexible antennas has resulted in intensified research on new materials for flexible antennas. The flexibility of antennas is a well-known requirement in wireless body area networks (WBAN), vehicle navigation system and wireless local area networks (WLAN) to improve seamless integration on devices. Compared with conventional rigid antennas, conformal antennas provide a larger coverage area with a broad beam radiation pattern due to the increase in the area of transmission and reception. This research aims to develop and explore a new organic polymer matrix composite (PMC) antenna with organic fibre to replace synthetic polymer composite which may release harmful chemical and also non-biodegradable. Organic PMC is not only low cost but able to promote sustainability for the environment. Size miniaturization also needs to be achieved for a more compact size antenna and also to enhance the bandwidth. The proposed antenna is a flexible monopole antenna based on organic PMC material produced from natural Basalt fibre and it proved to manage in operating at frequencies of 2.45 GHz and 5.8 GHz for WLAN application. The characterized Basalt composite substrate has a thickness of 0.42 mm, dielectric constant of 3.105 and tangent loss of 0.0299. The vacuum infusion technique is used to manufacture the composite material as this technique can increase the accuracy of fiber to resin ratio and give consistent resin usage. Before vacuum infusion, a layer of conductive fabric named ShieldIt with adhesive glue on its bottom layer will be ironed onto the basalt fiber fabric. Then, two layers of basalt fiber fabric with a layer of conductive fabric on the top layer were placed on the mold before vacuum conditions are created. Epoxy resin and hardener were then mixed in a ratio of 10:6. Vacuum pressure was turned on and pushed the epoxy mixture to the laminate through the tubing. The defected ground structure (DGS) were implemented to improve bandwidth and coplanar waveguide (CPW) as antenna feeding method. Top layer radiating element is conductive fabric and the lasercut machine cut out the antenna pattern precisely. Measured antenna gains at 2.45 GHz and 5.8 GHz are 3.865 and 4.8 with efficiency of 62.63% and 68.07%, respectively. As a flexible antenna, the bending test proved that the antenna performance did not compensate for bending at different curvature radii.

ABSTRAK

Permintaan yang semakin meningkat untuk antena telah menghasilkan penyelidikan yang lebih intensif mengenai bahan baharu untuk antena fleksibel. Fleksibiliti antena ialah keperluan yang terkenal dalam rangkaian kawasan badan wayarles (WBAN), rangkaian kawasan tempatan wayarles (WLAN) dan sistem pandu arah kenderaan untuk meningkatkan penyepaduan lancar pada peranti. Berbanding dengan antena tegar lazim, antena konformal menyediakan kawasan liputan yang lebih besar dengan corak sinaran rasuk yang luas disebabkan oleh peningkatan dalam kawasan penghantaran dan penerimaan. Penyelidikan ini bertujuan untuk meneroka antena komposit matriks polimer (PMC) organik baharu dengan gentian organik untuk menggantikan komposit polimer sintetik yang mungkin membebaskan bahan kimia berbahaya dan juga tidak biodegradabel. Antena yang dicadangkan ialah antena ekakutub fleksibel berasaskan bahan PMC organik yang dihasilkan daripada gentian Basalt semulajadi dan mampu beroperasi pada frekuensi 2.45 GHz dan juga 5.8 GHz untuk aplikasi WLAN. Substrat komposit Basalt yang dicirikan mempunyai ketebalan 0.42 mm, pemalar dielektrik 3.105 dan kehilangan tangen 0.0299. Teknik infusi vakum digunakan untuk mengeluarkan bahan komposit kerana teknik ini boleh meningkatkan ketepatan nisbah gentian kepada resin dan memberikan penggunaan resin yang konsisten. Sebelum infusi vakum, lapisan fabrik konduktif bernama ShieldIt dengan gam pelekat pada lapisan bawahnya akan diseterika pada fabrik gentian basalt. Kemudian, dua lapisan fabrik gentian basalt dengan lapisan fabrik konduktif pada lapisan atas diletakkan pada acuan sebelum keadaan vakum dicipta. Tekanan vakum dihidupkan dan menolak campuran epoksi ke lamina melalui tiub. Pandu gelombang coplanar (CPW) sebagai kaedah penyuapan antena dan struktur tanah yang rosak (DGS) dilaksanakan untuk meningkatkan lebar jalur. Elemen penyinaran lapisan atas ialah fabrik konduktif dan mesin potong laser memotong corak antena dengan tepat. Gandaan antena yang diukur pada 2.45 GHz dan 5.8 GHz ialah 3.865 dan 4.8 dengan kecekapan masing-masing adalah 62.63% dan 68.07%. Sebagai antena fleksibel, ujian lenturan membuktikan bahawa prestasi antena tidak mengimbangi dengan membongkok pada jejari kelengkungan yang berbeza.

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LIST OF ABBREVIATIONS

AUT	-	Antenna Under Test
CMC	-	Ceramic Matrix Composites
CNT	-	Carbon Nanotube
CPW	-	Coplanar Waveguide
CST	-	Computer Simulation Technology
EBG	-	Electromagnetic Band Gap
EMC	-	Electromagnetic Compatibility
FR4	-	Frame Resistance 4
FRP	-	Fibre Reinforced Polymers
HF	-	High Frequency
LCP	-	Liquid Crystal Polymer
MMC	-	Metal Matrix Composites
MWCNT	-	Multi-wall Carbon Nanotubes
PDMS	-	Polydimethylsiloxane
PET	-	Polyethylene Terephthalate
PMC	-	Polymer Matrix Composites
PTFE	-	Polytetrafluoroethylene
RCCF	-	Reinforced Continuous Carbon Fibers
TE	-	Transverse Electric
TEM	-	Transverse Electric and Magnetic Mode
UAV	-	Unmanned Aerial Vehicles
UTM	-	Universiti Teknologi Malaysia
UWB	-	Ultrawide Band
V2V	-	Vehicle to vehicle
VNA	-	Vector Network Analyzer
WBAN	-	Wireless Body Area Network
WLAN	-	Wireless Local Area Networks

LIST OF SYMBOLS

λ	-	Wavelength
S_{11}	-	Reflection Coefficients
δdc	-	Conductivity
Rs	-	Sheet Resistance
ε_r	-	Dielectric Constant
g	-	Gap between Feedline and Ground Plane
W	-	Width of Antenna
L	-	Length of Antenna
h	-	Height of Substrate
t	-	Thickness

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CHAPTER 1

INTRODUCTION

1.1 Research Background

In recent years, flexible antennas have drawn a great deal of attention following the rapid development of wireless communication systems. Researchers are growing interest in flexible antennas for its benefits of high flexibility, light weight, low cost, easily mounted on conformal surface and ease of fabrication. The flexible antenna are extensively studied and designed for wide range of applications such as the biomedical applications, wireless local area networks (WLAN), satellite communication and also vehicle navigation and communication. To catch up with latest trends of flexible antennas, requirements of light weight, thin, small, bendable, multiband and green material need to be fulfilled by the innovative designs. [1]-[2].

In order to achieve the flexibility of antenna, thin and flexible substrates such as composites and polymers will replace the typical rigid substrates such as FR4, Rogers and Taconic. The flexible substrate in this thesis is Basalt fiber composite which is a green and environment friendly product that does not pollute the environment. Basalt fiber is a natural material formed from melting volcanic stone at 1450 to 1500 degrees. It is called as the volcano rock silk and also an organic continuous fiber that produced by Platinum rhodium alloy brushing. Basalt fiber stood out from the rest as it had good tensile strength and thus can be used to reinforce composites. In addition, it has high corrosive resistance and chemical stability which enable it to withstand extreme acidic, alkaline or high humidity condition. Basalt fiber also has strong electrical insulation, high thermal stability and able to manufacture strong composite as it is well compatible with other materials [3].

The feeding technique for the designed flexible antenna is coplanar waveguide (CPW) as it is suitable for WLAN and wearable applications. CPW gives wider bandwidth and reduce overall thickness because it can be ungrounded so it only need single layer of radiating element. Besides that, it is capable to grant low dispersion, low radiation leakage and control the characteristic impedance. [4]-[5] The proposed flexible antenna is applicable to 2.4 GHz and 5.8 GHz WLAN systems that frequencies falls within 2.4-2.484 GHz for IEEE 802.11b/g and at 5.725-5.825 GHz for IEEE 802.11a. The aim of this design is to achieve dual band antenna by flexible monopole antenna with trapezoidal ground plane for WLAN systems while proving the flexibility and performance of flexible antenna in flat and bending condition with simulated and measured results. [6]-[7]

1.2 Problem Statement

Based on the investigation on recent antenna development, there are some challenges in antenna were discovered. The inflexible rigid antenna having limitation to mount perfectly to regular surfaces and also make it less robust. The alternative is the flexible antenna which contributes good flexibility while giving acceptable reflection coefficient and gain in different curvature of bending. Most of the rigid antenna cannot endure mechanical damages and low in mechanical strength but the environment friendly organic flexible substrate is high in oxidation resistance, compression strength and sheer strength. Besides wearable applications, these properties are also attractive in applications such as wireless local area networks (WLAN) and vehicle navigation [1-4]. Compared with the conventional rigid antennas, conformal antennas provide larger coverage area with a broad beam radiation pattern due to the increase in the area of transmission and reception. However, designing flexible antennas requires more complex optimization process to ensure satisfactory performance in both planar and conformal configurations [5-7]. Flexible antennas based on textiles, composites or polymers featuring thin, light weight and flexible properties are suitable alternatives the rigid antennas based on commercial substrates. While textiles are a good choice for wearable antennas due to its easier integration with clothes, its performance can be significantly affected by water absorption and humidity [8]. Meanwhile, chemically-produced synthetic polymers substrates such as polyethylene terephthalate (PET), polytetrafluoroethylene (PTFE) or polypropylene may increase health risk due to the possible of toxic chemical release during their manufacturing processes [6], [9-11]. On the other hand, composites substrates can be made using natural fibers such as basalt, jute or flax to promote sustainability. Basalt fiber is an environmentally-friendly material formed by melting crushed basalt rocks at 1400°C. It is physically and mechanically stronger compared to glass fibers, with good fire resistance, high corrosion resistance and strong electrical insulation [3],[12]. To explore a totally new material which is never use in any previous work is a big challenge as we need to characterize the new material and also need to determine the total layer of fabric that need to be use for the composite which can give satisfied flexibility but will not be too thin for lasercut process. By referring to the polypropylene-based monopole antenna from previous work, size miniaturization should be done to improve its antenna bandwidth and also to achieve a more compact size to reduce its occupy area on devices [6].

1.3 Research Objectives

The objectives of the research are :

(a) To characterize the flexible composite substrate that made from organic natural material.

(b) To design, simulate and fabricate the dual band flexible antenna for wireless local area network (WLAN) application.

(c) To test and evaluate flexibility and efficiency of the proposed flexible composite-based antenna under different bending conditions.

1.4 Scope of Work

This research will focused on the study of flexible antenna which using organic composite material as substrate and its flexibility enables it to adhere well on conformal and curved surface while providing satisfied efficiency and gain of antenna at different bending of curvature. The proposed antenna is designed for the practical frequency at 2.4 GHz and 5.8 GHz which allow wireless local area network (WLAN) and utilized for vehicular communication systems such as the unmanned aerial vehicle. The flexible antenna will be using the ungrounded coplanar waveguide (CPW) feeding technique which supposed to effectively control the characteristic impedance, low dispersion and low radiation leakage. Due to the absent of ground plane below the substrate, the overall thickness of antenna is reduced for better flexibility and it also ease the fabrication. Software CST Microwave Studio will be using throughout the design and simulation of flexible antenna. But manufacture and characterization of composite material will be carried on before designing and simulation of the antenna. Two layers of Basalt fibre which is natural material and a layer of conductive fabric is integrated with resin and hardener with the vacuum infusion process. Next, the designed antenna pattern on the conductive fabric is cut out using the laser cutter for precise result. On the other hand, bending abilities is examined to compare their performance in different radius curvature. Equipment such as vector network analyzer, laser cutter and composite material fabrication facilities is employed.

1.5 Research Contributions

The flexibility and properties of multiple elements antenna able to contribute in unmanned aerial vehicles (UAV), aircraft and military usage. To reduce air drag effect and make the antenna more robust, the flexible composite antenna can be used directly on the devices' surface instead of mounted on it. Moreover, the reflection coefficient and gain of the flexible antenna will not deteriorates when bending in different curvature. Calculated bandwidth at flat condition is 46.24% and 10.08 % for 2.45 GHz and 5.8 GHz and it decrease to 38% and 10.53% for 2.45 GHz and 5.8

GHz when bending at curvature radius of 20mm. This means there is only 8.24% downgrade for 2.4 GHz and 0.45% upgrade for 5.8 GHz. Based on the research, the adaptable and reliable antenna will definitely benefits the aircraft, unmanned vehicles, body worn applications from its bending abilities and also high efficient antenna performance. From this research, the flexible antenna are now proved that it is workable on an new explored eco-friendly and organic material, Basalt which is flexible and low cost to meet the high demands for flexible antennas. This studies also shows that the manufacturing method of this antenna which is vacuum infusion process is actually less complex and the antenna pattern can be fabricated easily and precisely with lasercut machine. By comparing with flexible polypropylene-based dual band antenna which works for 2.45 GHz and 5.8 GHz, the overall antenna size was reduce from 1645.92 mm^2 to 1007 mm^2 which equal to size reduction of 38.8% [6]. The bandwidth of this polymer matric composite antenna from basalt is increased after size miniaturization, the lower frequency bandwidth of the previous polypropylene-based dual band antenna is 18.5% but the achieved lower frequency bandwidth from this work is 46.24% [6].

1.6 Thesis Outline

This thesis is outlined in five chapters. First chapter introduces the whole studies with the research background, problem statement, the three research objectives, scope of work and research contributions. The next chapter is the literature review, where the overview of flexible antennas and the antenna applications are presented. The feeding method which is (CPW) coplanar waveguide and the bandwidth enhancement technique which is defected ground structure are also discussed. The structural aspects and electrical characteristics of different type of conductive textile and composite material are reviewed too. Last but not least, the requirements and challenges of composite antenna fabrication is given in this chapter.

Chapter three proposed the flowchart and the general phases to initiate and complete this research work. First phase is working on the problem statements, objectives of research and the literature review. Next phase is studying the various composite material and proceed to material characterization to obtain the electrical properties of the composite substrate for designation and simulation of flexible composite antenna. Fabrication of antenna and the measurement of antenna performance will be done in third phase while the measured and simulated results will be discussed in last phase.

Chapter four discusses the validation of flexible PMC polymer matrix composite antenna that designed and fabricated in chapter 3. The reflection coefficient, gain, antenna efficiency and radiation pattern of measured and simulated results are compared and analyzed. Besides that, the antenna performance of previous research works are compared with this achieved antenna performance. The last chapter including the conclusion and also recommend the possible future works.

REFERENCES

[1] Z. Hamouda, J. Wojkiewicz, A. A. Pud, L. Kone, S. Bergheul and T. Lasri, "Flexible UWB organic antenna for wearable technologies application," IET Microwaves, Antennas & Propagation, vol. 12, no. 2, pp. 160-166, 2018.

[2] H. K. Yoon, W. S. Kang, Y. J. Yoon, C. H. Lee, "A flexible UWB antenna attachable to various kinds of materials", Proc. IEEE ICUWB, pp. 204-209, 2007-Sep.

[3] Fiore V, Scalici T, Di Bella G and Valenza A, "A review on basalt fibre and its composites," Composites Part B: Engineering, pp. 74-94, 2015.

[4] Ahmed, S., Tahir, F.A., Shamim, A. and Cheema, H.M., "A compact kapton-based inkjet-printed multiband antenna for flexible wireless devices," IEEE Antennas and Wireless Propagation Letters, vol.14, pp.1802-1805, 2015.

[5] D. E. Anagnostou, A. A. Gheethan, A. K. Amert, K. W. Whites, "A direct-write printed antenna on paper-based organic substrate for flexible displays and WLAN applications", J. Display Technol., vol. 6, no. 11, pp. 558-564, Nov. 2010.

[6] M. E. de Cos and F. Las-Heras, "Polypropylene-Based Dual-Band CPW-Fed Monopole Antenna [Antenna Applications Corner]," IEEE Antennas and Propagation Magazine, vol. 55, pp. 264-273, 2013.

[7] H. Li, Y. Zhou, X. Mou, Z. Ji, H. Yu and L. Wang, "Miniature Four-Band CPW-Fed Antenna for RFID/WiMAX/WLAN Applications," IEEE Antennas and Wireless Propagation Letters, vol. 13, pp. 1684-1688, 2014.

[8] X. Lin, Y. Chen, Z. Gong, B. Seet, L. Huang and Y. Lu, "Ultrawideband Textile Antenna for Wearable Microwave Medical Imaging Applications," IEEE Transactions on Antennas and Propagation, vol. 68, pp. 4238-4249, June 2020.

[9] A. Kiourti and J. L. Volakis, "Stretchable and Flexible E-Fiber Wire Antennas Embedded in Polymer," IEEE Antennas and Wireless Propagation Letters, vol. 13, pp. 1381-1384, 2014.

[10] Y. Zhou, S. Sivapurapu, M. Swaminathan and S. K. Sitaraman, "Mechanical and High-Frequency Electrical Study of Printed, Flexible Antenna under Deformation," IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 10, pp. 1088-1100, 2020.

[11] S. F. Jilani, M. O. Munoz, Q. H. Abbasi and A. Alomainy, "Millimeter-Wave Liquid Crystal Polymer Based Conformal Antenna Array for 5G Applications," IEEE Antennas and Wireless Propagation Letters, vol. 18, pp. 84-88, 2019.

[12] Sim, Jongsung, and Cheolwoo Park, "Characteristics of basalt fiber as a strengthening material for concrete structures," Composites Part B: Engineering, pp. 504-512, 2005.

[13] El Atrash, M., M. A. Abdalla, and H. M. Elhennawy. "Gain enhancement of a compact thin flexible reflector-based asymmetric meander line antenna with low SAR." IET Microwaves, Antennas & Propagation, vol.13, pp. 827-832, 2019.

[14] A. Arif, M. Zubair, M. Ali, M. U. Khan and M. Q. Mehmood, "A Compact, Low-Profile Fractal Antenna for Wearable On-Body WBAN Applications," IEEE Antennas and Wireless Propagation Letters, vol. 18, no. 5, pp. 981-985, May 2019.

[15] H. A. Elmobarak Elobaid, S. K. Abdul Rahim, M. Himdi, X. Castel and M. Abedian Kasgari, "A Transparent and Flexible Polymer-Fabric Tissue UWB Antenna for Future Wireless Networks," IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 1333-1336, 2017.

[16] M. Cosker, L. Lizzi, F. Ferrero, R. Staraj and J. Ribero, "Realization of 3-D Flexible Antennas Using Liquid Metal and Additive Printing Technologies," IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 971-974, 2017.

[17] A. Mehdipour, I. D. Rosca, A. Sebak, C. W. Trueman and S. V. Hoa, "Full-Composite Fractal Antenna Using Carbon Nanotubes for Multiband Wireless Applications," IEEE Antennas and Wireless Propagation Letters, vol. 9, pp. 891-894, 2010.

[18] Abishek, E. Veera, A. Kumar Pc, K. Stephen and A. Raaza, Arun, "Study and Analysis of Conformal Antennas for Vehicular Communication Applications," ARPN Journal of Engineering and Applied Sciences, vol.12, pp. 2428-2433, 2017.

[19] J. R. James and P. S. Hall, Handbook of Microstrip Antennas. IEE Electromagnetic Wave Series, 1989.

[20] Chen, W.K., The electrical engineering handbook. Elsevier, 2004.

[21] C. P. Wen, "Coplanar Waveguide: A Surface Strip Transmission Line Suitable for Nonreciprocal Gyromagnetic Device Applications," IEEE Transactions on Microwave Theory and Techniques, vol. 17, pp. 1087-1090, 1969.

[22] S. Chaimool, P. Akkaraekthalin, "CPW-Fed Antennas for WiFi and WiMAX," Advanced Transmission Techniques in WiMAX, 2012.

[23] Y. J. Li, Z. Y. Lu and L. S. Yang, "CPW-Fed Slot Antenna for Medical Wearable Applications," IEEE Access, vol. 7, pp. 42107-42112, 2019.

[24] F. Faisal, Y. Amin, Y. Cho and H. Yoo, "Compact and Flexible Novel Wideband Flower-Shaped CPW-Fed Antennas for High Data Wireless Applications," IEEE Transactions on Antennas and Propagation, vol. 67, no. 6, pp. 4184-4188, 2019.

[25] Guha, Debatosh, S. Biswas, and C. Kumar, "Printed antenna designs using defected ground structures: a review of fundamentals and state-of-the-art developments," Forum for Electromagnetic Research Methods and Application Technologies (FERMAT), vol. 2, pp. 1-13. 2014.

[26] F. Yang, and Y. R. Samii, Electromagnetic band gap structures in antenna engineering, Cambridge University Press, 2008.

[27] C. S. Kim, J. S. Park, D. Ahn, and J. B. Lim, "A novel 1-D periodic defected ground structure for planar circuits," IEEE Microwave Wireless Components Letters, vol. 10, no. 4, pp. 131-133, 2000.

[28] G. Breed, "An introduction to defected ground structures in microstrip circuits." High Frequency Electronics, no. 11, pp. 50-54, 2008.

[29] M. A. Antoniades, and G. V. Eleftheriades, "A compact multiband monopole antenna with a defected ground plane," IEEE Antennas and Wireless Propagat. Lett., vol. 7, pp. 652-655, 2008.

[30] K. H. Chiang and K. W. Tam "Microstrip monopole antenna with enhanced bandwidth using defected ground structure," IEEE Antennas and Wireless Propagat. Lett., vol. 7, pp. 532-535, 2008.

[31] A. Nouri and G. R. Dadashzadeh, "A compact UWB band-notched printed monopole antenna with defected ground structure," IEEE Antennas and Wireless Propagat. Lett., vol. 10, pp. 1178-1181, 2008.

[32] Gibson, Ronald F., "Principles of composite material mechanics," CRC press, 2016.

[33] Daniel, I. M., Ishai, O., "Engineering mechanics of composite materials," New York: Oxford university press, vol. 1994, 2006.

[34] Munonyedi K. E., "A fundamental review on composite materials and some of their applications in biomedical engineering," Journal of King Saud University - Engineering Sciences, 2020.

[35] (2017). Guide To Composite Materials. Available: http://www.netcomposites.com/education.asp?sequence=2

[36] (2015) M. Akay, “An introduction to polymer matrix composites,” from: https://www.academia.edu/37778336/An_introduction_to_polymer_matrix_composites

[37] S.G. Advani, K.T. Hsiao, “Manufacturing Techniques for Polymer Matrix Composites (PMCs), ” UK: Woodhead Publishing ltd, 2012.

[38] U.S. Congress, Office of Technology Assessment, “Chapter 3 Polymer Matrix Composites,” Advanced Materials by Design, 1988.

[39] J.P. Jose, “Advances in Polymer Composites: Macro- and Microcomposites – State of the Art, New Challenges, and Opportunities,” Polymer Composites: Volume 1, 2012.

[40] R.M. Wang, S.R. Zheng, and Y.P. Zheng, “Introduction to polymer matrix composites,” Polymer Matrix Composites and Technology, 2011.

[41] “Processing of polymer composites,” 2012, from: http://www-materials.eng.cam.ac.uk/3C1archive/handout6.pdf

[42] Spasojevic, Pavle M., "Thermal and rheological properties of unsaturated polyester resins-based composites." Unsaturated Polyester Resins. Elsevier, pp. 367-406, 2019.

[43] N. Hashim, D. L. A. Majid, D. M. Baitab, N. Yidris, R. Zahari, “Tensile Properties of Woven Intra-Ply Carbon/Kevlar Reinforced Epoxy Hybrid Composite at Sub-Ambient Temperature,” Reference Module in Materials Science and Materials Engineering, Elsevier, 2019.

[44] M. Mrazova, "Advanced composite materials of the future in aerospace industry," Incas bulletin, vol. 5, pp. 139, 2013.

[45] J. HINRICHSEN, "Airbus A380: Requirements for the selection of materials and manufacturing technologies," ATB Métallurgie, vol. 41, pp. 24-30, 2001.

[46] P. Jerome, “Composite materials in the airbus A380-from history to future,” 2001.

[47] R. R. d. Assis and I. Bianchi, "Analysis of microstrip antennas on carbon fiber composite material," Journal of Microwaves, Optoelectronics and Electromagnetic Applications, vol. 11, pp. 154-161, 2012.

[48] E. Mangino, J. Carruthers, and G. Pitarresi, "The future use of structural composite materials in the automotive industry," International Journal of vehicle design, vol. 44, pp. 211-232, 2007.

[49] M. Won, T. Park, and S. H. Son, "Toward Mitigating Phantom Jam Using Vehicle-to-Vehicle Communication," IEEE Transactions on Intelligent Transportation Systems, vol. 18, pp. 1313-1324, 2017.

[50] E. Salernitano and C. Migliaresi, "Composite materials for biomedical applications: a review," Journal of Applied Biomaterials & Biomechanics, vol. 1, pp. 3-18, 2003.

[51] B. Suddell, "Industrial fibres: recent and current developments," in Symposium on Natural Fibres, 2008.

[52] A. Mehdipour, A.-R. Sebak, C. W. Trueman, I. D. Rosca, and S. V. Hoa, “Reinforced continuous carbon-fiber composites using multi-wall carbon nanotubes for wideband antenna applications,"IEEE Transactions on Antennas and Propagation, vol. 58, pp. 2451-2456, 2010.

[53] Agilent 85070E Dielectric Probe Kit 200 MHz to 50 GHz. Available: http://www.imperial.ac.uk/media/imperial-college/research-centres-andgroups/centre-for-bio-inspired-technology/11949699.PDF

[54] I. Inc., "IEEE Standard Test Procedures for Antennas," ed: distributed by Wiley-Interscience, 1979.

[55] A. Mehdipour, I. D. Rosca, A. Sebak, C. Trueman, and S. Hoa, "Advanced carbon-fiber composite materials for RFID tag antenna applications," Appl. Comput. Electromagn. Soc.(ACES) J, vol. 25, 2010.

[56] A. Mehdipour, A.-R. Sebak, C. W. Trueman, I. D. Rosca, and S. V. Hoa,"Reinforced continuous carbon-fiber composites using multi-wall carbon nanotubes for wideband antenna applications," IEEE Transactions on Antennas and Propagation, vol. 58, pp. 2451-2456, 2010.

[57] Explainer: In chemistry, what does it mean to be organic?. Available: https://www.snexplores.org/article/explainer-chemistry-organic-carbon

[58] H. I. Malik, M. Y. Ismail, Sharmiza Adnan, S. R. Masrol and N. Nafarizal, “A wideband reflectarray antenna based on organic substrate materials,” TELKOMNIKA, vol.17, pp.8-14, 2019.

[59] Elwi, Taha A. "Novel UWB printed metamaterial microstrip antenna based organic substrates for RF-energy harvesting applications." AEU-International Journal of Electronics and Communications, pp.44-53, 2019.

[60] B. Zhang, C. Kärnfelt, H. Gulan, T. Zwick and H. Zirath, "A D-Band Packaged Antenna on Organic Substrate With High Fault Tolerance for Mass Production," IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 6, no. 3, pp. 359-365, 2016.

[61] Hamouda, Zahir, Jean-luc Wojkiewicz, Alexander A. Pud, Lamine Kone, Said Bergheul, and Tuami Lasri. "Flexible UWB organic antenna for wearable technologies application." IET Microwaves, Antennas & Propagation 12, pp.160-166, 2018.

[62] Masihi, S., Panahi, M., Maddipatla, D., Bose, A. K., Zhang, X., Hanson, A. J., M. Z, “Development of a flexible tunable and compact microstrip antenna via laser assisted patterning of copper film,” IEEE Sensors Journal, pp. 7579-7587, 2020.

[63] Smida, A., Iqbal, A., Alazemi, A. J., Waly, M. I., Ghayoula, R., & Kim, S., "Wideband wearable antenna for biomedical telemetry applications," IEEE Access, pp. 15687-15694, 2020.

[64] Simorangkir, R. B., Kiourti, A., & Esselle, K. P., "UWB wearable antenna with a full ground plane based on PDMS-embedded conductive fabric," IEEE Antennas and Wireless Propagation Letters, pp. 493-496, 2018.

[65] Alqadami, A. S., Stancombe, A. E., Bialkowski, K. S., & Abbosh, "Flexible meander-line antenna array for wearable electromagnetic head imaging," IEEE Transactions on Antennas and Propagation, pp. 4206-4211, 2020.

[66] Sindhu, B., Kothuru, A., Sahatiya, P., Goel, S., & Nandi, "Laser-induced graphene printed wearable flexible antenna-based strain sensor for wireless human motion monitoring," IEEE Transactions on Electron Devices, pp. 3189-3194, 2021.

[67] C. Gennarelli, A. Capozzoli, L. J. Foged, J. Fordham, and D. J. Van Rensburg, "Recent advances in near-field to far-field transformation techniques," *Int. J. Antennas Propag.*, pp. 1–3, 2012.

[68] J. R. Perez and J. Basterrechea, "Near to far-field transformation for antenna measurements using a GA based method," *IEEE Antennas Propag. Soc. Int. Symp.*, vol. 1, pp. 734–737, 2002.

[69] Balanis, Constantine A, "Antenna theory: analysis and design," John wiley & sons, 2015.

[70] Fegade, Vishal, M. Ramachandran, S. Madhu, C. Vimala, R. Kurinji Malar, and R. Rajeshwari. "A review on basalt fibre reinforced polymeric composite materials." In AIP Conference Proceedings, vol. 2393, AIP Publishing LLC, 2022.

[71] Li, Zongwen, et al. "Properties and applications of basalt fiber and its composites." IOP Conference Series: Earth and Environmental Science. Vol. 186, 2018.

APPENDIX B

LIST OF PUBLICATIONS

1. L. Y. Ying, S. K. Abdul Rahim, A. B. Nawabjan and T. L. Hwa, "Flexible CPW Fed Antenna with Organic Substrate for WLAN Applications," *2019 6th International Conference on Space Science and Communication (IconSpace)*, pp. 218-221, 2019. (Published)

2. L. Y. Ying, S. K. A. Rahim, A. B. Nawabjan and T. L. Hwa, "Design of Dual Band Flexible CPW Fed Antenna Based on Basalt Fiber Composite," *2018 IEEE International RF and Microwave Conference (RFM)*, pp. 97-99, 2018. (Published)