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Design and analysis of flexible bow-tie antenna for medical application

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Abstract: This research presents an extensive investigation and analysis of bow-tie antenna performance made of three different flexible materials as the substrates. The antenna performance is address in terms of S_{11} and radiation pattern. The flexible antenna performance is simulated in free space condition and compared to the antenna performance in on-body environment. The aim of this research is to choose suitable flexible dielectric substrate which sustains its performance under on-body environment. The results of this research could provide guidance and has significant implication for future development of wearable electronics especially in medical monitoring application.

Keywords: bow-tie antenna, flexible antenna, radiation pattern, S_{11}, medical application.

1. INTRODUCTION

Wearable electronics are getting more attention due to the wide range of healthcare, sports, security, and also military applications. This wearable electronics are leading to the creation of wireless devices that is more easily to be carried out by the user. The wearable wireless device is usually being attached to the user body or being carried out in the pocket thus improves the user convenience. This phenomenon indicates a strong potential for wired-communication network to be replaced with wireless communication. Along with this trend, body centric wireless communication which refers as human-self and human-human networking has received more exposure especially for continuous monitoring application in medical sector. However, developing a fully flexible and wearable wireless electronics is extremely challenging due to the degradation of antenna performance when operating in close proximity to human body [1]–[11]. This issue is crucial since the antenna performance is subjected to the changes of human body posture and also body movement.

A conventional medical device for health monitoring, electrocardiogram (ECG) and electroencephalogram (EEG) for examples, use rigid electrodes coupled to the skin via electrolyte gels and affixed with adhesive tapes. Thus, to measure the bio-signal for everyday life may be tricky due to inconveniences that caused by bulk wire connection of the electrodes and the reliability of the measurement caused by gel drying. Besides, by using the rigid electrodes, the measurement procedure will be limited only to locate the sensor to the flat region of the body such as the forehead or chest. Therefore, recent researches have considered various types of material to be used as bendable substrate of the antenna such as different types of textile fabric [2], [4], [6], organic paper [14] , Kapton polyimide [15], [16], Polydimethylsiloxane (PDMS) [17]–[20] and also polyethylene terephtalate (PET) [21]. These materials however suffer from serious drawbacks such as prone to fluid, and also pattern distortion due to wrinkle and crumpling [15], [22]. However, to design a fully flexible antenna will expose to a variety of factors which degrades the antenna performance. In [15], [16], a flexible inkjet-printed ultra wideband antenna is proposed and fabricated on Kapton polyimide substrate. Although it is flexible and light weight, the results presented in this research show that the antenna resonant frequency and return loss tends to degrade when the antenna is measured in bent condition.

Hence, this research focuses on investigating and characterizing several types of flexible dielectric material as the antenna substrate that is suitable for wireless health monitoring purposes. A suitable material for substrate is crucial in order to develop the flexible antenna and choosing a suitable conducting material is also important to prevent even a minor crack on the radiating element which may result in performance degradation. The proposed substrate material will be easy to attach to the human skin and does not limit the possible antenna placements and body movement.

2. ANTENNA DESIGN AND FABRICATION

To start with, bow-tie antenna is designed and simulated using CST Microwave Studio. Bow-tie antenna is chosen due to its simplicity and offer wider bandwidth compared to conventional dipole antenna. There are three proposed dielectric materials used as the antenna’s substrate; self-adhesive cotton-crepe, semi-transparent film and skin-friendly patch. Besides that, a shieldit fabric (conductivity

= 100 S/m, surface resistivity = 0.01 Ω/m) is used as the radiating element.

2.1 Characterization of Substrate and Conducting Materials

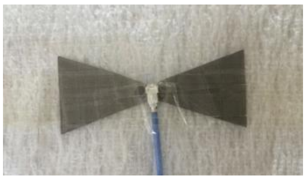
In this study, the dielectric properties of the proposed substrate materials are firstly characterized. The main dielectric properties that have been evaluated are permittivity and loss tangent. An open-ended coaxial probe method is used to measure the dielectric properties of each proposed materials. Table 1 tabulates the dielectric properties of the substrate materials used in this study.

Table 1. Measured permittivity and loss tangent of related substrate materials

Material	Permittivity	Loss Tangent
Cotton crepe bandage	1.2216	0.0214
Semi-transparent film	2.1373	0.0024
Skin-friendly patch	1.4597	0.0036

2.2 Bow-tie Antenna Design and Fabrication

Initially, the design parameters are calculated based on theoretical formulae [23]. The bow-tie antenna is designed and fabricated on the proposed substrate materials. Figure 1 illustrates three different types of substrate materials used in this study. The fabric is manually cut using a special electronic cutter machine. A part from that, a pigtail SMA connector is used as the cable connector as it is more suitable for wearable application if compared to the bottom fed SMA connector.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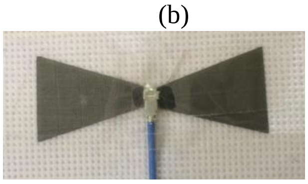
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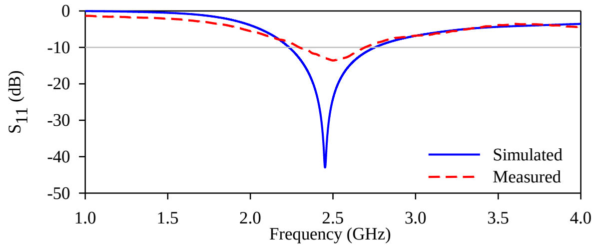
Figure 1. Bow-tie antenna fabricated on three different substrate materials (a) cotton- crepe bandage, (b) semi-transparent film and (c) skin-friendly patch

3. RESULTS AND DISCUSSIONS

The antenna performance in term of S-parameters and radiation pattern is presented in this paper. All measurement is done in free space condition and also on-body environment. The effect of different flexible substrate materials with different thickness will be carefully analyzed. In addition to that, the wearable antenna with flexible substrate is also being attached onto real human body to ensure its suitability to be used for continuous health monitoring. The effect of bending on curved body part is carefully studied.

3.1 Characterization of Substrate and Conducting Materials

Figure 2 compares the simulated and measured S_{11} for bow-tie antenna on the proposed substrates materials. From Figure 2, good agreement on resonant frequency is observed between simulated and measured results for all types of substrate materials. The measured reflection coefficient showed that antenna fabricated on cotton crepe bandage and semi transparent film could sustain a good impedance matching with return loss below the level of -10dB. The return loss is almost 15dB for cotton crepe bandage substrate and 20dB for semi transparent film. Therefore, only these two dielectric materials will be used in the next study (flexibility and repeatability test). From the results in Figure 2, it can be observed that there are discrepancies between simulated and measured S_{11} which is have been expected due to the dissimilarity between simulated structure and the prototype.



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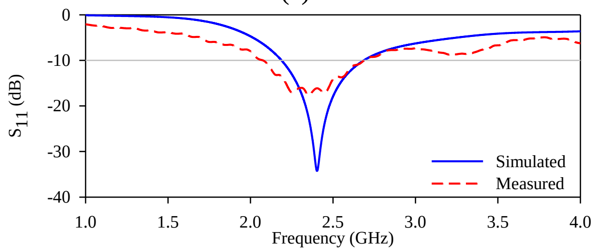

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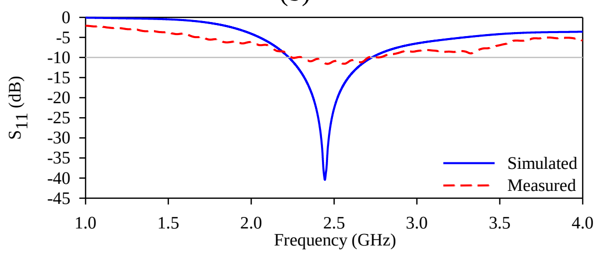

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Figure 2. Simulated and measured results of S_{11} of bow-tie antenna using (a) cotton crepe bandage, (b) semi transparent film and (c) skin friendly patch as the dielectric substrate

3.2 Simulated and Measured Radiation Pattern in Free Space Condition

The radiation patterns for the proposed antennas have been measured in an anechoic chamber. The measured and simulated radiation pattern are plotted and compared in Figure 3. Figure 3 represents the radiation patterns in E-plane and H-plane of bow-tie antenna on three different substrate materials at 2.45 GHz. Good agreement between simulated and measured radiation patterns has been obtained for all proposed antennas'. Figure 3 indicated that the bow-tie antennas fabricated on the proposed substrate has an omni-directional radiation pattern. The variation between simulated and measured results may occur due to the lack of fabrication technique and also misalignment during the measurement setup.

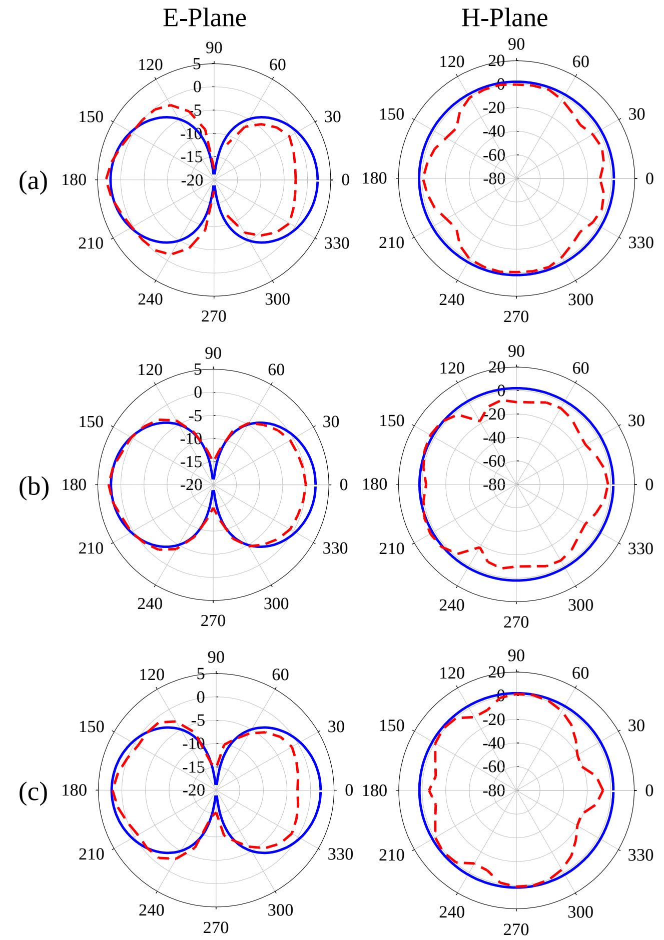


Figure 3. Measured and simulated radiation patterns of 2.45 GHz bow-tie antenna in E-plane and H-plane for antenna fabricated on (a) cotton-crepe bandage, (b) semi-transparent film and (c) skin friendly patch substrate

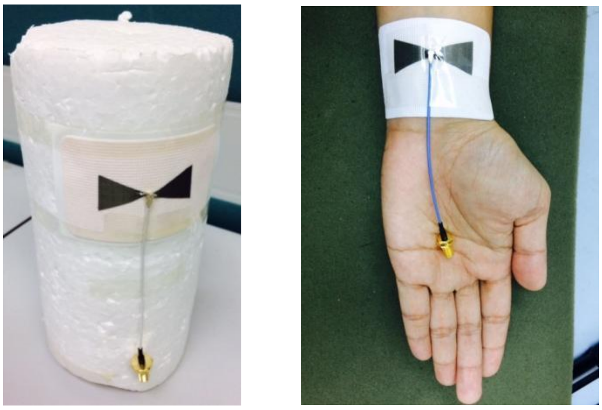
3.3 Flexibility Test

In body centric wireless system, the flexible antenna will be operated in close proximity to human body. Thus, the antenna performance will be affected due to the change of human body posture and movement. In this study, bending measurement is performed using polystyrene cylinder and the antenna is also bent on human hand. The polystyrene cylinder used to bend the antenna has a diameter of 60 mm which is approximately the size of the human hand that used in the measurement in this study.

Figure 4(a) shows the antenna bent along the curvature of polystyrene to represent the bending condition on human hand while Figure 4(b) depicts the antenna when positioned on the human hand at almost the same diameter of the polystyrene cylinder.

Figure 5 shows the effect of bending condition on the S_{11}. The solid black line illustrates the antenna resonant frequency in free space for flat condition while the red short-dashed line represent the measured S_{11} when the antenna is bent on polystyrene cylinder. The blue short-dashed line with x symbol shows the effect on S_{11} when the antenna is bent on human hand. Based on results presented in Figure 5, only a small variation can be noticed between the antenna in flat and bent condition. Slight increment is observed in the return loss. These results confirm that when the antenna is bent, the length of the radiating patch remain the same thus do not change the resonant frequency. In addition, the dielectric property of the polystyrene cylinder is almost 1.07 as similar as the dielectric constant of air and hence unlikely to have significant effect on antennas performances.

In the meanwhile, the measured S_{11} suffers a very significant shifting in resonant frequency when the antenna is placed on the human hand. The resonant frequency shifted to the lower frequency for all cases using three different substrate materials.



(a) (b)

Figure 4. The antenna is (a) bent on polystyrene cylinder and (b) attached and bent on human hand at d≈60 mm for bending measurement

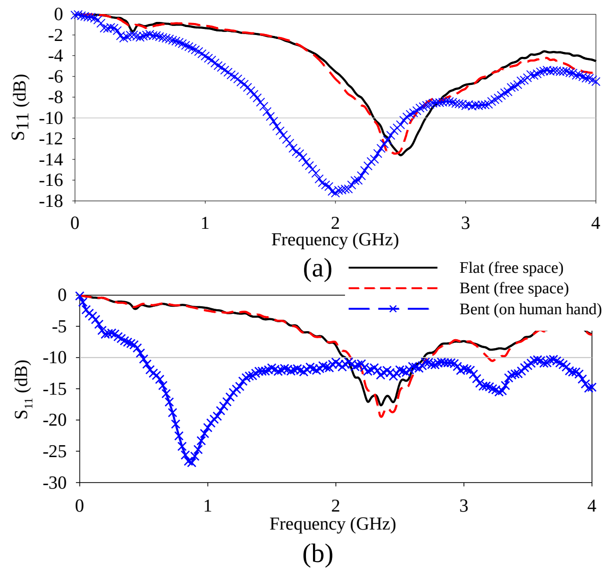


Figure 5. Bending and human body effects on measured S_{11} of the bow-tie antenna using (a) cotton-crepe bandage and (b) semi-transparent film as the antenna's substrate

3.4 Repeatability Test

For wearable antenna, the performance of the antenna after using it for several times is a crucial factor to be considered. In order to investigate the antenna performance while attached and after detached from the human hand, repeatability test have been conducted for the proposed substrates. In this study, the antenna performance of bow-tie antenna fabricated on cotton-crepe material is measured on a few layer of self adhesive cotton-crepe rolled on the human hand. Besides that, the antenna performance after five times attached and detached on human hand are measured for semi-transparent film material. The measurement results are discussed in term of S_{11}.

3.4.1 Cotton-crepe bandage

The effect of substrate's thickness on measured S_{11} is illustrated in Figure 6. In this study, the cotton-crepe substrate is rolled up to several layers on human hand and the bow-tie antenna is placed on top of the outer layer. The measured S_{11} presented in Figure 6 clearly shows that the antenna resonant frequency is significantly shifted when the antenna is placed on one layer of cotton-crepe substrate which is much closer to the human hand. The resonant frequency is shifted back to the original frequency (in free space) when the antenna is placed at least on the 5th layer of cotton-crepe substrate.

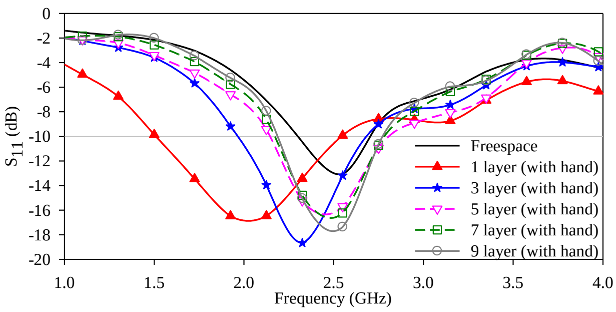
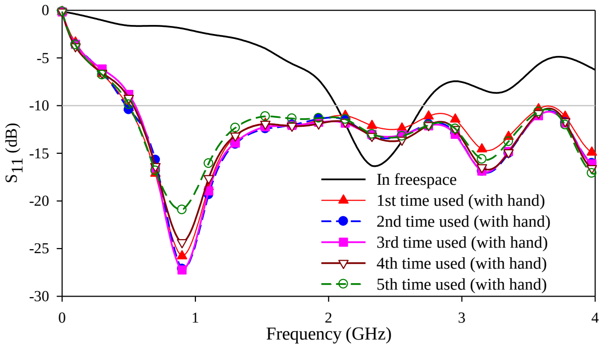


Figure 6. The effect of substrate's thickness on measured S_{11} in the presence of human hand

3.4.2 Semi- transparent film

Figure 7 shows the measured S_{11} of bow-tie antenna fabricated on semi transparent film material while using the antenna from the 1st application up to 5th application and also after detached it from the human hand. Figure 7(a) shows that the antenna on semi transparent film substrate could resonate at the same frequency even though after using it up to 5th times. Only a minor variation on impedance matching is observed which may due to the connection between the radiating patch and flexible port. Besides that, the S_{11} of the antenna is also measured after the antenna is detached from the human hand. The measured result is illustrated in Figure 7(b). The graph depicts that the antenna performance remain the same after using it up to 5th times. These results show that the brown film substrate is reliable to be chosen and use for wearable antenna.



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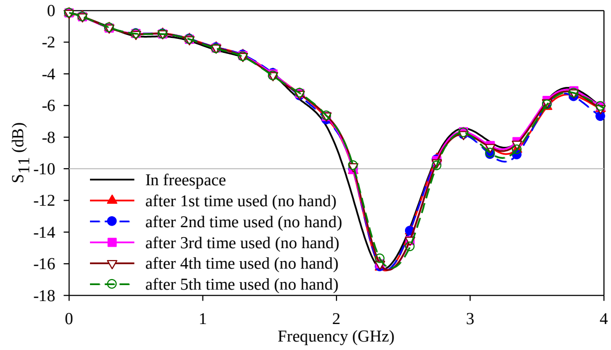

(b)

Figure 7. Measured S_{11} of bow-tie antenna on semi-transparent film substrate for on-body measurement

4. CONCLUSION

In this research, three types of flexible dielectric materials are proposed as the antenna's substrate. 2.45 GHz bow-tie antenna has been designed and fabricated on the proposed dielectric materials. The antenna performances in free space, bent and on-body condition have been evaluated in order to confirm the feasibility of the proposed dielectric materials to be used as the antenna's substrate for medical monitoring. Based on the results presented in this research, cotton-crepe bandage and semi-transparent film are the most suitable materials to be considered as the substrate for future development of flexible antenna in order to improve user convenience. For future works, the antenna performance fabricated on the proposed dielectric materials should be further investigate under certain extreme condition such as when the body is moving, the material is crumpled and under wetness condition.

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