The Design of an Inset Fed Wide Band Antenna Operating from 23 to 30 GHz for Wearable Smart Watch Applications

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Abstract: ***This paper presents a novel broad band antenna structure, that measure 7 x 8 x 1.6mm^3 on Roger5880 substrate for installations in smart watches of the wearable device sector. Gain, reflection loss and radiation patterns, are investigated intensively. Good performance is shown with an excellent bandwidth of 23 to 30GHz, suitable for wearable devices. As the smart watch is worn on the wrist and may be brought near the mouth for speaking through the smart watch, the SAR is also examined using multilayer human hand wrist and near CST Voxel model Gustav's mouth. A highest SAR of 1.0654W/kg on a CST human mouth model Gustav was recorded when the antenna was installed at 3mm distance with an input power of 125mW at 28GHz which is within the permissible limit of 2W/Kg for 10grams of tissue. According to the findings, the suggested antenna is ideally suited for smart watch and WBAN applications since its SAR value is mostly in compliance with Federal Communications Commission (FCC) regulations.***

Keywords: 5G, Smart watch, Wideband, WBAN

1. Introduction

Smart watches, similar to smart phones, are gaining popularity and are drawing interest from many businesses and consumer sectors. Due to their diminutive size, majority of smart watches include compact antennae, but the current technology supports only the ISM Band for Bluetooth and Wi-Fi applications [1-3].

With an exponential rise in the use of wearable devices for healthcare and other applications, the need for novel designs with emphasis on high performance, improved connectivity and reliability, increased flexibility, and application-specific features is at its peak currently. In the future, the Internet of Things (IoT) will rely significantly on 5G technology in order to provide stable and constant worldwide connection for all the connected “things” to communicate with each other [4-5], typically in the microwave and millimeter wave frequencies [6,7]. The advancements in microelectronics, sensor technology, and telecommunication technologies have made the Wireless Body Area Network (WBAN) to be a member of this network ecosystem. Sporting activities, defense, and universal healthcare are just a few of the areas where WBANs have attracted attention [8-9]. Wearables may use sensors with integrated antennas to transmit measured physiological and biochemical variables and patient’s locationto remote places continuously [10].

Antennas having a maximum gain of 9.6dBi and a radiation angle of about 75° were developed by H. Qiu et al [11]. At 35GHz, a two-element array of millimeter wave antenna on a flexible liquid crystal polymer substrate with a maximum gain of 11.35dBi was suggested by in other works [12]. For on-body communications, the authors of [13] proposed a 3d - printed finger nail shaped Microstrip patch antenna on detachable Acrylonitrile Butadiene Styrene substrate fabricated through aerosol-jet. They tested two antennas at 15 GHz and at 28 GHz, produced using nanoparticles conductive silver ink. The millimeter wave antenna has another copper covering via electroplating, and the On and off the finger designs were modelled. The research [14] designed a compact (10 mm x 27.7 mm) circularly polarized antenna for wearable electronics at 28GHz with bandwidth of 27 to 30 GHz and a gain of 11.65dBi.[15] presented a flexible broad antenna array used at 28 GHz. The wideband frequency response is efficiently preserved despite structural deformation and human body integration, the results show. Their proposed antenna had a compact dimension, sized 80x22x0.25 mm^3, and a gain of 14.02dBi at 28GHz and 15.2dBi at 31.4GHz.

A number of novel microstrip antennas at the operating frequency range of 28 GHz in 5G systems have been reported in the literature [16-33]. These structures are characterized by their compactness, small geometric dimensions, and antenna bandwidths of roughly 2 GHz. Antennas reported have rectangular radiators, powered by a microstrip line. With the potential high data rate capacity combined with low latency across all communication channels, the 5G technology has attracted several researchers. Since the presently available sub-6GHz spectrum is already congested with a heavy weight of applications, it is necessary to build physical communication for mm wave with unlicensed and unconstrained capacity. Unresolved technical issues in the undiscovered spectrum of the 26GHz and 28GHz bands, with frequencies ranging from 24.25-27.5 and 26.5-29.5 GHz, still stand in the way of commercial implementation of mm Wave technology. In this context, the design of a 23to 30GHz antenna and studies on its performance in the vicinity of human body is deemed very essential.

In this paper, the study of an inset fed wide band antenna operating between 23 to 30 GHz is performed for wearable smart watch applications. CST microwave studio is used for simulation.

2. Substrate material selection

The resonant frequencies determine the size of the antenna, and the permittivity of the dielectric substrate serves as the basis for the formulation of the antenna's construction. With a 28.00 GHz centre frequency and frequencies ranging from 23 GHz to 30 GHz, the antenna is intended to function in a 5G system. Microstrip antenna efficiency and bandwidth are proportional directly and indirectly to its height (h) making it a critical design factor [34]. The theoretical upper limit of h, is often determined by the following equation (1)[35].

$$h \leq \frac{0.3\,c}{2\pi f \sqrt{2.2}} \leq 3.45mm \qquad \text{Eqn (1)}$$

where c = velocity of light and f is operating frequency (28GHz). In accordance with the above findings, the height h of the substrate is chosen as 1.6mm and Roger's RT Duroid 5880 is a material that performs better in high-frequency applications, high-speed performance in both wired and wireless communication circuits. The frequency range of operation is 8MHz to 40GHz, having a dielectric constant of 2.2 and a tan δ of 0.0009 [36].

3. Antenna design specification and fabrication

The front and rear perspectives of the inset feed antenna are shown in Figure 1. The antenna dimensions are determined based on the governing equations reported elsewhere [37]. The optimum dimensions of the antennas are shown in Table I.

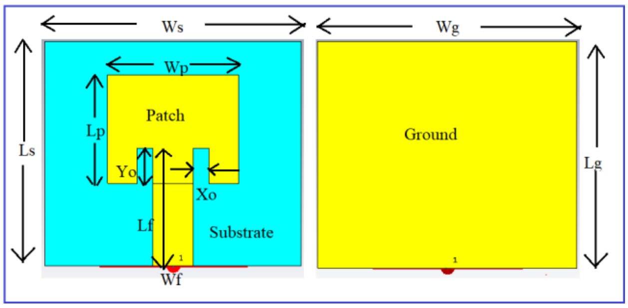

Figure 1: Front and rear view of the Inset fed antenna

Table 1: Designed dimensions of the Antenna

Antenna dimensions in mm	Ws=8	Wp=4.1	X0=0.5	Wf=1.26	Wf=8
	Ls=7	Lp=3.4	Y0=1.1	Lf=2.66	Lg=7

The proposed antenna shape is imported from CST to MITS Design Pro software in gerber / dxf format. The antenna is then milled by removing copper on a two-sided (Copper) Roger 5880 using MITS electronics' Eleven Lab antenna printing machine at the in-house facilities established in the department of ECE, BNMIT with support from AICTE-MODROBS. Once the patch antenna is produced, a SMA connection is made to the feed. The S_{11} measurement is carried out with the aid of an Anritsu portable VNA.

4. Results and Discussions

In the following subsections, the results obtained in free space and in the vicinity of the human are discussed in detail.

4.1Return loss, gain and efficiency in free space

The benchmark return loss is presumed to be -10dB which is suitable for wireless communication devices. The developed antenna, as shown in Figure 2, has a broad bandwidth of 6.43GHz, ranging from 23.01GHz to 29.44GHz.

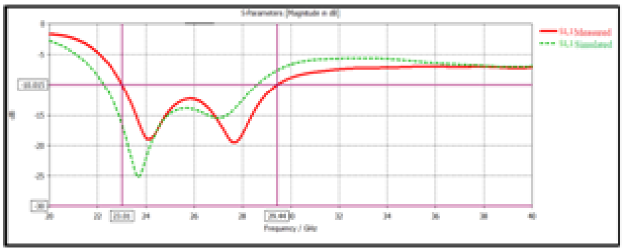

Figure 2: Simulated and Measured S_{11}

The planned antenna recorded a return loss of -18.68dB at 24GHz, -12.38dB at 26GHz, and-18.04dB at 28GHz. At the same frequencies, it recorded gains of 6.710, 6.541 & 6.011dBi with 97.67, 94.20 and 97.02 percent total efficiency. The proposed antenna has a broad bandwidth and a multi-band response, as well as a VSWR of 2 and a return loss of less than -10dB of S_{11}, making it ideal for UWB and WBAN applications.

4.2 Radiation pattern

Figure 3 shows the gain pattern of the antenna in free space at 28GHz. The findings show that the antenna is essentially directional and has peak gain and efficiency of 6.011dBi and 97.02% respectively at 28GHz

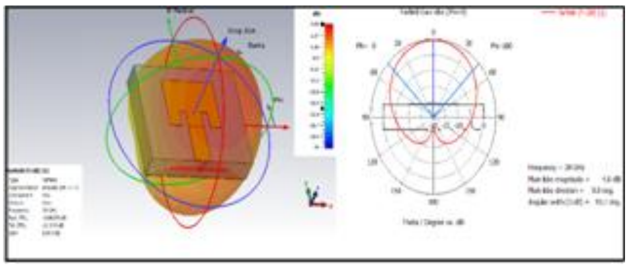

Figure 3: Gain Pattern of Polyimide Substrate antenna

4.3Return loss, gain and efficiency on human tissue model

Three scenarios are studied in this section: three-layer homogenous flat tissue layers, a CST voxel model and the author's hand.

Case (1): 3 Layer tissue model.
Body tissue model consisting of flat muscle, fat, and skin is put 1mm away from the antenna. For the three layers of skin, fat and muscle with respective thicknesses of 2, 4, and 10 millimeters, the area is kept common at 50 x 50 mm^2. Table II, lists the dielectric characteristics and sizes of

various tissue layers. The antenna recorded a gain of 4.899dBi with an efficiency of 67.34 percent at 28GHz when put on the 3-layer tissue model at a distance of 1mm above the skin with S_{11} of -14.28dB as shown in Figure 4.

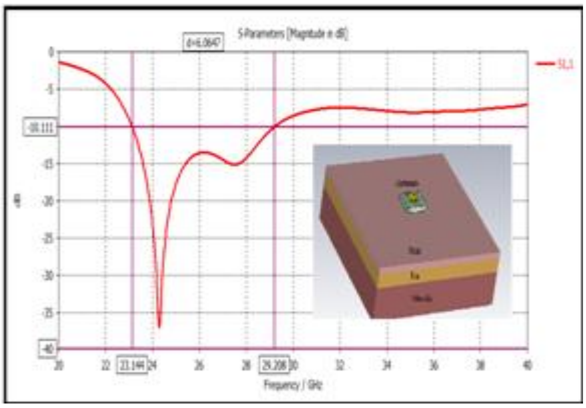

Figure 4: $S_{11}$of 3-layer homogeneous body tissue model, consisting of Muscle, Fat and skin at 1mm distance

Table II: Tissue Properties [38]

Tissue	Conductivity (S/m) at 28GHz	Permittivity at 28GHz	Tissue dimension In mm^3
Skin	25.8	16.6	50x50x2
Fat	5.04	6.09	50x50x4
Muscle	33.6	24.4	50x50x10

Case (2): CST voxel model

The CST Voxel Family has seven human model voxel data sets with varying height, age, and gender. The antenna was intended to be utilized by individuals of all ages and genders. In order to explore the impact of these human models on the antenna parameters, the four voxel models as listed in Table III are used.

The designed antenna is located 1mm away from the subject's wrist, since the designed antenna is intended for use with a smart watch worn on the subject's wrist, as seen in Figure 5.

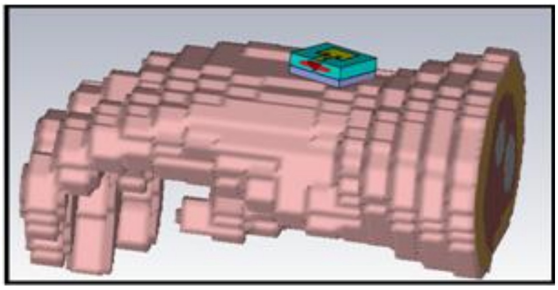

Figure 5: Antenna placed on the wrist of the CST Voxel model

Table III: CST VOXEL MODEL DETAILS [39]

Model	Age/Sex	Size/cm	Mass/kg	Resolution / mm
(1)	Baby, 8-week female	57	4.2	0.85 × 0.85 × 4.0
(2)	Child, 7year female	115	21.7	1.54 × 1.54 × 8.0
(3)	Gustav, 38year male	176	69	2.08 × 2.08 × 8.0
(4)	Katja, 43year pregnant	163	62	1.775 × 1.775 × 4.84

For Model (1), an antenna positioned 1mm above the wrist provides a bandwidth of 23.13 to 29.43GHz, with a gain of 8.374, 7.143, and 6.481dBi at 24, 26, and 28GHz, respectively. The bandwidth attained by the Model (2) is from 23.55 to 31.72GHz, with gains of 7.097, 6.662, and 10.20dBi at 24,26, and 28GHz, respectively. At 24, 26, and 28GHz, the antenna's gain ranges from 8.867dBi to 11.44dBi when positioned 1mm above the wrist of the Model (3).Antenna gain at 24, 26, and 28GHz is 9.846, 8.368 and 9.477dBi when the antenna is positioned 1mm above the wrist of the Model (4).

Based on the results of the aforementioned experiment, we can infer that the developed antenna worked from 23 to 30GHz with a high gain ranging from 6dBi to 11dBi when mounted on human models of varying ages and genders.

Case (3): Real human

The author's wrist is used to evaluate the proposed antenna for return loss S_{11} using an Anritsu portable Vector Network analyzer. At 23.84 GHz, the antenna resonated with a return loss of -33.35dB and a bandwidth of 22.91 to 31.09. At 24, 26 and 28GHz, the antenna recorded gain of 7.63dBi, 7.417dBi, and 7.471dBi, respectively, and radiation efficiency of 96.61 percent, 96.46 percent, and 96.13 percent. Figure 6. illustrates the return loss S_{11} measured on the Model (1) to Model (4) as well as the author's wrist.

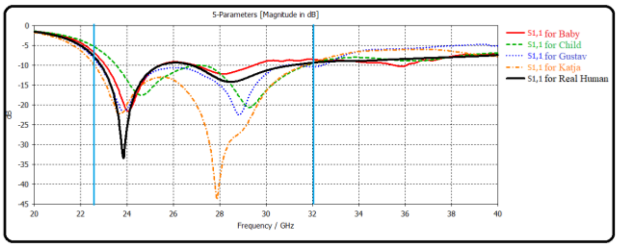

Figure 6: The S_{11} versus frequency response on real human and on CST Voxel models

4.4 SAR Calculations near 3-layertissue model and CST Voxel models

In this section, we analyse the SAR performance of the antenna under two key conditions: i) the antenna on the wrist; and ii) the antenna situated near the mouth, which is critical for smart watches that have built-in microphone capabilities. These SAR results are compared to the Federal Communications Commission's authorised limits of 2W/kg for 10g of human head tissue near the mouth and 4W/kg for 10g of human hand tissue near the wrist [40-47].

Case (i): The SARis calculated at 24, 26 and 28 GHz based on human wrist-antenna distance of 1mm using 3-layer tissue model and CST Voxel model Gustav for an input power of 250mW, 125mW, and 10mW is tabulated in Table IV. When the antenna was installed at 1mm distance with an input power of 250mW at 28GHz, the highest SAR was 6.0580 W/kg on a 3-layer tissue model and 6.3140 W/kg on a CST human model Gustav. As illustrated in Figure 7, the highest SAR of 3.0290 W/kg on a 3-layer tissue model and 3.1570 W/kg on a CST human model Gustav was recorded when the antenna was installed at 1mm distance with an input power of 125mW at 28GHz. When an input power of

125mW is provided to the antenna, the values are under the FCC standard limitations of 4W/Kg for 10grams of tissue, and it is highly desirable for on-body communication in WBAN applications.

Case (ii): For a sample of 10g of tissue, the SAR was estimated at 24, 26 and 28GHz using the CST Voxel model Gustav for an input power of 125mW and calculated at 1mm and 3mm human mouth-antenna distances. The results are shown in Table V.

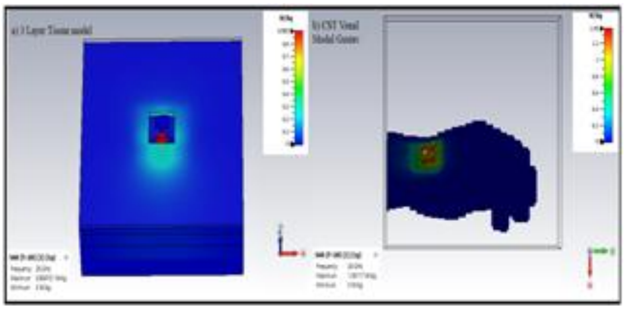

Figure 7: SAR on 3-layer tissue and on CST Voxel models

Table IV: SAR measured on wrist models with an input power of 250MW and 125MW

Tissue	SAR with input power of 250mW			SAR with input power of 125mW		
	24GHz	26GHz	28GHz	24GHz	26GHz	28GHz
3 Layer Tissue	3.1989	4.3752	6.0580	1.6553	2.1876	3.0290
Gustav	4.3245	4.6264	6.3140	2.1622	2.3132	3.1570

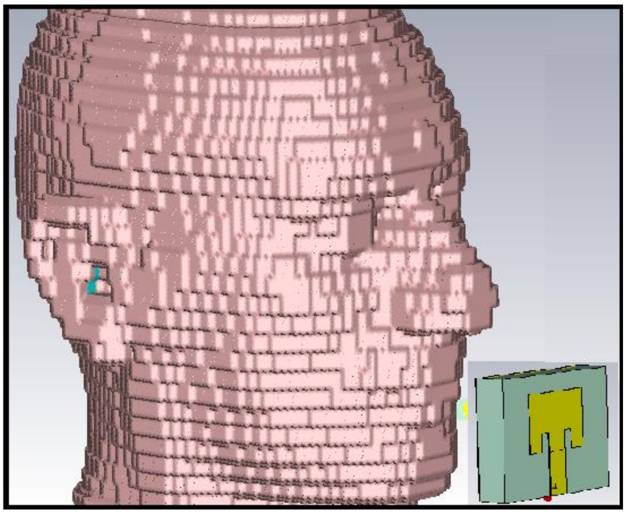

Figure 8: Gustav's Head model available in CST studio

Table V: SAR measured on Gustav mouth model with an input power of 125MW

Frequency	SAR at 1mm	SAR at 3mm
24GHz	1.4858	0.8348
26GHz	1.6606	0.9127
28GHz	2.2968	1.0654

Whenever the antenna is positioned 1mm from the Gustav's mouth as illustrated in Figure 8, the highest SAR recorded is 2.2968W/kg, just above FCC standard value of 2W/kg. but when the antenna is positioned 3mm from the Gustav's mouth, the greatest SAR recorded is 1.0654W/kg for a 125mW input power. Thus, the maximum power that may be utilised to keep the antenna within the safe limit is 125mW, and the minimum distance between the antenna and the mouth is 3mm.

5. Conclusion

A novel, low-cost, wideband, inset-fed antenna was introduced in this work for use in smart watches and other fitness bands. The antenna's basic planar structure and broad band functioning from 23 to 30GHz is investigated. The suggested antenna, has very compact dimensions of 7 x 8 x $1.6mm^3$and its gain pattern, efficiency, and reflection coefficient demonstrate its suitability for WBAN applications.

Experimentation has confirmed the modelling results, demonstrating that the antenna, which has a peak gain of 7.63 dBi and 96% efficiency, is capable of covering all of the necessary technical bands including the 24, 26, and 28GHz bands required for smart watch applications. It was tested on the author's wrist, three tissue layers and CST Voxel Gustav mouth model to study SAR for 10g tissue at each frequency. A 3mm separation for 125mW input power yields SAR compliance values below the 4 W/kg limit for the hand wrist model and 2 W/kg for the Gustav head model. Accordingly, the suggested antenna is proposed to be suitable for smart watch and WBAN applications since its SAR values is mostly in compliance with Federal Communications Commission (FCC) regulations.

6. Acknowledgments

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