The Design and SAR Analysis of Wearable UWB Antenna for Radiative Near-Field Wireless Power Transfer

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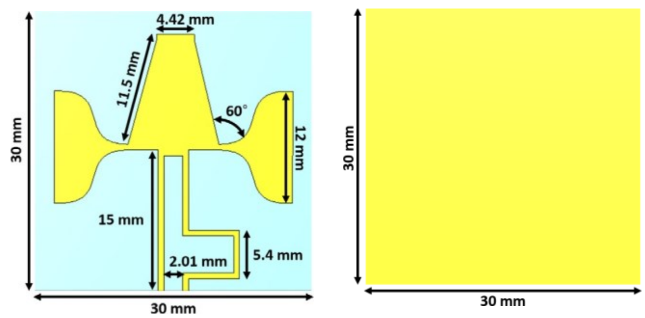
***Abstract*—This paper presents design of a wearable UWB (ultra-wide band) antenna and its corresponding SAR (specific absorption rate) analysis and power transfer capability estimation when it is placed on a human body. In this work, Polyimide with a thickness of 0.1 mm is used as the substrate material, and gold with a thickness of 200 nm is used for the patch and ground material. The dielectric constant and tangent loss of the polyimide substrate are 3.5 and 0.0002, respectively. The dimensions of the proposed antenna are 30×30×0.1004 mm^3. The designed antenna has the resonating frequency at 3.11 GHz and a bandwidth of 3.06GHz. The near-field gain of the designed antenna is 6.43 dBi. TheSAR analysis generated SAR values of 0.138 W/kg and 0.147 W/kgfor antenna placed on flat body model and curved body model, respectively, which are within the safe limit of 2 W/kg averaged over 10g of tissue as specified by the ICNIRP (International Commission of Non-Ionization Radiation Protection). This indicates that the antenna is safe and suitable for use in wireless wearable sensors.**

Keywords—wearable antenna, ultra-wide band antenna, Flexible antenna, SAR analysis, wireless power transfer.

I. INTRODUCTION

Since Nikola Tesla discovered wireless energy transmission it became an increasingly interesting subject of research at the end of the 19th century. In recent literature concerning wireless power transfer (WPT), the radiative near-field region has become a popular research area as it has a better transmission range than the reactive near-field WPT and is more efficient than far-field WPT [2,3]. Antenna is the most important component when building wireless communication or wireless power transfer systems. The rapid development of wireless technologies requires the design of effective ultra-wideband antennas. Today, there are many sensors that are directly attached to or embedded on the human body [5,6]. Wearable technology enables remote patient monitoring, enabling clinicians to diagnose and manage illness while working at home or in the clinic [7]. The antenna needs to be designed in such a waythat it should be compact, flexible and should be safe to the human body while simultaneously maintaining high gain and ultra-wide bandwidth The majority of literature researchers suggest that microstrip patch antennas are the best candidates for these wireless data and power transfer applications because of their low profile, conformal, and cheap cost properties. Material selection aside, designing a portable antenna is a difficult task



(a) (b)

Fig 1. Design of the antenna (a) Front view (b) Back view.

due to the effects of bending, crumpling, stretching and folding caused by the presence of the human body. SAR (specific absorption rate) is a measure of the amount of energy absorbed per unit mass of the human body. The maximum amount of SAR in a 10 g of tissue is set at 2 W/kg by the ICNIRP (International Commission of Non-Ionization Radiation Protection). Even though there are few prior works that contributed antenna designs for wearable applications [1,4], there are very few which actually worked on ultra-wideband operability of the antenna in the safe limit as suggested by the ICNIRP. The UWB (Ultra-wide band) is essential for low-power wearable sensors, UWB is very efficient in terms of power consumption and uses wide frequency range (3.1 GHz to 10.6 GHz) which allows it to send data at very high data-rate without increasing the power consumption significantly. This work targets to achieve the wide-band operability along with maintaining the SAR value within the safe limit. In addition, the wireless power transfer capability of the designed UWB antenna is estimated. The novelty of our work is that the conventional shape of bow-tie antenna is modified to make it ultra-wide band operable, and an isosceles trapezoidal shape is integrated in the design to enhance gain and return loss parameters of the antenna. In addition, suitable materials are chosen to achieve the low SAR value making it safe and suitable for the wearable electronics.

II. ANTENNA DESIGN AND SIMULATION

The proposed antenna's substrate material is chosen as polyimide as it is bio-compatible and possess flexible nature. The gold is used as the patch and ground material due to its high conductivity and good performance in terms of gain of antenna.

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The dimension of the designed ultra-wide band antenna is 30×30×0.1004 mm^3. The proposed antenna design is shown in the Fig. 1, where 1(a) shows the front view and 1(b) shows the back view with full ground plane. The full ground plane is used in order to ensure the unidirectional propagation of radiation pattern, CPW is used as it reduces the spurious radiation. The trapezoidal shape enhanced the operating bandwidth of the designed antenna.

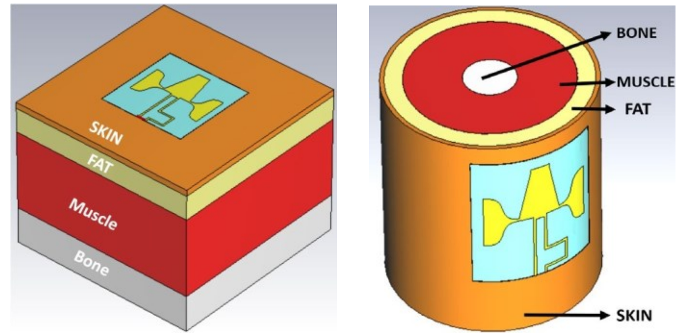
The thickness of the polyimide substrate used is 0.1mm and the thickness for both the patch and the ground materialis 200 nm. The design and simulation of the antenna are performed using the CST (computer simulated technology) studio suite. The shape of the conventional bowtie antenna is modified by introducing a loop strip with 5.4 mm gap to boostthe gain in the low frequency region. In addition, an isosceles trapezoidal shape has been integrated at top middle portion of the design. Both of the ends (left and right regions) of conventional bowtie are modified by introducing a smooth curve making 60° angular distance with trapezoidal strip to enhance the bandwidth and return loss parameters. The designed antenna is edge-fed using CPW (Coplanar Waveguide) port.

III. SAR ANALYSIS AND SIMULATION RESULTS

The SAR analysis has been performed by placing the designed antenna on to two types of human body models, i.e., on the flat model and cylindrical model resembling curved human body. The designed human body model consists of different types of layers such as Skin (2 mm), Fat (8 mm), Muscle (26 mm), and bone (12 mm). The material properties for each of these body layers are designated as mentioned in the Table 1 []. The designed models for SAR analysis are as shown in the Fig 2. In order to evaluate the performance of the WPT system, S-parameter is an important indicator, the value of which is expected to be below -10 dB at the desired frequency. The S_{11} simulation result shown in the Fig. 3 portrays the wide operational bandwidth value of 3.06 GHz and the center frequency of the antenna at 3.1 GHz. The far-field radiation simulation has been performed to assess the gain of the antenna as shown in the Fig. 4. The far-field results showed that the antenna has high gain of 6.43 dBi and has wide beamwidth of 97.8°. The SAR analysis generated the values of 0.138 W/kg and 0.147 W/kg for antenna placed on flat body model and curved body model respectively as shown in Fig 5 and Fig 6, both of the values are within the safe limit of 2W/kg averaged over 10g of tissue as specified by the ICNIRP. As frequency increases the radiation (SAR value) increases as a result it will have a drastic effect on the human body. It is always better to restrict the operating frequency within 6GHz to avoid the ill effects of radiation on the human body. In this work, the human body is not affected much with the radiation because the thickness used for patch and ground materials is in few nanometers.

Table 1. Properties of the human body tissues.

Tissue	Permittivity (ε_r)	Conductivity (S/m)	Loss Tangent	Density (Kg/m^3)
Skin	31.29	5.013	0.283	1100
Fat	5.27	0.12	0.192	1100
Muscle	52.79	1.8	0.242	1060
Bone	12.62	3.85	0.252	1850



(a) (b)

Fig 2. The antenna patch placed on two types of human body models (a) on flat model (b) on curved model.

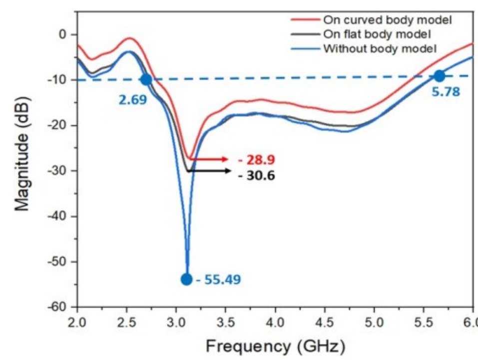


Fig 3. Simulated S_{11} parameter results.

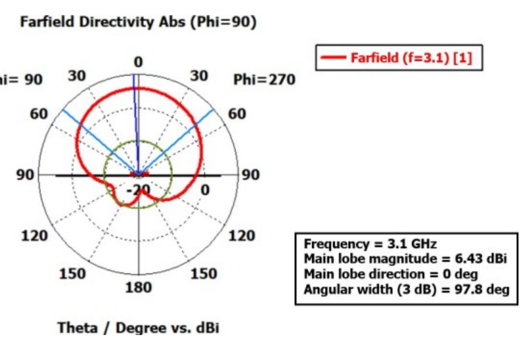


Fig 4. Far field directivity of the designed antenna.

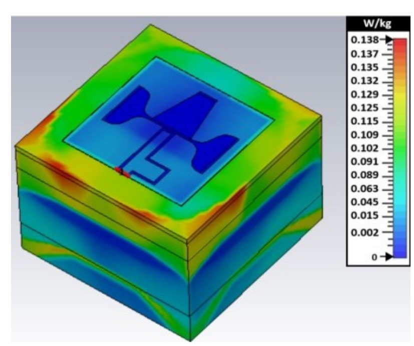


Fig 5. SAR simulation result when placed on flatbody model.

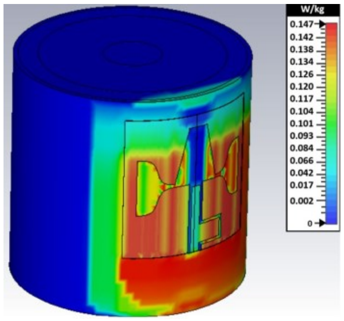


Fig 6. SAR Simulation result when placed on curvedbody model.

Table 2. Comparison among prior works.

Parameters	[2]	[3]	[4]	This work
Dimensions L×W (mm^2)	30×30	40×40	21×12	30×30
Bandwidth (GHz)	0.5	0.9	3	3.06
Resonating frequency (GHz)	0.905	0.920	3.2	3.11
SAR value	0.15	1.35	0.19	0.138
Minimum value of S_{21} (dB)	-11	-30	-40	-10.5

IV. ESTIMATION OF POWER TRANSFER CAPABILITY

The power transfer capability is estimated for three different case scenarios. The first two scenarios are when antenna is placed on flat and curved body models, and the third scenario iswithout the body model. The transmitter antenna is a replication of the receiver antenna where both are placed in the radiative near-field region to one another. In most antenna applications, far-field antennas are commonly used as the propagation is uniform and predictable in the far-field. However, for WPT (wireless power transfer), the radiation near-field area is more effective and safer. The radiative near-field region is defined asshown in the equation 1. Where D is the sphere that can enclosethe entire antenna and λ is the wavelength of the designed antenna. The antenna length is 30 mm, and the center frequency is 3.11 GHz, by using the formula $\lambda = c/f$, where c is the speed of light (3×10^8 m/sec), the corresponding λ value is 96 mm and the radiating near field estimation can be obtained as 18.612 mm by using (1).

$$\sqrt{\frac{2D^3}{\lambda}} \leq Radiating\ Near\ field\ region \leq \frac{2D^2}{\lambda} \quad (1)$$

The simulated S_{21} parameters for all considered three cases are presented in Fig. 7. It is observed that for the cases where transmitting antenna is placed on flat and curved human body models, the S_{21} values were around -15.09 dB and -16.25 dB with corresponding power transfer efficiency values of 84.1 % and 83.8 % respectively. For the case where the body model is not considered, the S_{21} value is around -10.5 dB with power transfer efficiency 89.5%. Which implies that when there is 1 Watt (or 0 dB) is delivered through transmitting antenna to the receiver antenna placed at near field radiating distance, there will be approximately -10 dB (0.1 Watt) of power loss for the scenarios where the body models are considered, For every 1 Watt of power transfer, there will be 0.159 Watt and 0.162 Watt of power loss for flat body and curved body scenarios respectively, which indicates that the power transmission efficiency is 84.1 % and 83.8 % for flat body and curved body scenarios respectively. The cases for which the body models are considered, there is a bit more power loss when compared to thecase where there is no body model. This is because the effectivedielectric constant of the substrate changes when in contact of the body. Power transfer efficiency is calculated using the following equations:

$$S21 = 20 * log\ \left(\frac{Output\ power}{Input\ Power}\right) \quad (2)$$

$$\text{PTE} = \frac{\text{Output power}}{\text{Input power}} * 100\ \% \quad (3)$$

V. CONCLUSION

The simulation results portray the suitability of the designed antenna as a wearable antenna for WPT application. The low SAR values of 0.138 W/kg and 0.147 W/kg for antenna placed on flat body model and curved body model respectively, indicates that it is safe to wear on human body. When compared to similar prior works the proposed antenna is relatively better and has its advantages when factors such as low SAR value, high gain, wider bandwidth and power transfer capability are taken into consideration. As a future work, we plan to fabricate the proposed antenna to conduct a thorough analysis by comparing the simulated and practical measured values.

ACKNOWLEGMENT

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