Determination of Dielectric Constant of Fabric Materials and Their Use as Substrates for Design and Development of Antennas for Wearable Applications

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***Abstract*—A novel approach to measure the dielectric constant of fabric substrate materials used for the development of wearable antennas (also called textile antennas) is presented in this paper. The technique reported here is based on the resonance method and focused on the use of microstrip patch radiator, which contains fabric material as its substrate. The accurate value of the dielectric constant of the fabric material can easily be extracted from the measured resonant frequency of the patch radiator. The dielectric constant values of six fabric materials, including jeans cotton, polyester combined cotton, and polyester, have been determined by this way. As an extended objective of this paper, initial investigations are done to study the performance/behavioral characteristics of wearable antennas in the Bluetooth industrial, scientific, and medical band. Two of the six textile antenna structures, developed to meet out the primary objective of determining the dielectric constant of fabrics, are tested, and their performance characteristics, such as impedance bandwidth, gain, efficiency, etc., are measured. In addition, another Bluetooth antenna employing polyester fabric substrate is designed considering its measured accurate value of dielectric constant and subjected to radiation pattern measurements. In general, all the measured antennas yield very good results, fulfilling the requirements for practical applications, and in particular, the third fabric antenna utilizing the accurate value of the dielectric constant determined shows superior performance characteristics compared to others, indicating the correctness of our approach. Thus, the suitability of fabric substrate materials for the development of textile antennas with microstrip patch configuration is also well demonstrated.**

***Index Terms*—Antenna measurements, dielectric measurements, fabric substrates, rectangular microstrip wearable antenna, resonance method, textile antennas.**

I. Introduction

BODY AREA networks (BANs) are a natural progression from the personal area network concept, and they are networks with nodes normally situated on the human body or in close proximity to it [1]. Advances in communication and electronic technologies have enabled the development of compact and intelligent devices that can be placed on the human body or implanted inside it, thus facilitating the introduction of BANs. Huge processing and complex BANs will be needed in the future to provide the powerful computational functionalities required for advanced applications. These requirements have led to increasing research and development activities in the area of wireless BAN (WBAN) applications for many purposes [2], with the main interest being in health care and wearable computers. WBANs can be applied in many fields, such as the following:

1) assistance to emergency services, such as police, paramedics, and fire fighters;
2) military applications, including soldier location tracking, image and video transmission, and instant decentralized communications;
3) augmented reality to support production and maintenance;
4) access/identification systems by identification of individual peripheral systems;
5) navigation support in cars or while walking;
6) pulse rate monitoring in sports, among others.

The ultimate WBAN should allow users to enjoy such applications with minimum interference, low transmission power, and less complexity. A wearable antenna is an essential part of any wireless body-centric network. A microstrip patch is a representative antenna for wearable applications, as it can be made conformal for integration into clothing [3]–[5].

The primary objective of this paper is to propose a novel technique to measure the dielectric constant of fabric substrate materials suitable for the development of wearable antennas by employing the resonance method. The work meant for this task is further extended in order to carry out investigations to get preliminary results on the performance characteristics of wearable/textile antennas, such as impedance bandwidth, radiation patterns, gain, efficiency, etc. The rest of this paper is organized as follows. Section II discusses the possible methods of measuring the dielectric constant of substrate materials. The theoretical background of our technique for the measurement of the dielectric constant of fabrics is explained in Section III, along with a brief note on the microstrip patch radiator design procedure. The experimental procedure is described in Section IV, depicting the measurement setup details together with validation of the proposed technique. Section V focuses on the measurement of the performance characteristics of wearable antennas, with comments on the results obtained. Concluding remarks are offered at the end of this paper in Section VI.

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II. Methods of Material Characterization

The microwave methods of measuring the dielectric properties of the material can be divided into the following two main categories [6]:

1) nonresonant methods;
2) resonance methods.

Nonresonant methods mainly include reflection methods and transmission/reflection methods. Reflection methods utilize information on the reflection of electromagnetic (EM) wave from free space to the sample under test to extract the value of the dielectric constant of the sample. In transmission/reflection methods, the dielectric properties are calculated on the basis of reflection from the sample and transmission through the sample.

Resonance methods are used to get accurate knowledge of dielectric properties at a single frequency or several discrete frequencies. These methods generally include the resonator method and the resonance perturbation method. The resonator method is based on the fact that the resonant frequency and quality factor of a dielectric resonator with given dimensions are determined by its permittivity and permeability. The resonance perturbation method is based on resonance-perturbation theory. For a resonator with given EM boundaries, when some of the EM boundary conditions are changed by introducing a sample, its resonant frequency and quality factor will also be changed. From the changes of the resonant frequency and quality factor, the properties of the sample can be derived.

The most common resonance techniques are those based on resonant cavities formed from a rectangular or circular waveguide. A piece of sample material placed therein affects the resonant frequency and quality factor of the cavity. The fundamental advantages of using a cavity resonator are narrow bandwidth (hence, it is perturbation sensitive) and high fields (hence, it is able to achieve a substantial change in signal due to small change in permittivity). The complex permittivity of the material can be calculated at a single frequency by simply measuring the shift in frequency and the value of Q-factor. These techniques may require more complex sample preparation. In practice, it is very difficult to place the sample at exactly the same position for each measurement, which can lead to nonrepeatability in the measurement data and large errors in the measurement values. In addition, the samples require precise machining, and the cavity needs to be dismantled and reassembled each time a new sample is tested. In spite of these drawbacks associated with sample preparation and testing, the cavity perturbation technique has been widely used to date by researchers [3], [4] for the characterization of materials. The work presented here is also based on the resonance method but is focused on the use of microstrip patch radiator, which also possesses the advantage of low bandwidth. In this paper, a novel technique for the determination of the real part of the permittivity of fabric substrate materials used in the development of wearable antennas is proposed. In general, the resonance method is more accurate than any reflection or transmission/reflection method. Recently, Declercq *et al.* [7] have made a very good attempt to use the transmission/reflection method for the characterization of fabric materials and have determined both real and imaginary parts of permittivity. In that work [7], the well-known two-line method, which measures the propagation characteristics of microstrip lines, is combined with the matrix-pencil technique in order to reduce the perturbations in the transmission line parameters. However, the procedure involved in that technique is substantially more complex than the technique reported in this paper.

The most advantageous feature of this technique, which makes it distinct from other standard resonance methods, such as the cavity perturbation method, lies in sample preparation. We need to have only a scissor and a measuring tape for preparing the sample. Like the cavity resonance technique, this method also yields good measurement accuracy as the patch radiator possesses narrow bandwidth, and so, a small change in the value of dielectric constant results in a substantial shift in resonant frequency.

In this approach, the loss tangent of the fabric substrate material is not determined as we intend to perform only a conservative design of the wearable antenna. Standard empirical formulas [8] used for the design of microstrip antennas do not require the value of the imaginary part of the permittivity of the substrate material employed. Therefore, much attention is given to the real part of the permittivity of fabric materials considered. Moreover, a patch antenna's resonant frequency depends only on the real part of permittivity and not on its imaginary part for the most commonly used low-loss substrates, including fabrics. The loss tangent component of the permittivity of the fabric material definitely influences only the efficiency of the wearable antenna. However, the fabric materials are not very lossy, and hence, they can be considered for antenna applications without bothering much about the antenna efficiency. Six fabric substrate materials, including jeans cotton, polyester combined cotton (65:35), and polyester, have been tested.

III. Theoretical Background and Microstrip Patch Radiator Design Procedure

In the proposed measurement technique, a rectangular microstrip patch radiator utilizing the given fabric material as its substrate is to be designed assuming an approximate value of dielectric constant. The value of the dielectric constant of this fabric substrate material may be computed by simply measuring the resonant frequency of the patch radiator. The design of the microstrip patch radiator involves the computation of its patch dimensions. The patch width (W) has a minor effect on the resonant frequency (f_r), and it is calculated using the following formula [8]:

$$W = \frac{c}{(2f_r)}\sqrt{\frac{2}{(\varepsilon_r + 1)}} \tag{1}$$

where c is the speed of light in free space and ε_r is the relative permittivity of the fabric material under test. The microstrip patch lies between air and the dielectric material, and thus, the EM wave sees an effective permittivity $(\varepsilon_{\text{reff}})$ given by [8]

$$\varepsilon_{\text{reff}} = \left[\frac{\varepsilon_r + 1}{2}\right] + \left[\frac{\varepsilon_r - 1}{2}\right]\left[1 + \frac{12_h}{W}\right]^{-\frac{1}{2}} \tag{2}$$

where h is the thickness of the substrate.

The patch length (L) determines the resonant frequency and is a critical parameter in design because of the inherent narrow bandwidth of the patch. The design value for L is given by [8]

$$L = \left[\frac{c}{(2f_r\sqrt{\varepsilon_{\text{reff}}})}\right] - 2\Delta L \tag{3}$$

where $\varepsilon_{\text{reff}}$ is the effective permittivity of the material under test. The additional line length on ΔL both ends of the patch length, due to the effect of fringing fields, is given by [8]

$$\frac{\Delta L}{h} = 0.412\left[\frac{(\varepsilon_{\text{reff}}+0.3)}{(\varepsilon_{\text{reff}}-0.258)}\right]\left[\frac{\left(\frac{w}{h}+0.264\right)}{\left(\frac{w}{h}+0.8\right)}\right] \tag{4}$$

The effective patch length L_e is written as

$$L_e = L + 2\Delta L. \tag{5}$$

Hence, the knowledge of the actual (measured) resonant frequency paves way for extracting the value of ε_r of the fabric material.

IV. Measurement Setup and Experimental Procedure

Basically, the test equipment consists of a rectangular microstrip antenna, the patch of which is fed by a coaxial line and a vector network analyzer (model #5071B) from Agilent Technologies. The network analyzer is calibrated using the two-port electronic calibration module [9], bearing model #85092C for an operating frequency ranging from 300 kHz to 9 GHz, which provides excellent accuracy, with results being, in general, better than that of short-open load-thru calibration but somewhat less than that of a properly performed thru-reflect-line calibration.

The following steps are involved in the measurement procedure and parameter extraction.

1) Design a microstrip patch antenna for a resonant frequency f_{rD} assuming an approximate value of ε_r of the fabric material. The ε_r value is assumed based on the literature data [3]–[5], [9] and the crude measurement data obtained from an impedance analyzer [10].
2) Simulate the antenna structure using an IE3D EM simulator [11]. While modeling the probe feed to patch using this software, the dimensions of a standard SubMiniature version A (SMA) connector (inner diameter: 1.3 mm; outer diameter: 4.1 mm) are considered. Optimize the feed position to get good impedance matching (50 Ω).
3) Fabricate the antenna elements and assemble them. The ground plane dimensions are 120 mm × 120 mm, and its thickness is 0.5 mm. The patch material is 0.1 mm thick and fabricated with 20-μm accuracy. Both ground plane and patch are made up of copper. The size of the fabric material is 120 mm × 120 mm. The fabric pieces are stacked to get the required thickness. While assembling the antenna elements, the copper sheets are just fixed on the fabric material with a tape, and due care is taken such that there is no air gap between the fabric material and the conducting parts of the antenna.

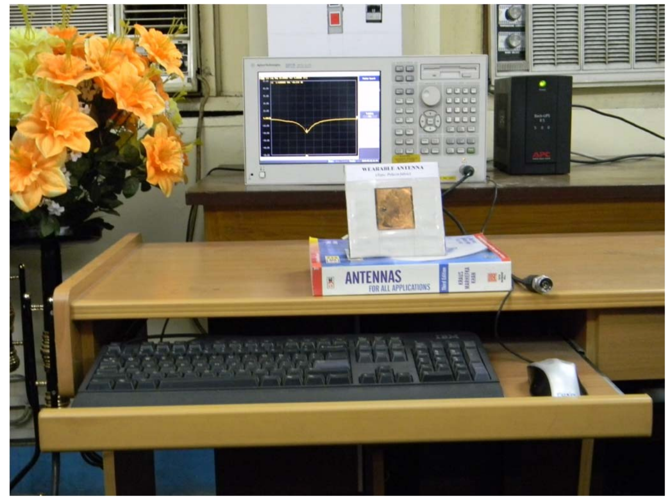

Fig. 1. Snapshot of the experimental setup used for the determination of resonant frequency.

Fig. 2. S_{11} plot of a patch antenna employing wash cotton fabric.

4) Measure the resonant frequency f_{rM} using a vector network analyzer.
5) Compute $\varepsilon_{\text{reff}}$ at the measured frequency [(3) and (4)].
6) Extract the value of ε_r from $\varepsilon_{\text{reff}}$ [(2)].

Special care has been taken in such a way that the area of the ground plane and the dielectric material to be measured is at least five times larger than that of the rectangular patch in order to achieve the following: 1) avoid backlobes in the radiation pattern of the antenna; 2) reduce the diffraction and scattering effects at the edges of the ground plane; and 3) minimize the undesirable effects of surface waves. Fig. 1 shows a snapshot of the experimental setup used. In order to determine the accurate dielectric constant value of six different types of fabric materials, the microstrip patch radiators are designed for a frequency of 2.45 GHz for each material, and the aforementioned procedure is followed.

To illustrate the procedure involved in this technique, let us consider, for example, the wash cotton fabric material. A rectangular microstrip patch radiator is designed for a frequency of 2.45 GHz. The thickness of the substrate is taken as

TABLE I
VALUES OF VARIOUS PARAMETERS INVOLVED IN THE DETERMINATION OF THE DIELECTRIC CONSTANT OF SOME FABRIC MATERIALS

Name of the fabric material tested	Design freq. - f_{rD} (GHz)	Assumed ε_r value	Fabric height – h (mm)	Patch width – W (mm)	Patch length - L (mm)	ΔL (mm)	Feed position* (mm)	Measured freq. – f_{rM} (GHz)	S_{11} at f_{rM} (dB)	ε_{reff}	Extracted ε_r value
Wash cotton	2.45	1.6	3.0	53.67	45.98	1.73	11.10	2.519	-17.5	1.45	1.51
Jeans cotton	2.45	1.6	2.84	53.67	45.98	1.73	11.10	2.403	-15.4	1.59	1.67
Polycot	2.45	1.3	3.0	57.47	50.70	1.89	13.40	2.247	-19.1	1.50	1.56
Curtain cotton	2.45	1.47	3.0	55.06	47.32	1.78	11.62	2.450	-17.5	1.42	1.47
Polyester	2.45	1.4	2.85	55.89	48.70	1.72	11.60	2.420	-25.4	1.39	1.44
Bed sheet / Floor spread	2.45	1.8	3.0	51.74	43.00	1.66	10.10	2.700	-15.6	1.41	1.46
Validation of the proposed technique using a standard PCB substrate											
PTFE (make: Neltec - France)	2.45	2.65	1.524	45.32	36.20	0.84	11.75	2.479	-18.2	2.57	2.70

* denotes the position of the feed from the centre of the patch along the length direction towards the width edge.

3.0 mm. The assumed value of the dielectric constant of this fabric material is 1.6. The computed values of the patch dimensions are $L = 45.98$ mm and $W = 53.67$ mm. The value of ΔL is 1.73. The feed position is optimized at 11.10 mm from the center of the patch along the length direction toward the width edge. The measured resonant frequency is 2.519 GHz, as shown in Fig. 2, against the design frequency of 2.45 GHz.

Then, the value of the effective dielectric constant is calculated as 1.45 using (3) and (4). Finally, the actual value of the dielectric constant of the wash cotton fabric is calculated as 1.51 using (2). In this way, five more fabrics are also investigated and characterized. The values of the various parameters involved while employing this routine to all six fabric materials tested are listed in Table I. The literature data [3] reveal that the values of the dielectric constant of different fabric materials lie in the range of 1.1–1.9. Before taking these measurements on the fabric materials under test, the validity of this proposed technique is demonstrated for a well-characterized reference dielectric material, i.e., PTFE (Teflon), whose vendor-supplied value of dielectric constant is 2.7. A 2.45-GHz rectangular patch antenna with Teflon as the dielectric substrate is fabricated using a copper laminate (make: Neltec-France) assuming an approximate value of dielectric constant of 2.65. The antenna resonates at a frequency of 2.479 GHz against the design frequency of 2.45 GHz, as shown in Fig. 3. The value of dielectric constant of Teflon is therefore extracted as 2.70, which is in excellent agreement with the vendor-supplied data.

The authors [12] have also plotted a graph, as shown in Fig. 4, showing the variations of ε_r of a finely woven cotton fabric as a function of frequency by employing the measurement technique reported in this paper and by repeating the aforementioned six steps at various discrete frequencies in the range of 0.9–10.0 GHz.

This graph serves as a reference chart for getting the tentative value of the dielectric constant of the said fabric material for the design of wearable antennas. By a 1-D data interpolation technique, one can easily find the accurate value of the dielectric constant of this fabric material at any

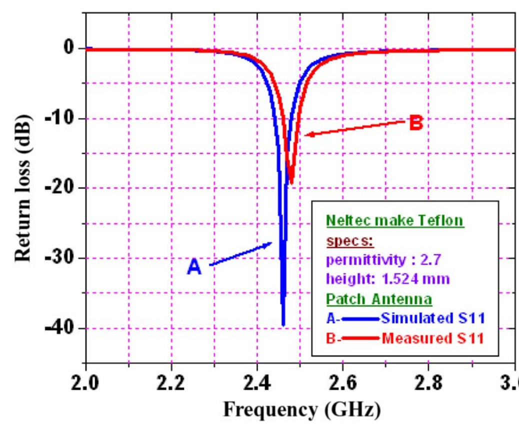

Fig. 3. Validation of the proposed technique using a standard substrate (Teflon).

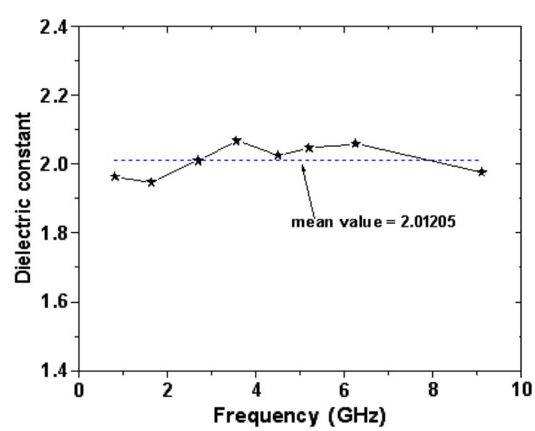

Fig. 4. Dispersion characteristics of the dielectric constant of a finely woven cotton fabric.

frequency within this range. The variations in ε_r shown in the graph may be due to the inhomogeneous nature of the tested fabric. However, a static value of dielectric constant can always be obtained by averaging the values of dielectric constant at different frequencies. Even if these variations of dielectric constant are due to some other reasons (e.g., due to the usage of fixed SMA connectors that are nonidentical and soldering inaccuracies), these data can be cleaned using the matrix-pencil averaging method proposed in [7].

V. Measurement of Performance Characteristics of Wearable Antennas

In this part of the work, three antennas are tested for their performance characteristics. The first two antennas are the ones that are developed for the purpose of determining the dielectric constant of fabrics. Antenna 1 is the jeans cotton antenna, and antenna 2 is the one fabricated for measuring the dielectric constant of polycot fabric. Therefore, these two antennas are the ones that are constructed by assuming approximate values of the dielectric constant of the respective fabrics. Antenna 3 is fabricated employing polyester fabric substrate and by considering its measured accurate value of dielectric constant obtained by our technique.

A. Return Loss Characteristics

1) Simulated and Measured Results: The simulated and measured S_{11} plots as functions of frequency for the case of jeans cotton antenna (antenna 1) are shown in Fig. 5. Similarly, Fig. 6 shows the simulated and measured S_{11} plots of polycot antenna (antenna 2). Simulations and measurements are carried out over a frequency range of 2.0–3.0 GHz in each case. In the simulation process, the values of dielectric constant considered for jeans cotton and polycot fabrics are 1.67 and 1.56 (as determined accurately by our procedure), respectively. However, the tested antennas (1 and 2) had assumed values of 1.6 and 1.3, respectively. From the measured quantities, it is evident that the jeans cotton textile antenna (antenna 1) resonates at a frequency of 2.403 GHz and provides a -10-dB $(\text{VSWR} < 2)$ return loss bandwidth of 170 MHz (7.07%). The corresponding values obtained by the simulation process are 2.449 GHz and 118.7 MHz (4.84%). On the other hand, the polycot textile antenna (antenna 2) resonates at 2.247 GHz with a -10-dB return loss bandwidth of 106 MHz (4.7%) against the corresponding simulated values of 2.46 GHz and 101 MHz (4.1%). For polyester antenna (antenna 3), which was built using the accurate value of dielectric constant determined by our technique, the measured values of resonant frequency and -10-dB return loss bandwidth are 2.456 GHz and 100 MHz (4.07%) against the corresponding simulated values of 2.449 GHz and 98 MHz, as shown in Fig. 7. At the simulated resonant frequency, the return loss is -32.2 dB, whereas the same antenna provides a return loss of -32.5 dB at its measured resonant frequency. The simulated and measured values of resonant frequency and impedance bandwidth (-10-dB return loss) for all three antennas are listed in Table II.

2) Discussions: Among the three antennas tested, the first two antennas assumed an approximate value of dielectric constant obtained from an impedance analyzer [10] employing the parallel-plate capacitance method. The error in this approximation is about 4.19% for antenna 1 and 16.67% for antenna 2. Hence, a deviation between the simulated and measured values of resonance frequency is expected, and it is 1.8% for the case of jeans cotton antenna 1 and 8.6% for polycot antenna 2. For polyester antenna 3, which uses the measured value of dielectric constant obtained through the technique reported herein, it is observed that there is an excellent agreement between the simulated and measured values of resonance frequency. This demonstrates the usefulness of our technique for the determination of dielectric constant of fabric materials suitable for the design and development of wearable antennas.

Considering the impedance bandwidth, the deviations between the simulated and measured values are about 30.1%,

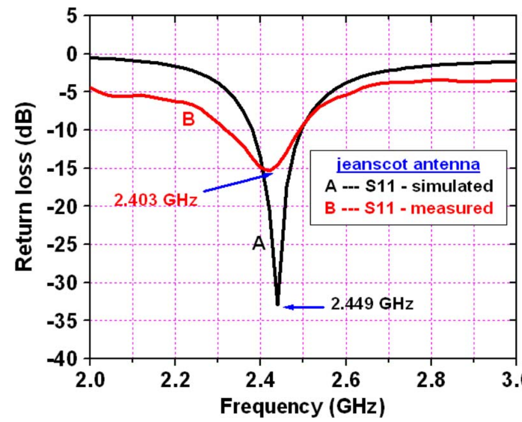

Fig. 5. S_{11} plot of a patch antenna employing jeans cotton fabric.

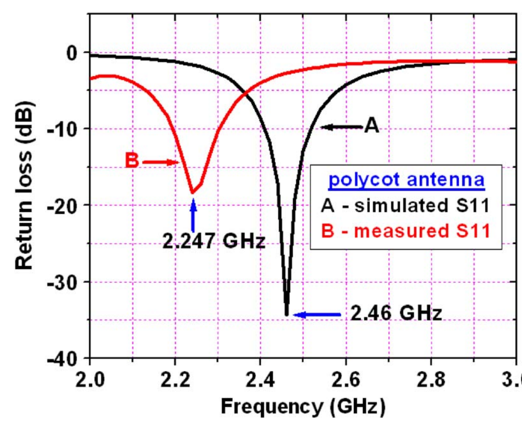

Fig. 6. S_{11} plot of a patch antenna employing polycot fabric.

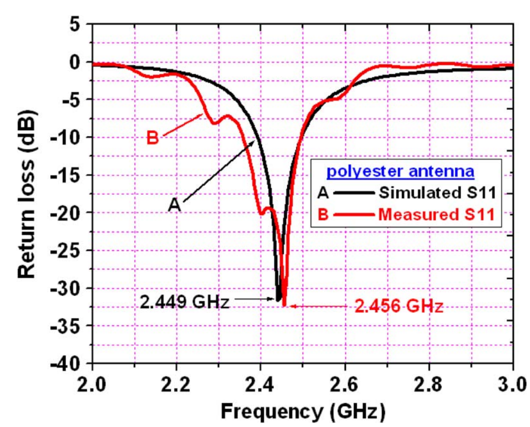

Fig. 7. S_{11} plot of a patch antenna employing polyester fabric.

TABLE II
PERFORMANCE CHARACTERISTICS OF WEARABLE ANTENNAS UNDER INVESTIGATION

Sl. No.	Parameter	Jeans cotton antenna (#1)		Polycot antenna (#2)		Polyester antenna (#3)	
		Simulated	Measured	Simulated	Measured	Simulated	Measured
01	Resonant frequency (GHz)	2.449	2.403	**2.46**	2.247	2.449	2.456
02	Impedance bandwidth (MHz) [-10dB points]	118.7 (4.84%)	170 (7.07%)	101 (4.1%)	106 (4.7%)	98 (4.0%)	100 (4.07%)
03	Gain in azimuth (dBi)	5.91	5.94	6.84	6.96	7.14	9.61
04	Gain in elevation (dBi)	5.91	5.77	6.84	6.91	7.14	9.61
05	3 dB beam-width in azimuth (deg)	79	59	79.0	60	72	65
06	3 dB beam-width in elevation (deg)	74	67	70.0	66	72	62

4.7%, and 0.02% for antennas 1, 2, and 3, respectively. The measured value of return loss bandwidth is greater than the simulated value for all the three cases, which may be due to the variations in inductive reactance offered by the coaxial probe. It is quite interesting to note that the bandwidths yielded by all these antennas are greater than the industrial, scientific, and medical bandwidth of 85 MHz, and therefore, these antennas can be designed and applied for Bluetooth applications.

B. Far-Field Radiation Characteristics

1) Radiation Patterns (Simulated and Measured Results): The three antennas are subjected to far-field radiation pattern measurements in a rectangular shielded anechoic chamber with dimensions of 10.6 m in length, 6.9 m in width, and 6 m in height. The chamber has performance in a spherical quiet zone with a diameter of 1.5 m. The center of the quiet zone is positioned in the middle of the chamber height and width. The transmitting antenna is positioned 3 m above the ground on a fixed positioner at the transmit end wall side. The receiving antenna is positioned in the quiet zone at the same height as the transmitting antenna on a traversing mechanism with azimuth and roll positioner near the receive end wall. The chamber has a maximum transmission length of 6.75 m between the apertures of the antennas. This indoor far-field measurement system has an Agilent-make performance network analyzer (model # PNA E8362B) along with an automated positioner controller with an integrated personal computer unit. The instrumentation system is housed in a control room adjacent to the chamber. The chamber is equipped with a closed-circuit television (CCTV) facility to visualize the activity inside during antenna pattern measurement. A snapshot of the pattern measurement setup recorded by the CCTV arrangement housed in the indoor far-field measurement facility is shown in Fig. 8.

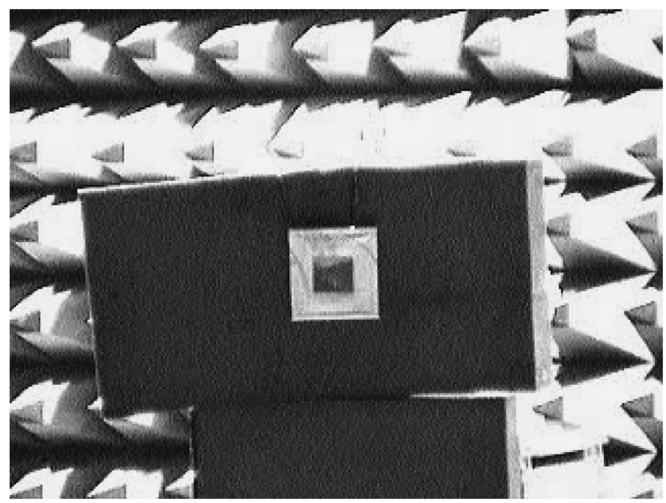

Fig. 8. Snapshot of the radiation pattern measurement setup inside an anechoic chamber (the test antenna is seen to be mounted at the receiving end of the measurement setup).

The simulated radiation patterns plotted at the simulated resonant frequency of 2.449 GHz for the jeans cotton antenna (antenna 1) are shown in Fig. 9. From the simulated results, it is observed that the jeans cotton textile antenna provides a gain of 5.91 dB and a 3-dB beamwidth of 79° in the $x-z$, azimuth, or E plane (phi $= 0°$). Its gain and beamwidth in the y–z, elevation, or H plane (phi $= 90°$) are 5.91 dB and 73°, respectively. The measured radiation patterns at 2.403 GHz in the azimuth and elevation planes are shown in Figs. 10 and 11, respectively. The values of 3-dB beamwidth in these principal planes are 59° and 67°. The measured discriminations between co- and cross-polar components in the azimuth and elevation planes along the on-axis (boresight) are 12.13 and 10.02 dB, respectively.

For polycot antenna (antenna 2) also, the simulated radiation patterns are obtained at its resonant frequency of 2.46 GHz. Using antenna 2, pattern measurements are done at the measured resonant frequency of 2.247 GHz. The measured discriminations between co- and cross-polar components in the azimuth and elevation planes are 7.33 and 11.64 dB, respectively.

Considering polyester antenna (antenna 3), the simulated and measured resonant frequencies are 2.449 and 2.456 GHz. From the radiation patterns obtained in the principal planes of antenna 3 at its measured resonant frequency of 2.456 GHz, it is observed that the measured discriminations between co- and cross-polar components in the azimuth and

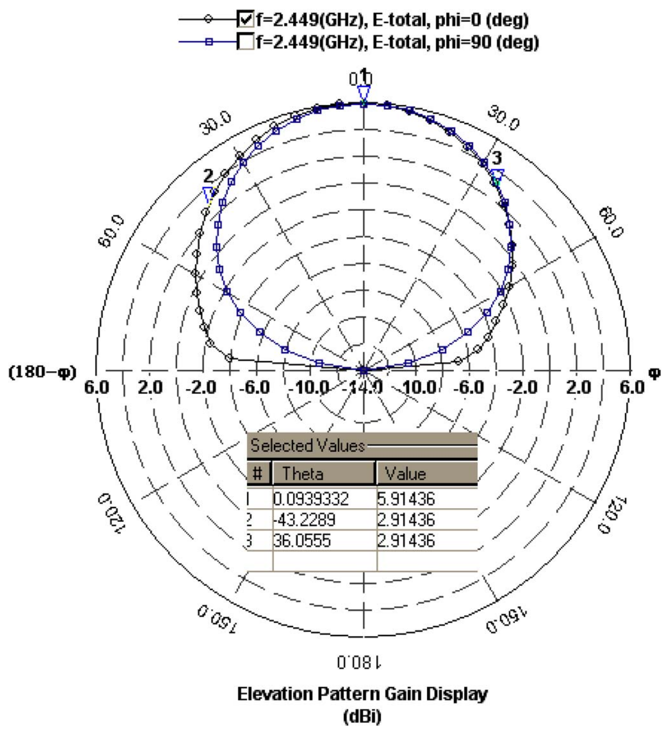

Fig. 9. Simulated total radiation pattern of a jeans cotton antenna.

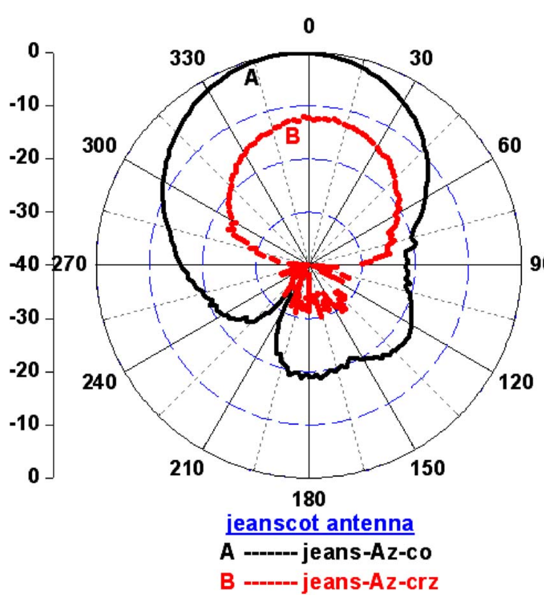

Fig. 10. Measured azimuth radiation pattern of a jeans cotton antenna.

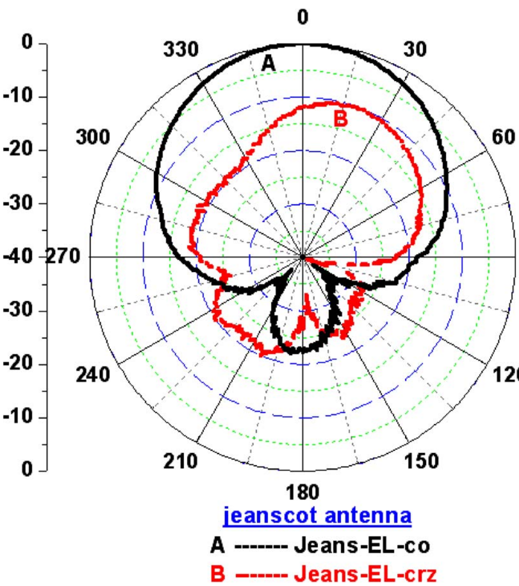

Fig. 11. Measured elevation radiation pattern of a jeans cotton antenna.

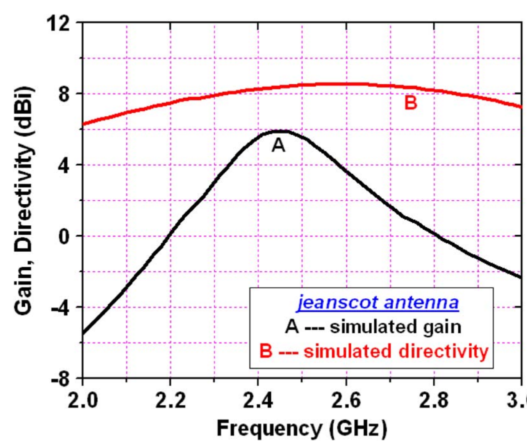

Fig. 12. Gain and directivity versus frequency of a jeans cotton antenna.

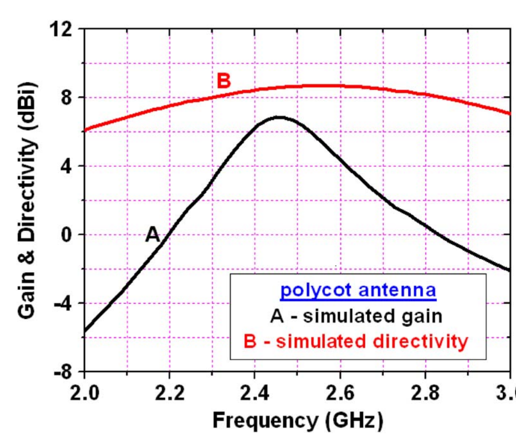

Fig. 13. Gain and directivity versus frequency of a polycot antenna.

elevation planes along the on-axis are 30.7 and 28.9 dB, respectively.

2) Gain and Efficiency: Simulations are done for a range of frequencies of 2.0–3.0 GHz for all three antennas. The variations of gain and directivity as functions of frequency, as obtained from these simulations for antennas 1 and 2, are shown in Figs. 12 and 13, respectively. At the center frequency of 2.45 GHz, the jeans cotton antenna's directivity and gain are 8.39 and 5.91 dBi, respectively. Therefore, the efficiency of the antenna works out to 70.48%. In the same fashion, at the center frequency of 2.45 GHz, the polycot antenna's directivity and gain are 8.55 and 6.84 dBi, respectively, yielding an efficiency of 80.0%. The variations of gain, directivity (simulated), and measured gain as functions of frequency are shown in Fig. 14 for the case of polyester antenna. At the design frequency, the directivity and gain of the antenna are 8.87 and 7.14 dBi, respectively, projecting a predicted efficiency of 80.56%. The gain is measured by the gain comparison method, and the

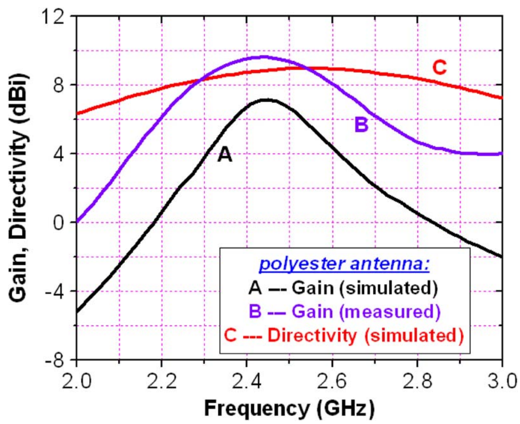

Fig. 14. Gain and directivity versus frequency of a polyester antenna.

polyester antenna measures a gain of 9.61 dBi at its design frequency.

3) Discussions: The simulated and measured values of gain and 3-dB beamwidth for all three antennas are listed in Table II. For all three antennas, the values of the measured gain are slightly higher than that of the simulated ones. This is because our aim is a conservative design of wearable antennas focusing only on the proper resonant frequency with a minimum acceptable gain. Moreover, the simulation process assumes an infinite ground plane, whereas we have a finite ground plane for practical measurements. The size of the ground plane also influences marginally the radiation characteristics of the antennas. The values of the cross-polarization ratio obtained in the principal planes of polyester antenna are the best compared to those with other two antennas. It is evident from the observed readings that antenna 3 gives the best performance characteristics among the three tested antennas, demonstrating the correctness of our approach.

VI. Conclusion

In this paper, a novel technique for the characterization of insulating fabric materials has been presented. The technique reported is one type of resonance method and utilizes the microstrip patch radiator concept. The salient feature of the microstrip antenna is its narrow bandwidth, and hence, even a small change in the value of the dielectric constant of the fabric substrate material produces a substantial shift in the resonant frequency of the antenna. The advantages of this method are as follows: 1) good accuracy; 2) simple sample preparation; and 3) fast measurement speed. Moreover, this is a nondestructive method. By performing this experiment, it is understood that the textile materials have generally low dielectric constant and are useful substrates for flexible antennas.

The following conclusions may be drawn from the extended part of this paper. The microstrip antenna is a suitable candidate for wearable applications, as it can be built using fabric substrate materials. In this paper, three antenna structures have been tested in order to get preliminary results on the performance of textile antennas. The antennas presented are very versatile, and it is easy to make them operate at various frequency bands. In addition, the well-known techniques [13] of improving bandwidth and obtaining different polarizations, adopted for microstrip patch antennas, are readily suitable for wearable antennas too. It may be concluded that these textile microstrip patch antennas may eventually replace patch antennas on standard printed circuit board substrates for various applications. The textile antennas must be drapable, as the fabrics can take diverse shapes because of human body movements. It is under consideration to study these bending effects on the performance characteristics of wearable antennas. The authors' research activity is also under way to use electrotextiles [14] instead of copper conductive parts in order to further facilitate antennas' integration into clothing.

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