MICROSTRIP ARRAY ANTENNAS FOR BANDWIDTH ENHANCEMENT BY USING POLYMERIC MAGNETO DIELECTRIC SUBSTRATES

WAN ASILAH BINTI WAN MUHAMAD

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To

My beloved father, Wan Muhamad

His words of encouragement and inspiration in pursuit of excellence gives me strength throughout my life

To

My lovely mother, Narimah

Her encouragement, support, and constant love have sustained me throughout my life

To

My husband, brothers, sisters, and friends

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ABSTRACT

Microstrip antennas are fabricated using commercially available dielectric substrates such as Rogers, Taconic and FR4. However, microstrip antennas built using these materials have limited bandwidth besides would incur high losses. This thesis presents the development of a class of polymeric magneto used as antenna substrates. These new composite substrates are capable of boosting antenna bandwidth, miniaturizing antenna size and improving gain. In the study, Polydimethylsiloxane-magnetite iron oxide (PDMS-Fe_3O_4) dielectric composite consisting of Fe_3O_4 nanoparticles (sized at 10 nm) and polymeric PDMS was introduced. PDMS-Fe_3O_4 and PDMS exhibit favorable characteristics such as transparency, lightweight, low losses and ease of dielectric permittivity tuning by loading using different material compositions. In this case, Fe_3O_4 nanoparticles are suited for specific microwave/radio frequency applications. Furthermore, the study implemented a bandwidth enhanced microstrip grid and comb array antennas on molded PDMS and PDMS-Fe_3O_4 for high frequency applications as the first of their kind. The grid and comb array antennas were embedded inside the PDMS and PDMS-Fe_3O_4 dielectric substrates, which offer water resistance and improve mechanical robustness for the antenna. Four antennas structures were designed to validate the merit of the PDMS-Fe_3O_4, namely microstrip grid array antenna (MGA), microstrip polymeric grid array antenna (PGA), microstrip polymeric comb array antenna (PCA) and microstrip polymeric magneto comb array antenna (PMCA). Simulation and measurement results indicated increments in relative bandwidths, starting from 1.43% for MGA antenna, followed by PGA antenna with 6.43%, 18.21% for PCA antenna and nearly 56.25% for PMCA antenna. Measurements showed good agreement with simulations in terms of reflection coefficient and radiation patterns. Besides significant bandwidth improvements, the gain for all antennas have also improved, with 12.26 dBi obtained for MGA antenna, 14.79 dBi for PGA antenna, 11.38 dBi for PCA antenna and 11.34 dBi for PMCA antenna. Thus, it can be concluded that the use of PDMS-Fe_3O_4 composites and polymeric dielectric as substrates is suitable for use in high frequency applications to improve bandwidth and antenna compactness.

ABSTRAK

Antena mikrojalur direka menggunakan substrat dielektrik yang boleh didapati secara komersial seperti Rogers, Taconic dan FR4. Walau bagaimanapun, antenna mikrojalur yang dibina menggunakan substrat-substrat ini mempunyai lebar jalur yang terhad selain menyebabkan kehilangan yang tinggi. Tesis ini membentangkan pembangunan kelas baru magneto polimer yang boleh digunakan sebagai substrat antena. Substrat ini merupakan komposit baru yang mampu meningkatkan lebar jalur antena, mengecilkan saiznya dan meningkatkan gandaan. Komposit dielektrik polydimethylsiloxane-oksida besi magnetit (PDMS-Fe_3O_4) yang diperkenalkan ini terdiri daripada nanopartikel Fe_3O_4 (bersaiz 10 nm) dan polimer PDMS. PDMS-Fe_3O_4 dan PDMS mempamerkan ciri-ciri baik seperti kelutsinaran, ringan, kehilangan yang rendah dan kemudahan penalaan ketelusan dielektrik dengan menggunakan komposisi bahan yang berbeza. Di dalam kes ini nanopartikel Fe_3O_4 sesuai digunakan dalam aplikasi gelombang mikro/frekuensi radio. Tesis ini juga mencadangkan peningkatan lebar jalur dengan menggunakan antena mikrojalur tatasusunan grid dan tatasusunan sikat yang direkabentuk pada PDMS dan PDMS-Fe_3O_4 untuk aplikasi frekuensi tinggi, yang pertama seumpamanya diperkenalkan. Antena grid dan antena sikat dibenamkan di dalam substrat dielektrik PDMS dan PDMS-Fe_3O_4, yang kalis air dan keteguhan mekanikal antena yang lebih baik. Empat struktur antena direka untuk mengesahkan sumbangan yang dicadangkan PDMS-Fe_3O_4: antena mikrojalur tatasusunan grid (MGA), antena mikrojalur polimer tatasusunan grid (PGA), antena mikrojalur polimer tatasusunan sikat (PCA) dan antena mikrojalur polimer magneto tatasusunan sikat (PMCA). Keputusan menunjukkan kenaikan di dalam lebar jalur relatif, bermula dari 1.43% bagi antena MGA, diikuti oleh antena PGA dengan 6.43%, 18.21% bagi antena PCA dan sehingga 56.25% bagi antena PMCA. Pengukuran menunjukkan persamaan yang baik dengan simulasi dari segi pekali pantulan dan corak radiasi. Selain daripada peningkatan lebar jalur yang besar, gandaan untuk semua antena yang diperkenalkan juga memberikan bacaan yang baik, dengan 12.26 dBi diperolehi bagi antena MGA, 14.79 dBi untuk antena PGA, 11.38 dBi untuk antena PCA dan 11.34 dBi untuk antena PMCA. Oleh itu, dapat disimpulkan bahawa penggunaan komposit PDMS-Fe_3O_4 dan polimer dielektrik sebagai substrat adalah sesuai untuk digunakan dalam aplikasi frekuensi tinggi dengan lebar jalur yang lebih baik dan antena yang kompak.

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D	-	Electric flux density
E	-	Electric field strength
ε	-	Dielectric permittivity
P_D	-	Dielectric loss
μ_r	-	Permeability of substrate materials
$tan\delta_\varepsilon$	-	Dielectric loss tangent
W	-	Width of the microstrip patch antenna
d	-	Thickness of substrate
B	-	Magnetic flux density
H	-	Magnetic field
μ'	-	Real part permeability
μ''	-	Imaginary part permeability
Z_0	-	Free space impedance
V_m	-	Wave velocity
λ_m	-	Wavelength in material
λ_0	-	Wavelength in free space
a	-	Width of the patch
t	-	Thickness of the substrate
$P_{ACCEPTED}$	-	Accepted power
Q	-	Radiation quality factor
W_t	-	Radiated power
P_{MD}	-	Magneto dielectric losses
Y_{ri}	-	Radiation admittance and transformer
Z_i	-	Properties impedance

L_i	-	Effective length of the stub
Γ	-	Reflection coefficient
t	-	Propagation factor
c	-	Speed of light, $3x10^{11}$ m/s^{-1}
f	-	Operating frequency
ω_x	-	Angluar frequency
Y_0	-	Characteristic admittance

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Wireless communication technologies has become more trendy in last few years due to the revolution and evolution from first generation (1G), second generation (2G), third generation (3G) as example mobile networks (UMTS - Universal Mobile Telecommunication System, cdma2000), fourth generation (4G) for instance Long Term Evolution - Advanced (LTE-A), and latest one is fifth generation (5G). These revolution and evolution is due to the demand on high-speed data rate communication. As one of the critical enablers in this revolution, the antenna acts as a front-end in developing a communication network.

Small cell access, wireless backhaul, and cellular access are the network system components for 5G communications. Small cell access is deployed in the underlying macro cells as WPANs or WLANs as shown in Figure 1.1 and as a solution for capacity improvement in 5G cellular networks. Such small cells have been targeted by 2020 to achieve one thousand fold increase in network capacity besides providing wideband multimedia applications and multi-gigabit rates with huge bandwidth (Baldemair, 2015) (Ghosh, 2014) (Rappaport, 2013). The cellular cell access operates in the millimeter-wave bands of 28, 38, 71-76 and 81-86 GHz for 5G enhanced local area access (Ghosh, 2014).

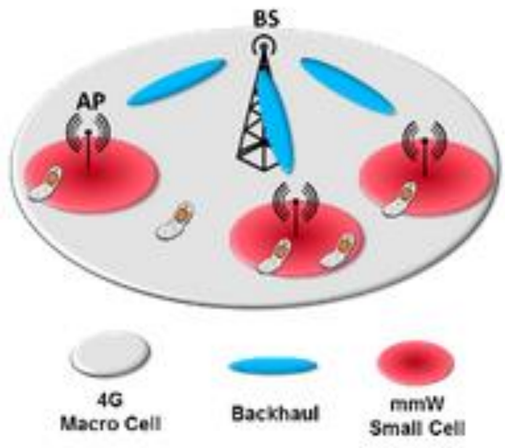

Figure 1.1: Millimeter-wave 5G Small cell access network communication (Niu 2015)

Figure 1.2 shows the wireless backhaul communication networks. This type of network is defined to connect 5G base stations to other 5G base station and to the network by fiber based backhaul with small cells densely deployed in this network (Sridharan, 2015). Furthermore, the E-band backhaul provides high speed transmission between base station and gateway or between small cell base stations. The operating frequency band for the wireless backhaul is in the range of 60 GHz band and E-band (71-76 GHz and 81-86 GHz) which offers several Gbps of data rates and can be a promising backhaul solution for small cells (Niu, 2015)

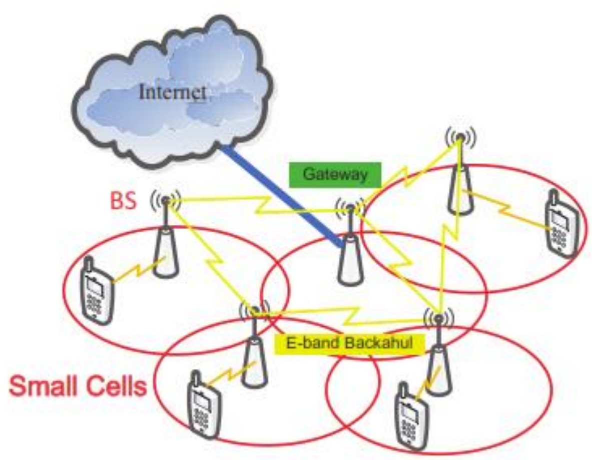

Figure 1.2: Millimeter-wave 5G E-band wireless backhaul access communication network (Niu 2015)

For cellular access, the huge bandwidth capability promotes the usage of millimeter-wave communications in 5G cellular access (Rappaport, 2013) (Rangan, 2014). It also has a potential for high capacity and coverage as long as the infrastructure is densely deployed as reported in (Bai, 2015) (Bai, 2014). The increment of capacity is based on the arbitrary pointing angles of directional antennas, expected to be 20 times greater than the 4G networks, and can be further improved by pointing directional antennas in the strongest transmit and receive directions (Sulyman, 2014). Figure 1.3 is shows the 5G cellular access network communication. The device-to-device (D2D) communication in cellular access network refers to a radio technology that enables devices to communicate directly with each other without routing the data paths through a network infrastructure. Since the D2D communications enhances spectral efficiency and devices are in close proximity to save power, it is capable of supporting context aware applications, which involves communication with and discovery of nearby devices within the cellular access network.

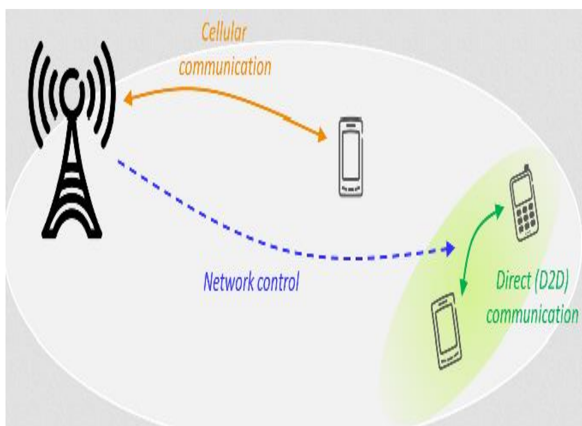

Figure 1.3: Millimeter-wave 5G Cellular cell access network communication (Mumtaz, 2014)

Table 1.1 summarizes previous researches according to scenario, frequency band, and the main applications. Based on (Niu, 2015), many works are concentrated on the indoor WLAN/WPAN applications in 60 GHz band at the moment, while other bands need further investigation. To the best author’s knowledge, this is the first time that antennas operating between 28 and 43 GHz for 5G cellular access network communications using polymeric magneto dielectric and polymeric dielectric has been reported.

Table 1.1: Applications of 5G Communications

Publication	**Frequency band (GHz)**	**Scenario**	**Application**
Niu (2015)	60	Small cells in HetNets	Access, backhaul D2D
Wu (2015)	60, 70	indoor	Multimedia
Sridharan (2015)	28	Outdoor cellular	In-band backhaul
Ghosh (2014)	28, 38, 71-76, 81-86	Urban street	Access and backhaul
Chen (2013)	60	WLAN	Uplink channel access
Son (2012)	60	WPAN	Transmission between devices
Singh (2009)	60	Indoor office	Internet Access

The capability in obtaining a large bandwidth in millimeter-wave for cellular access network communication is contributed by the use of polymeric magneto dielectric substrate (PDMS-Fe_3O_4) and also polymeric dielectric substrate (PDMS) for microstrip antennas (Trajkovikj, 2013) (Balanis, 2005). Besides, microstrip antenna is one of the best options to suit 5G requirements due to its low profile, simple structure and ease of fabrication (Escuderos, 2013) (Niu, 2015). Typically, microstrip antennas have been fabricated using commercially available antenna substrates as known as Taconic, Rogers, PCB and many more (Chin, 2011) (Bunea, 2011) (Carver, 1981). However, the polymeric magneto dielectric composite substrate and polymeric substrate are used in this project.

Polymeric magneto dielectric and polymeric dielectric have been attracting attention of microwave antennas and RF field. Numerous classes of natural materials in the market are iron oxides, garnets, and metals which exhibit magnetic properties. However, most common magnetic materials are ferromagnetic materials such as nickel, cobalt, and transition metals- iron (Hage-Ali, 2009) (Babar, 2012) (George, Raman, Mohanan & Sebastian, 2010). Ferrites is a class of materials which contains of permittivity, permeability and electromagnetic conductivity that are suitable for electromagnetic interference suppression from centimetre to sub-millimeter wavelengths of the electromagnetic spectrum.

The aim this research is to introduce and develop polymeric magneto dielectric composite and polymeric substrates based antennas for high frequency application with bandwidth enhancement. The proposed magneto dielectric composite substrate contains polydimentylsiloxane (PDMS) and (10 nm) nanoparticles of magnetic (Fe_3O_4) iron oxide. Both materials have been composited in difference ratio to form the polymeric magneto dielectric (PDMS- Fe_3O_4) composite substrate. Here, four types of antenna's designed are proposed and tested starting from the microstrip grid array antenna (MGA), microstrip polymeric grid array antenna (PGA), microstrip polymeric comb array antenna (PCA), and microstrip polymeric magneto comb array antenna (PMCA). All proposed antennas are designed using Computer Simulation Technology software (CST) and measured using the Agilent Technologies E8051C ENA Network Analyzer and an anechoic chamber. Simulation and measurement results are analysed and compared to prove the antenna performance improvements of polymeric magneto dielectric composite materials and polymeric material in 5G application.

1.2 Problem statement

Nowadays, modern wireless communication system such as medical diagnosis, 5G technologies and navigation system demand lightweight, robust, conformal, and small antennas. On the other hand, improving their bandwidth potentially improves its data-rate transmission. Many researchers argue that 5G technology should adopt higher-frequency millimeter wave bands where much more bandwidth is available. However, the typically used normal microstrip patch antennas and arrays are narrowband in nature. Besides this, the size of the antenna will be reduced inherently when designed for use in higher frequency due to its shorter wavelengths. For instance, the expected antenna size that operates at millimeter waves e.g. 28 GHz for a single patch is about 2.199 mm x 3.94 mm in length (L) and width (W) respectively. Such small size results in the degradation of the antenna performance, especially in terms of gain.

One of parameters to control the bandwidth of antenna is the material of the substrate. Commonly, planar antennas have been fabricated using commercially available rigid substrate such as Taconic, FR-4 and Rogers. Unfortunately, the main limitations of these materials are narrow bandwidth, rigid, and possible high losses for some of these materials. The implication of narrow bandwidth is difficult for high speed data rate communication meanwhile a higher frequency application requires for a wider bandwidth for a faster communication.

1.3 Objectives

The objectives of this dissertation are as follows:

1. To develop a polymeric dielectric substrate (PDMS) and polymer based on magneto dielectric (PDMS-Fe_3O_4) substrates.
2. To design lightweight PDMS and (PDMS-Fe_3O_4) based antennas for higher frequency.

3. To analyse the effect of polymeric magneto dielectric substrate (PDMS-Fe_3O_4) and polymeric dielectric substrate (PDMS) on microstrip comb array antenna and microstrip grid array antenna in terms of bandwidth enhancement.

1.4 Scope of works

The scope of works is been described in Stage 1 until Stage 5 which consist of literature review, analytical calculation, antenna design, simulation and optimization using software, fabrication prototyping, and finally testing and measurement.

Stage 1: Literature Review

This stage includes the revision and analysis of earlier works related to substrate materials and their effect on antennas characteristics and performance. Two antennas, the microstrip comb array antenna and microstrip grid array antenna are discussed. Moreover, the characteristics of polymeric magneto dielectric substrate are explained as well. The existing polymer based substrates in pure PDMS form and in the PDMS-Fe_3O_4composite form are studied and discussed.

Stage 2: Materials specifications and synthesis

In this section, electrical parameters of the dielectric substrate such as permittivity, permeability, loss tangent of PDMS and PDMS-Fe_3O_4 composite materials have been determined. Agilent 85070E Dielectric Probe Kit and E8051C ENA Network Analyzer were used to measure permittivity; whereas the permeability of magneto dielectric is extracted using the transmission line test fixture, free space measurement and Nicolson Ross Weir methods.

Stage 3: Analytical Calculation

Basic parameters such as frequency, loss tangent, permeability effect and dielectric permittivity of substrates are decided first before proceeding to specific analytical calculations to determine the patch dimension and transmission line. They are calculated using specific equations provided in (Balanis, 2011) (Pirhadi, 2010)

Stage 4: Antenna Design, Simulation and Optimization

The project is initiated by identifying the new material in terms of electrical and mechanical parameters, including permittivity, permeability, loss tangent, thermal conductivity and Young's modulus. Then, simulation has been performed using Computer Simulation Technology (CST) software. Using CST, the proposed antenna with initial dimensions is simulated to determine the best reflection coefficient, gain, bandwidth and radiation pattern.

Stage 5: Prototype Fabrication and Measurement

The proposed antennas are fabricated after simulation process. Four different structures antennas on PDMS and PDMS-Fe_3O_4 are fabricated, starting from synthesizing and composting jelly sylgard 184 silicone elastomer (PDMS) with ferrite iron oxide (Fe_3O_4). The prototype will then be measured in Advanced Communication Engineering Centre (ACE) anechoic chamber, Universiti Malaysia Perlis (UniMAP) and Antenna Research Group (ARG) lab, Faculty of Electrical Engineering (FKE), UiTM Shah Alam. Simulation and measurement data of all prototypes are recorded, compared and analyzed.

1.5 Contributions

The main contribution from this dissertation work is the development and implementation of polymeric magneto dielectric composite (PDMS-Fe_3O_4) substrate for size reduction, conformal, transparent, lightweight, robustness, with a permeability of more than unity and low loss. Bandwidth enhancement of the microstrip antenna is another contribution while maintaining acceptable performance as well as functional radiation characteristics. The deployment of the newly developed polymeric magneto dielectric offered a good alternative for the design of 5G antennas. The design's process includes free space measurement, transmission line theory, Nicolson-Ross-Weir (NRW) concept, microstrip comb and grid array antenna and measurement methods. Multilayered patch antenna designs have been developed to demonstrate the usefulness of magneto dielectric, polymeric dielectric, ease of their processing, and simple in fabrication. The effect of the polymeric magneto dielectric and polymeric dielectric have been systematically studied and successfully identified for bandwidth enhancement and reduced the antenna size.

1.6 Thesis organization

This thesis consists of five chapters. Chapter 1 presents the background of the research, problem statements, and objectives, scope of works, contributions, and thesis organization. Chapter 2 provides an overview of the 5G technology and introduction of the polymeric magneto dielectric substrates, their effects on antenna development and implementation, the existing polymeric magneto dielectric substrates and existing polymer based magneto dielectric antennas. Thereafter, a brief overview of microstrip comb array antennas and microstrip grid array antennas is also presented.

Chapter 3 introduces the methodology and procedures of characterization and composition of the Polydimethylsiloxane (PDMS) and ferrite III oxide (Fe_3O_4) nanoparticles. This includes the methods of extracting and measuring magnetic and dielectric properties of PDMS-Fe_3O_4 and PDMS materials in terms of permeability, permittivity and loss tangent. Experimental results of the material's electrical properties such as permittivity, permeability, dielectric, and magnetic loss tangents are shown to substantially influence the performance of the polymeric magneto dielectric antennas. The designs of four antennas structure and fabrication process are then presented. Chapter 4 presents the simulations and measurements results of proposed antennas. A detailed analysis and discussion on the obtained results is also provided. Chapter 5 concludes the overall finding of this research and future work for further investigation are proposed.

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