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Structural Design of Wearable Miniaturized Textile Antenna

Pranita M. Potey, Kushal R. Tuckley

Abstract**: *Worldwide demand of wearable devices is arduous. In field of movable technology 'hands-free' status is requirement of persistent communication. With this regards, extensive research has been carried out on wearable technologies. Antennas made of fully fabric material are natural choice. This work presents performance comparison of between classical micro-strip antenna, fabric antenna with metal patch and fully fabric antenna. The fabric antennas show better gain and return loss but are larger in size owing to lower dielectric constant of fabric material. The fabric antennas being conceptually similar to the traditional micro-strip antennas, almost all the micro-strip design techniques could be seamlessly applicable to them. This work further presents an innovative technique of introducing an edge slot in the radiating patch and achieves a reasonable size reduction. This edge slot wearable antenna has been fabricated and the results are compared well with simulated results.***

Keyword: Specific absorption rate, non-textile, wearable, fully textile, semi textile, slots.

I. INTRODUCTION

Textile body worn antennas are special antenna type and they are partly or entirely made up of textile material. These antennas are documented as wearable gadgets which can be assimilated into the "smart garment". Textiles are considered as reasonable resource to design, as they are easily available in market. Microstrip patch designs are most popular in wearable application because this structure can be easily mounted on human body and its ground plane can guards the biological tissues from hazardous radiation. This structure also radiate vertically to its plane [6] and therefore they are generally used as a part of customs. Characteristics of nominated fabric material, plays an important part in the performance and antenna design. Permittivity of fabric material is an important parameter because it decides the patch dimension [4]. Similarly conductivity of the radiating patch material must be good enough.

Some fundamental parameters used for design and examinations of wearable textile antenna (WTA) are given as follows: [1-2].

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* Correspondence Author
Pranita M. Potey*, Department of Electronics & Telecommunication, Lokmanya Tilak College of Engineering, Navi Mumbai, India. Email: pranitampotey@gmail.com
Dr. Kushal R. Tuckley, department of Electrical Engineering, Indian Institute of Technology (IITB), Mumbai, India. Email: kushal@ee.iitb.ac.in

When an antenna is in transmitting mode current and voltage ratio at antenna terminals is known as antenna input impedance, Input impedance Zin comprises of two parts input resistance Rin and input reactance Xin, known as real and an imaginary part, respectively.
Resistance in input is due to the power radiated (Ra) and other owing to ohmic
Losses in the conductive and dielectric materials (R_{cd}) of an antenna, mathematically given as, R_{in} is due to the power radiated (R_a) and other owing to ohmic losses in the conductive and dielectric materials (R_{cd}) of an antenna, mathematically given as,

$$Z_{in} = R_{in} + jX_{in} = R_{cd} + R_a = R_{cd} + Z_a \quad (1)$$

Where, Xa = Xin. Radiation impedance Za which indicates the part of input impedance. It only takes into account the energy stored and power radiated by an antenna. Likewise, the radiated field power Ra and surplus energy in near field is Xa. The another fundamental parameter related to input impedance is reflection coefficient denoted by τ, it is given as,

$$\tau = \frac{Z_{in} - Z_a}{Z_{in} + Z_a} \quad (2)$$

The part of inserted power that is returned back at the terminals of transmitting antenna, due to impedance mismatch among generator and antenna is known as Reflection coefficient. Practically used equivalent parameter known as reflection coefficient and it is measured in dB, which is define as an reverse of the magnitude of the gives return loss and it is given as.

$$Return\ Loss\ (dB) = 20\ Log_{10}\ 1/T \quad (3)$$

The return loss and reflection coefficient are function of the frequency. Reflection coefficient should satisfies S11 < -10 dB, for fL < f < fH, it indicates, power less than 10% inserted at the terminals of antenna can be redirected back.
Amount of hazardous energy absorption by electromagnetic field affecting biological tissue is express by term specific absorption rate (SAR).
It is state as amount of change in the infinitesimal energy absorbed or ingest by a small portion of skin tissue, with respect to time. It is given by the following formula,

$$SAR = \frac{d}{dt}\frac{dW}{dM} = \frac{d}{dt}\frac{dW}{\rho}\,dv \qquad (4)$$

Where, W is energy absorbed and ρ indicates mass density of the human tissue. The unit of SAR is watt per kilogram.

II. FEATURES OF WEARABLE TEXTILE ANTENNA

Selection of substrate material for design of wearable textile antenna [1] is of critical importance.

When textile antennas are placed on the human body its basic requirement is to increase efficiency of an antenna that is done by selection of low loss substrate material. Textiles are planer and fibrous, generally their properties are identified by assembly and component of the yarn used. Also textiles are pores in nature, its behaviour are determined by density of air molecules, air permeability, dimensions of the pores and thermal insulation. Due flexibility and compressibility property of material, its thickness and density may vary with low pressure. Practically using fabric as substrate, above mention features need to be control and it is quite difficult. Therefore it is significant to know its effect on performance of antenna so as to reduce any undesirable effects. Essential parameter permittivity; it is a complex value factor, symbolized by ε. Generally stated as,

$$\varepsilon = \varepsilon_0\,\varepsilon r = \varepsilon_0\,(\dot{\varepsilon} - j\ddot{\varepsilon}) \qquad (5)$$

Where, ε0 = 8.85 × 10-12 F/m indicates permittivity of vacuum. Usually, dielectric properties of material depend upon frequency of operation, temperature and roughness of surface [10]. Relative permittivity εr is real part of permittivity, but it is not constant with frequency, also called as dielectric constant. Comparative parameter known as loss tangent, it is define as,

$$\tan\delta = \ddot{\varepsilon} / \dot{\varepsilon} \qquad (6)$$

Loss tangent indicates the loss in dielectric material, low loss tangent is essential for good antenna efficiency. Some investigators have reviewed and studied the textiles dielectric properties [4, 15]. Materials characterization depends on orientation of the electric field as textiles are anisotropic in nature. It permits the antennas improvement in form of efficiency and gain [3, 14–16].

Normally, textiles are holey and exhibits low value of dielectric constant. Due to presence of air molecules in its hole this makes the value of relative permittivity equals to unity. Dielectric constant of fabric material is governed by property of fiber component [12], and fiber filling density [11, 13].

The exact calculation of dielectric properties of fabric material is difficult and various investigational methods have proposed. Methods of determining the dielectric properties of the textile material are categories by [4], non-resonant methods and resonance methods [8].

Fig. 1 depicts device name broadband spectrometer used to measure properties of used fabric at 2.5GHz. Initially Sample holder is calibrated is done with open and short condition using two reference material Teflon and air, after line calibration.

Sample material with small diameter around 4mm with 0.06 mm thick is used and it is properly loaded in sample holder of broadband. Fabrics properties measured at 2.5GHz are shown in Table 1.

Table I Substrate material properties used for designing of antenna at 2.5GHz

Material properties	Values
ε'	6.06
ε''	1.59e-02
|ε|	6.06
Loss Tangent	2.62e-03
Modulus'	1.64e-01
Modulus''	4.32e-03

Fig.1 Measurement of fabric properties on dielectric Broadband spectrometer

Deviation in the value of dielectric constant with presence of moisture inside the textile substrate affects bandwidth of an antenna [2, 15]. The change in value of relative permittivity lies within a specific range. Nevertheless, the variation in permittivity is out of scope of this paper. Substrate material thickness and dielectric constant determines performance in terms of bandwidth and efficiency of antenna [4]. In fabric materials, permittivity values are narrow in range and their thickness has more variations, which will decide the bandwidth and input impedance [14]. Thus in the design of fully textile antennas fabric thickness plays important role [2]. For a certain value of relative permittivity, thick substrate may increase the bandwidth of antenna but this will not improve efficiency. Therefore, one can conclude that the selection of material thickness is a negotiation between two antenna parameters that is bandwidth and efficiency [4]. This can be further explained by equation,

$$BW = 1/Q \qquad (7)$$

Where, Q is the quality factor of an antenna. The quality factor is affected by losses due to space wave, ohmic losses, surface wave losses in conductor and dielectric losses in substrate. The Conductive Fabric Surface Resistivity also plays an important role in designing. Electrical properties of fabric are characterized by resistivity of surface and calculated by the surface resistance. Unit of surface resistance is given by ohm (Ω), and it is the ratio of a DC voltage to the flow of current among electrodes. Also, the surface resistivity is defined as the ratio between per unit voltage to per unit surface current along width.

It is expressed in Ohm/square. For designing of antenna, the related parameter is conductivity (σ) of fabric, measured in Siemens per meter (S/m). It has close relation with surface resistivity which is given by Equation,

$$\sigma = \rho . t \tag{8}$$

Where, t is fabric thickness. For assurance of good performance of rectangular patch antenna, choice of ground plane conductive patch is most essential. To increase antenna efficiency and minimize electric losses, textile material with less electrical surface resistance is to be selected.

III. DESIGN PROCEDURE OF ANTENNA

Initially antenna is design with basic rectangular patch structure. Three important parameters for the designing of textile antennas are substrate relative permittivity, conductivity of radiating material and resonance frequency. Normally according to application, for which antenna is to be design, selection of frequency is done. For this work ISM band is selected as it is license free band and therefore it can use for industrial scientific and medical application. Thus these design antennas are operating at frequency 2.5 GHz. Primarily for this investigation using dissimilar material three similar basic rectangular patch antennas are design shown in Fig. 2; those are semi textile, fully textile and non-textile.

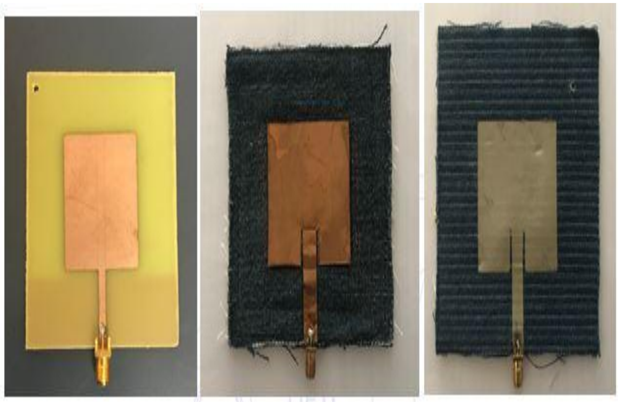

Fig. 2 Antennas (a) Non textile (b) Semi textile (c) Fully textile.

For semi textile, Denim fabric for substrate material, flexible copper foil for ground plane and radiating part is used. Fully textile antenna is fabricated using complete fabric materials, substrate and radiating patch both. Denim fabric is chosen because it is most popular and which is commonly used by male and female as well. Used denim has value of relative permittivity loss tangent equal to 1.6 and 0.02 respectively at 2.5 GHz. For non-textile antenna FR-4 is used as it is commonly available. It is the prime insulating backbone with the help of it commonly printed circuit boards (PCB) are made. Materials used are composite in nature and consist of woven glass-fibre and epoxy resin is used as a binder. An epoxy resin binder has a flame resistant property with relative permittivity 4.4 at 2.5 GHz frequency. Dimension for designing of all three antennas like width, length etc. calculated [5] are shown in Table 2.

Table II Antenna dimensions used in design

Antenna Parameter	semi Textile/Textile Antenna (mm)	Non Textile Antenna (mm)
Material Type	Denim + Copper foil	FR4
Width (W)	52.62	36.51
Length (L)	46.9	28.08
Ground plane	71×77	50×58
Substrate height (h)	1.6	1.6
Feed line width (W_f)	2.8	2.8
Dielectric constant (ε_r)	1.6	4.4
Total Feed Length	35.3	21.5
Inset Feed length	11.5	7.0

Reason behind selection of low value fabric substrate dielectric, surface wave losses get reduces and bandwidth increases. Textile used as a substrate is very thin; hence two to three layers are stacked together to achieved desired height [6]. Therefore material becomes heterogeneous due to occurrence of extra air layers between two materials of fabrics. Substrate height 1.6 mm is considered to minimize losses. Normal scissors are used for cutting fabrics and a special small distance stitch with analogous kind of thread is used to attach the pieces of fabric together.

For measurement and feeding purpose 50Ω SMA connector is attached with less power soldering gun also superior glue is use.

This carefully design basic rectangular patch antenna originates its uses on garment sleeves, collars, pockets or in some special application it can be use like embroidery.

IV. RESULT ANALYSIS OF DESIGN ANTENNAS

Simulation of all basic designs that is non textile, semi textile and fully textile are done using CADFEKO software. All three basic antennas types are fabricated and Table 3 indicates performance analysis of all three basic antennas, here semi textile and fully textile antenna performance is near about same.

Table III Performance analysis of all antenna designs

Type of Antenna (Basic Structure)	Freq. (GHz)	S11 (dB)	Gain (dB)	η (%)	F/B Ratio [dB]
Non Textile	2.51	-19.47	4.4	62.3	13.7
Semi Textile	2.50	-20.13	6.6	68.4	24.0
Full Textile	2.50	-19.81	6.6	68.0	24.5

Fig. 3 show simulated reflection coefficient verses frequency graph for all basic antennas and each antenna exhibited well at a resonant frequency.

In fact semi textile and fully textile exhibit same performance in return loss and radiation pattern as well. Radiation plot of non-textile and semi-textile antenna are depicts in Fig. 4.

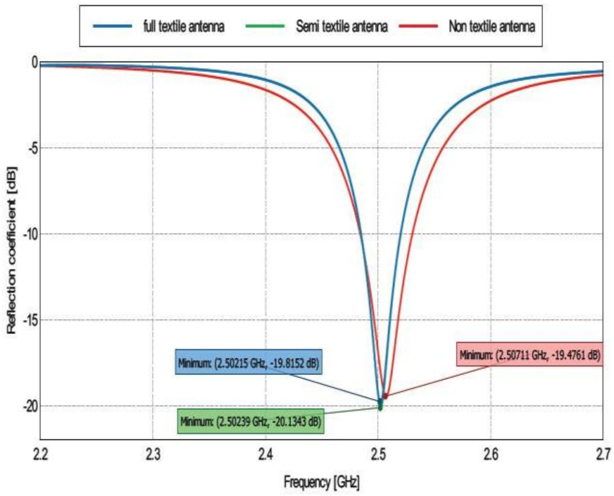

Fig. 3 Simulated return loss of all three antenna

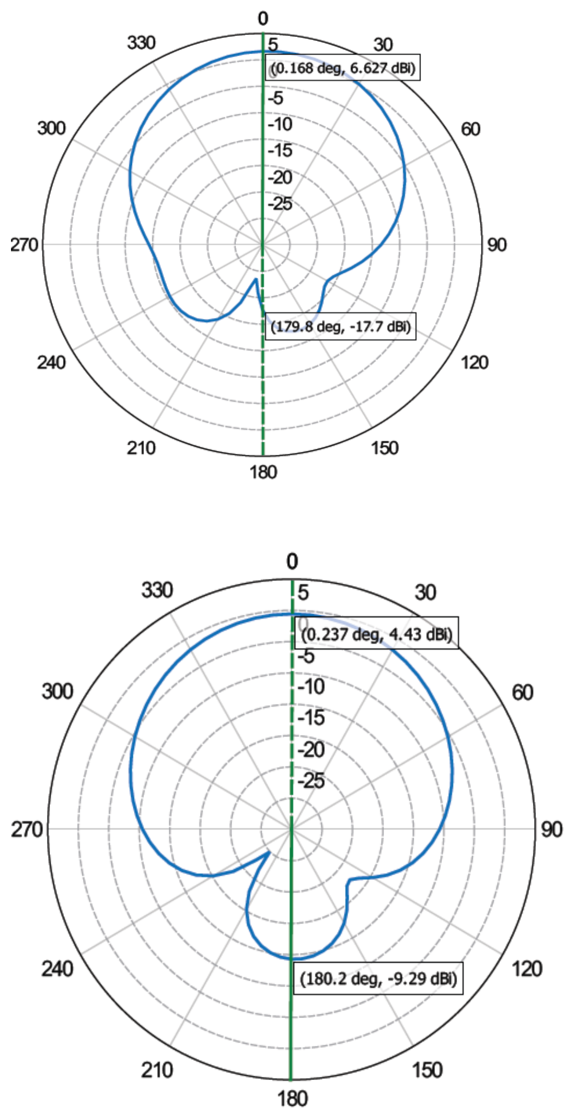

Fig. 4 Radiation plot of non-textile and Fully-textile antenna.
(Note: Radiation performance of semi textile and fully textile antennas are same.)

From radiation pattern it is concluded that maximum power is radiated in forward direction whereas very less amount of power in backward direction. This implies less harmful radiation towards human body.

Also from above results it is concluded that, the fabric antennas have better gain and efficiency but are bigger in size due to lower dielectric constant value of fabric material. Thus, for size reduction and further improvement in gain, return loss and efficiency some modifications in the structure of existing basic fully textile patch are proposed. With the proper examination of surface current density these modifications in antenna structure are executed. This revised wearable antenna design exhibits two similar slot at middle and edges both show a self-symmetry pattern. Fig. 5 shows the design of proposed textile antenna and Fig. 6 shows fabricated design.

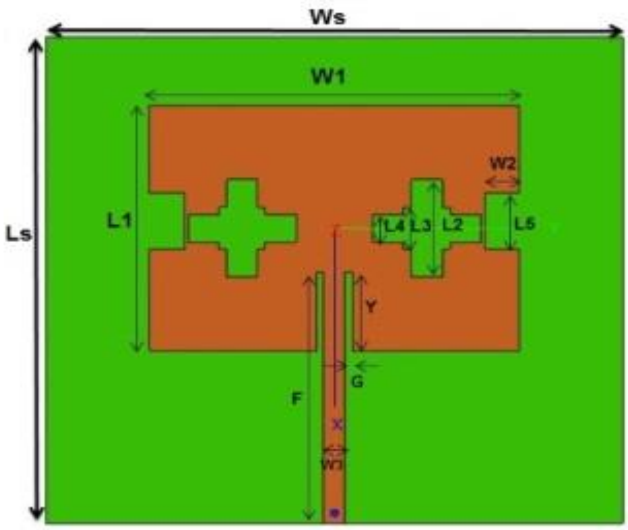

Fig. 5 Demonstrated modified geometry of revised wearable fully textile antenna.

Table IV. Dimension of edge slot antenna

W_S	L_S	W1	W2	W3	F
71	77	40.8	4	2.8	35.3
L1	**L2**	**L3**	**L4**	**L5**	**G**
46.9	13	5	4	7	0.5

Fig. 6 Demonstrated modified geometry of revised wearable fully textile antenna.

Conductive fabric has less conductivity [9] then flexible copper. Revised antenna assembly has substrate dimension of 66 mm × 61 mm attached on a textile radiating patch of dimensions 45.9 mm × 40.8 mm, with a full ground plane to meet modified structural changes.

Further dimensions are of the revised fully textile antenna is explained in Table 4.

Fig. 7 indicates improvement in return due to insertion of slot in existing design at the same resonant frequency. Thus, insertion of edge slot reduces antenna size around 25% which comparable with the size of non-textile antenna.

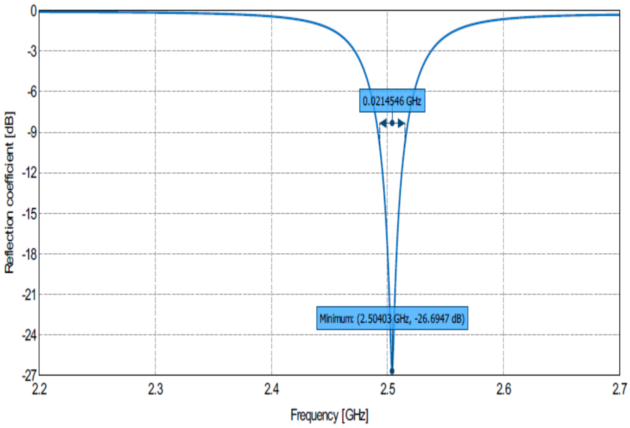

Fig. 7 Simulated reflection coefficient of revised fully textile antenna.

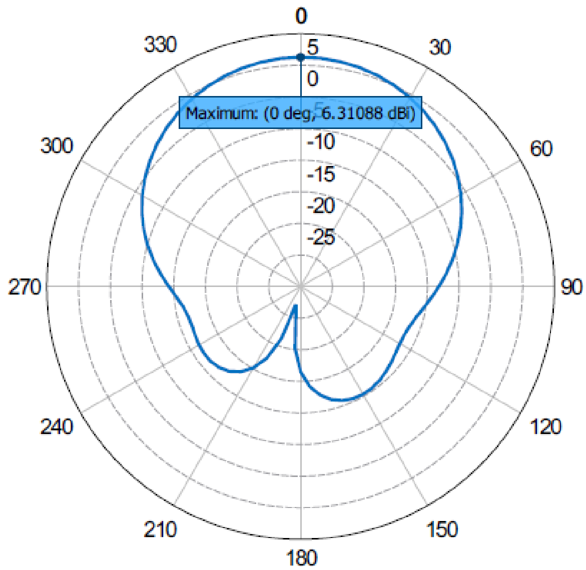

Fig. 8 Comparison of simulated and measured return loss of proposed fully textile antenna.

Owing to addition of two symmetrical slots with appropriate dimensions return loss, gain and efficiency is improves [7]. Gain is improved by 0.3 dB; whereas return loss and efficiency is measured at -25.10 and 69% respectively is summarized in Table 5. This simple method of insertion of slot reduces the size of antenna including enhancement in overall performance.

However in recent literature [17-19] researchers has opted various complicated methods like use of EBG, metamaterial, complicated layered structure etc. Measured and simulated results also show a decent settlement with minor deviation in return loss.

Also Fig. 8 indicate radiation plots of proposed antennas, front lobe indicates approximately 80% radiation in forward direction and very less radiation in backward direction.

This specify energy absorb by the human tissue when it is place on human body is very less which is necessary in wearable case. Low SAR value is noteworthy parameter.

Table V Comparison of measured and simulated results

Antenna Type	Freq. (GHz)	S11 (dB)	SAR (W/Kg)	Gain (dB)	η (%)
Measured	2.50	25.10	---	6.8	69.0
Simulated	2.51	-26.69	0.5	6.5	70.6

V. CONCLUSION

Textile material usage in the antenna designing makes it wearable which is unlike from regular rigid antenna. Relative analysis of textile antenna with non-textile is investigated meticulously.

Owing to the small dielectric constant, textile antenna has large patch sixe. In order to reduce size and boost the efficiency of antenna few alterations are done in the traditional rectangular antenna design.

The proposed investigated patch is 25% smaller in size than the traditional rectangular patch.

This proposed and investigated design use simplest technique for miniaturization. Thus, the simulated and measured results of proposed design indicate this antenna is appropriate for various compact wearable applications.

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AUTHORS PROFILE

Pranita Manish Potey, Received M.E degree from University of Mumbai and is currently pursuing Ph.D. from RGIT, Versova, Mumbai, India in the Department of Electronics and Communication Engineering. She is currently working as an Assistant Professor in the Department of Electronics and Communication Engineering at Lokmanya Tilak College of Engineering, Koparkhairne, Navi Mumbai, India. She has more than 15 years of teaching experience. She is the author of reputed journal and conference papers. Her research interests include wearable textile Antennas, Body Wearable Conformal Antennas and Reconfigurable Antennas etc.

Dr. Kushal R. Tuckley Received M.Tech and Ph.D. from IIT Bombay, Mumbai, India from the Department of Electrical Engineering. He is Chairman and Director R&D, Company AGV Systems Pvt. Ltd also currently working as Adjunct Professor, at IIT, Bombay in the Department of Electrical Engineering. He has more than 20 years of research experience. He is the author of many reputed journal and conference papers. His research interests include Radar Engineering, Body Wearable antenna, microwave systems etc.