DESIGN AND DEVELOPMENT OF WEARABLE FLUIDIC ANTENNA WITH AMC

by

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LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
ABS	Acrylonitrile-Butadiene Styrene
ACE	Advanced Communication Engineering Centre
AD1	Antenna Design 1
AD2	Antenna Design 2
AMC	Artificial Magnetic Conductor
CST	Computer Simulation Technology
dB	Decibel
EBG	Electromagnetic Band Gap
EGaIn	Eutectic Gallium Indium
EM	Electromagnetic
E-Textile	Electronic Textiles
FBR	Front Back Ratio
FBW	Fractional Bandwidth
FCC	Federal Communications Commission
GHz	Giga Hertz
Galinstan	Gallium Indium Tin
HIS	High Impedance Surface
IFA	Inverted-F Antenna
ISM	Industrial Scientific Medical
LCP	Liquid Crystal Polymer
MHz	Mega Hertz
MOH	Ministry of Health
MWS	Microwave Studio
PDMS	Polydimethylsiloxane
P-Health	Predictive Health
PLA	Polylactic acid
RFID	Radio Frequency Identification
SAR	Specific Absorption Rate
UNEP	United Nations Environment Programme

UniMAP	Universiti Malaysia Perlis
WLAN	Wireless Local Area Network
WWHMS	Wearable Wireless Health Monitoring System

LIST OF SYMBOLS

r	Radius
W	Watt
kg	Kilogram
g	Gram
σ	Sigma
E	Electric field
ρ	Rho
S	Siemens
m	Meter
V	Volt
m^3	Cubic in meter
%	Percentage
m^3	Cubic in meter
cm^3	Cubic in centimeter
mm	Millimeter
µm	Micrometer
w	Width
l	Length
h	High
$L1$	Inductance
$C1$	Capacitance
f_r	Resonant frequency
BW	Bandwidth
$\mathcal{E}_r$	Relative permittivity
$\mathcal{E}_0$	Permittivity in free space
μ_0	Permeability in free space
η_0	Efficiency in free space
Ω	Ohm
tan-δ	Loss tangent
λ	Lambda

Rekabentuk dan Pembangunan Perambat Bendalir Boleh Pakai dengan AMC

ABSTRAK

Dalam tahun-tahun kebelakangan ini, perambat boleh pakai banyak digunakan dalam perkhidmatan kecemasan dan keselamatan, bagi tujuan pengesanan, aplikasi ketenteraan dan pemantauan parameter fisiologi manusia. Rekabentuk perambat untuk aplikasi boleh pakai amat mencabar kerana operasinya di sekitar tubuh manusia boleh menyebabkan gangguan, sehingga mempengaruhi prestasi keseluruhan perambat. Sebab utamanya adalah kerana badan manusia boleh menyerap gelombang elektromagnetik yang dipancarkan dari perambat, yang membawa kepada pengurangan kecekapannya apabila ia diletakkan berdekatan dengan badan. Selain itu, sinaran gelombang elektromagnet (*EM*) dari perambat mungkin membahayakan kesihatan manusia dalam jangka panjang apabila terdedah secara berlebihan. Objektif projek ini ialah untuk merekabentuk, membangun dan menghasilkan perambat bendalir boleh pakai dengan kadar penyerapan spesifik gelombang eletromagnetik (SAR) yang rendah, serta kekalisan terhadap air dan kelembapan yang baik. Untuk mengurangkan kesan kepada pengguna antenna ini dan memastikan penggunaan yang selamat, penggunaan Konduktor Magnetik Tiruan (*AMC*) merupakan suatu penyelesaian yang sesuai. Ia direka untuk menyaring dan memantulkan gelombang EM pada set-set frekuensi dan pada arah-arah tertentu. Perambat bendalir boleh pakai fleksibel yang terbenam dalam struktur polydimethylsiloxane (*PDMS*) dan digabungkan dengan Konduktor Magnetik Tiruan (*AMC*) dikaji dalam penyelidikan ini. Perambat ini direka berdasarkan prinsip operasi perambat tampal dengan slot dan celah untuk menampung operasi di jalur komunikasi tanpa wayar pada 2.45 GHz dan 5.8 GHz. Rekabentuk pertama yang dilabel sebagai Rekabentuk Perambat 1 (*AD1*) diimplementasikan dengan menggunakan *PDMS* sebagai substrat, *AMC*nya dibina menggunakan tembaga, dan perambatnya menggunakan Eutectic Galium Indium (*EGaIn*). Gandaan *AD1* mencapai 3.58 dB pada 2.45 GHz bersama lebar jalur 85 MHz, dan gandaan 6.08 dB pada 5.8 GHz dengan lebar jalur 278 MHz. Manakala bagi SAR, kesemua nilai SAR bagi *AD1* dalam keadaan rata dan bengkok tidak melebihi 2 W/kg, berdasarkan piawaian keselamatan di Eropah. Rekabentuk kedua yang dilabel sebagai Rekabentuk Perambat 2 (*AD2*) direka untuk mengatasi kelemahan *AD1*, dengan *PDMS* sebagai substrat dan cecair logam *Galinstan* sebagai elemen konduktif *AMC* dan antenna. Inovasi utama dalam penyelidikan ini adalah integrasi antenna dan *AMC* yang dibuat sepenuhnya dengan menggunakan logam cecair yang terbenam didalam *PDMS* untuk membolehkan perambat yang lebih fleksibel dan kuat, selain berpotensi menambah ciri bolehubah pada masa akan datang. *AD2* menunjukkan prestasi yang baik dengan jalur lebar 80 MHz dan 460 MHz masing-masing dalam jalur lebar bawah, berserta gandaan di antara 5.2 dan 4.12 dB. Bagi analisis *SAR*, kesemua nilai SAR *AD2* dalam keadaan rata dan bengkok tidak melebihi 2 W/kg, sekaligus menunjukkan bahawa antenna ini selamat digunakan sebagai antenna boleh pakai. Akhir sekali, menerusi ujikaji yang dijalankan, perambat bendalir ini turut menunjukkan prestasi yang lebih baik dari segi kekalisan air berbanding perambat tekstil.

Design and Development of Wearable Fluidic Antenna with AMC

ABSTRACT

In recent years, most wearable antennas are used for emergency and rescue services, tracking purposes, military applications and monitoring human physiological parameters. Design of antennas for wearable applications is challenging due to their operation in the vicinity of human body which causes interference, thus affecting the overall performance. The main reason is because human body absorbs electromagnetic waves emitted from antennas, which leads to the reduction of antenna efficiency when they are placed near to the body. Besides, their electromagnetic (EM) radiation are possibly harmful to human health in the long term when exposed excessively. The objective of this project is to design, develop and fabricate wearable fluidic antennas with low Specific Absorption Rates (SAR) and good resistance to water and moisture. To reduce the impact of the user on the antenna and provide a safe emission level, Artificial Magnetic Conductor (AMC) is a suitable solution. They are typically designed to filter and reflect possible EM wave propagating at predefined sets of frequencies towards a certain direction. A flexible wearable fluidic antenna embedded in a polydimethylsiloxane (PDMS) structure integrated with a liquid metal AMC plane is presented. The antenna is designed based on the operating principles of a patch antenna with slots and slits to cover its operation in the 2.45 GHz and 5.8 GHz wireless communication bands. The first design, denoted as Antenna Design 1 (AD1) is implemented on a PDMS substrate, its AMC is formed using copper sheet, and its radiator using liquid metal Eutectic Gallium Indium (EGaIn). AD1 achieved a gain of 3.58 dB at 2.45 GHz with a bandwidth of 85 MHz, and 6.08 dB at 5.8 GHz with a bandwidth of 278 MHz. For SAR, all planar and bent conditions of AD1 did not exceed 2 W/kg based on the European regulatory requirement. The second design, denoted as Antenna Design 2 (AD2) was designed to improve the drawbacks of AD1, using PDMS as its substrate and Galinstan as the conducting elements of both the AMC and radiator. The main innovation of this work is the integration of an antenna and AMC plane fully made using liquid metal embedded into PDMS to enable a highly flexible and robust antenna, besides potentially adding tunable feature to the structure in the near future. AD2 showed a bandwidth of 80 MHz and 460 MHz in the lower band and upper band, respectively, with gains of between 5.2 and 4.12 dB. In terms of SAR, all planar and bent conditions for AD2 did not result in SAR exceeding 2 W/kg, indicating its safe use as wearable antenna. Finally, experimental validated has indicated that the fluidic antenna is improved in terms of resistance to water compared to textile antennas.

CHAPTER 1 : INTRODUCTION

1.1 Introduction

The Ministry of Health Malaysia (MOH) Strategic Plan 2016 – 2020 reported that the government expenditure for the health sector amounted to about RM7.32 billion in 1997. This amount tripled 16 years later in 2013, amounting to about RM23.25 billion. It is also foreseen that the cost will continue to increase to about RM30 billion in 2020 (Ministry of Health Malaysia, 2016). Besides that, the life expectancy of the country's population in 2014 is 77.2 years for women and 72.5 years for men, indicating a rising number of elderly citizens. Therefore, it is important that a sustainable healthcare system for people across all range of ages is planned to manage the issue of rising costs. One of the potential solutions to this is via the implementation of smart wearable technologies.

It is expected that such sustainable healthcare service will enable more patients with long-term illnesses to be monitored or treated from home. Besides comfort, such mechanism also allows for a more quality emotional engagement with their family and loved one (Tzavaras & Spyropoulos, 2013). In such context, health personnel from the nearest hospital can perform regular monitoring remotely without the need of face-to-face consultations. With such system, the efficiency of the health facilities and personnel can be significantly improved and ultimately optimizing costs.

In recent years, flexible wearable antennas capabilities of simultaneously supporting computing and wireless communication functionalities have garnered a great amount of interest in academia and industry. Such technology facilitates task execution in emergency and rescue services, tracking, military applications and monitoring human physiological parameters (Agneessens, Member, Lemey, Vervust, & Rogier, 2015; Babar et al., 2016; H. Lee, Tak, & Choi, 2017; Peter S. Hall, 2012). To ensure health and safety of human when using wearable antennas, mechanisms to minimize potentially harmful electromagnetic (EM) radiation towards human body in these applications must always be considered during the design process. One method is by implementing metasurface on the reverse side of the antenna to ensure that the EM wave is radiated outwards from the body (Di, Liu, & Tentzeris, 2014; Jiang, Brocker, Sieber, & Werner, 2014) .

Most conventional antennas are fabricated by etching or milling rigid sheets of copper. However, such material choices are unsuitable for wearable antennas as they are easily damaged when bent repeatedly. Besides ensuring user comfort, satisfactory robustness, size compactness and maintenance-free installation are also important considerations in such antennas (Kubo et al., 2010). These reasons have made the choice of antenna topology and flexible materials of paramount importance.

Previously, the research field of wearable antennas has been mostly dominated by the use of textile as the material for wearable antennas (Chen, Kaufmann, Ranasinghe, & Fumeaux, 2016; Rajo-Iglesias, Gallego-Gallego, Inclan-Sanchez, & Quevedo-Teruel, 2014; Yuk, Sun, & Cheung, 2014). Besides textiles, other flexible materials include Polydimethylsiloxane (PDMS) and Eutectic Gallium Indium (EGaIn) liquid metal (Hayes, So, Qusba, Dickey, & Lazzi, 2012). The combination of PDMS and EGaIn results in a flexible and durable wearable antenna. Such combination is able to withstand severe mechanical deformation (bending, stretching, rolling and twisting), and it is capable of returning to its original state upon the removal of the applied stress. (Nawaz, Mao, Stratton, & Huang, 2013).

A flexible and robust antenna implemented using PDMS as its substrate and liquid metals as its conductor was introduced in (Dickey et al., 2008; So et al., 2009). The antenna also features an Artificial Magnetic Conductor (AMC) plane to minimize potential risks to the user. Liquid metals such as EGaIn and Galinstan are injected into fluidic channels embedded in the multi-layered elastomeric substrate. Such structure provides extra robustness against water and dust, besides enabling better flexibility for the antenna due to the low viscosity of the liquid metals (Hayes et al., 2012).

1.2 Problem Statement

Recently, conductive textile has been used as the common material for wearable antennas. However, its main drawback is that it will easily absorb water and thus will easily change the reflection coefficient and bandwidth of the antenna (Osman, Rahim, Samsuri, Elbasheer, & Ali, 2012). In order to overcome this problem, a more suitable material for the antenna should be chosen to improve antenna performance. For this means, new materials to improve the waterproof capability need to be used for wearable antennas. A good example is PDMS, as it features the same flexibility as textiles for such antenna applications.

Meanwhile, design of antennas for wearable applications is challenging due to their operation in the vicinity of human body which causes interference, thus affecting the overall performance (Agarwal, Guo, & Salam, 2016). The main reason is because human body absorbs electromagnetic waves emitted from antennas, which leads to the reduction of antenna efficiency when they are placed near to the body. Besides that, their electromagnetic (EM) radiation are possibly harmful to human health in the long term when exposed excessively (Kwak, Sim, Kwon, & Yoon, 2017). To reduce the impact on the user from the antenna and provide a safe emission level, AMC metasurface is deemed as a suitable solution. They are typically designed to filter and reflect possible EM wave propagating at predefined sets of frequencies towards a certain direction (Di et al., 2014;

Jiang et al., 2014). Furthermore, based on the literature review, none of available research on wearable fluidic antenna studied on the Specific Absorption Rate (SAR) effects for on body operation, which is a critical safety aspect in such antennas for wearable application.

Therefore, liquid metal and the flexible PDMS substrate are used to create a new class of wearable antenna. It features numbers of attractive characteristic with mechanical stability. This opens up vast possibilities for the implementation of more sophisticated and attractive capabilities in wearable antennas.

1.3 Objectives

The main objectives of the study are as follows:

i. To develop a wearable fluidic antenna operating in the Wireless Local Area Network (WLAN) and Industrial, Scientific and Medical (ISM) 2.45 GHz and 5.8 GHz bands using liquid metal and flexible polymer-based substrate for improved water resistance and wetness.

ii. To develop a wearable fluidic antenna with AMC with SAR of less than 2 W/kg, based on European regulatory requirements.

iii. To fabricate and evaluate the wearable fluidic antenna in terms of performance in free space and on body.

1.4 Scope of Work

The scope of this research consists of several phases to achieve the objectives of this project. The phases are divided into three major phases as follows:

Stage 1: Choice of Antenna and AMC Topology

A comprehensive review and analysis of previous researches related to fluidic antenna is first been performed to understand the issues and challenges in its implementation. This is also to generate new ideas on improving the previous works in terms of reflection coefficient and radiation performance. Finally, a set of antenna and AMC topologies will be chosen from the literature upon the understanding of required wearable antennas characteristics.

Stage 2: Design Calculation, Simulation and Optimization

Design calculations for the fluidic antenna and AMC have been performed based on basic microstrip patch and AMC design equations. Next, the parameters of then proposed fluidic antenna topology are inserted into the commercial electromagnetic solver. Once the target resonant and radiation requirements are fulfilled, the proposed antenna will then be simulated using a detailed mesh setting. Parameter sweeps must be performed on the antenna to identify its critical parameters. All simulations have been performed using Computer Simulation Technology (CST) Studio Suite software. Further optimizations of the initially calculated antenna and AMC dimensions also have been performed using the solver.

Stage 3: Fabrication, Performance Assessments and Result Analysis

Upon the complete optimization of the flexible fluidic antennas, they are then prototyped using fluidic metals such as EGaIn and Galinstan as their metallic components and PDMS as their substrates. Then, the simulated antenna models are further assessed via comparison with experimental evaluations. Measurements are performed at the Advanced Communication Engineering (ACE) Centre of Excellence in Universiti Malaysia Perlis (UniMAP). Additional on-body simulations such as bending and SAR are also performed using the same simulator.

1.5 Contribution of the Thesis

i. Wearable fluidic antenna integrated with AMC based using liquid metal and flexible substrates has been developed, it is first effort to integrate wearable antenna and AMC using liquid metal.

ii. The fluidic wearable antenna with AMC has been investigated in both flat and bent conditions and indicated good performance.

iii. SAR reading for the wearable fluidic antenna maintained below values of 2 W/kg when averaged over 10g of tissue, based on the European regulatory requirements.

1.6 Thesis Outline

This thesis is organized into five chapters. Chapter 1 introduces the work presented in this thesis, problem statements, objectives, scope of work, contributions and thesis outline. In Chapter 2, a brief background of wearable antennas is presented in two parts; flexible materials and SAR. Besides that, the design and properties of the liquid metal and AMC are also explained in this chapter. Finally, a summary of past researches on fluidic antennas with different types of liquid metals is presented in this chapter.

Chapter 3 first presents the systematic steps used in the modelling the fluidic antenna with AMC. The methodology and fabrication process are then explained with illustrations. Finally, the design of the two new fluidic antennas integrated with AMC is also presented in Chapter 3.

Chapter 4 presents the simulation and measurement results for both fluidic antennas with AMC. The phase response of the AMC, reflection coefficient of the antenna, bending evaluation and SAR are investigated and analysed in this chapter. Finally, the summary of the investigation and conclusion is explained in Chapter 5, along with several suggestions for future work that can be applied to enhance this project.