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Study on the effect of bending on CNT's flexible antennas

V K Lamba[a*], D Engles[b], Sandeep Dhariwal[c] & Ajay Kumar[d]

[a]Global College of Engineering & Technology, Kahnpur Khui 140 117, India
[b]Guru Nanak Dev University, Amritsar 143 001, India
[c]Lovely Professional University, Jalandhar 144 411, India
[d]G J U University, Hissar 125 001, India

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With the development and an increasing interest in flexible electronics for different applications, a patch antenna has been designed and fabricated using carbon nano tube-polymer ink on fabrics. The antenna has been fabricated on cotton and songket fabric which have permittivity of $\varepsilon_r \approx 1.5$, and 1.6, respectively. The thickness of the fabric substrate has been varied to study the effect on antenna performance in a range of 1.5 mm to 2.2 mm. Measured and simulation results show that bandwidth depends on thickness and type of fabrics used.

Keywords: Antenna, CNT, Flexible electronics, Fabrics, Wetness, Bending

1 Introduction

In the advent of flexible[1-4] and organic electronics[5-8], a vast number of potential applications and other supporting systems has been emerged. These systems are of interest for monitoring the heart rate and blood pressure for medical diagnosis, security systems, detecting systems for child protection, hospital patient health management and for general network connections. These occurrences are possible with the advancement in communications systems and compact low power devices. A low power transmitter and an antenna designed specifically (flexible) are required to realize such system. Flexible antennas may be made from textiles[9-11] and attached on body or into clothing, or may be worn as a button antenna. More recently, antennas incorporating single frequency electromagnetic band gap materials (EBGs) integrated into the designs have been reported[12-15].

In the future, a person is likely to carry a range of devices and sensors. To address a few, there will be more comfortable solutions for cardiac diagnosis[15-17] real-time physiological measurement systems[16-18], military applications such as backpack radar[16-19], etc. Flexible electronics[20-22] also attracts industry because it provides a cheap and environmental safe solution to the rapidly evolving wireless world. A key technology to achieving this is flexible, wearable electronics and antennas. The antenna requirements are given by the particular specification, but common to all applications are light weight, inexpensive cost, zero maintenance, no set-up requirements, and no damage from obstacles. Here we present two fabricated antenna with carbon nanotube (CNT) and conductive polymer inks[10,22-26] instead of metallic conductors. We used cotton and songket fabric as a substrate as these fabric have low dielectric constant ($\varepsilon_r \approx 1.5$ for cotton and $\varepsilon_r \approx 1.6$ for songket), which improves impedance bandwidth of antenna and reduces spurious radiation loss in the substrate. In the present study, the effect of antenna bending on performance and characteristics of a flexible antenna has been investigated.

2 Materials

The fabrics used is cotton cloth consisting of 100% cotton materials with a smooth, firm surface, and the songket consisting of 50% cotton with 50% silk material having rough surfaces (specifications is given in Table 1), and CNT polymer conducting ink for printing patch antennas on the fabric.

For fabrication of ink we used sample that contains typically ca. 80% of single walled carbon nanotubes (SWCNT), together with 20% of multi-wall carbon nanotubes by weight. Initially we treated CNTs with a mixture of nitric and sulfuric acid (1: 3 molar ratio) for 1 h, to introduce carboxylic acid functionalities, to make tubes, more reactive, and water-soluble without altering the electronic properties significantly. We used poly-vinyl-pyrrolidone (PVP) as a polymer and

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*Corresponding author (E-mail: lamba_vj@hotmail.com)

Table 1 — Properties of the substrate textile materials

Substrate	Thickness [mm]	Material	ε_r	MR(%)	Density (g/m^2)	tan δ
Cotton cloth	2.2	Cotton 100%	1.5	6.5	480	0.020
Songket	1.5	Cotton 50%, silk 50 %	1.6	3.2	244	0.024

the sodium dodecyl-benzene sulfonate (SDBS), as a surfactant in ratio of 1.8:1.2. Common salt (1.2 mg) is added to increase the strength of these two species in water[24-27]. For formation of CNT ink we used 1 g of functionalities CNTs, 0.3 g of PVP and SDBS mixture, with 1.2 mg of salt mixed together in 80 mL of deionised water.

The components are mixed together with sonication in a bath sonicator for about thirty minutes, followed by centrifugation to separate undissolved SWCNT bundles and impurities. It is important to prevent nozzle clogging during the printing due the flocculation of long SWNTs in solution. A commercial Epson Artisan 50 piezoelectric printer with a resolution of 1440×1440 dots per inch (dpi) was used in this study. For printing, functionalized SWCNT inks were loaded into cleaned Epson T078120 (black) ink cartridges through a syringe and allowed to equilibrate for several minutes before printing was performed. Pattern designs were printed onto cloth fabrics. The printed film thickness was determined by topographical analysis of the films by using atomic force microscopy (AFM). The mass of SWCNTs deposited on each substrate was determined by weighing the substrates before and after printing process. We have measured the impedance of CNT ink after the water was evaporated, and we repeated the measurements after several hours, and then days with increase in no of ink coatings. The pattern we formed by the CNT ink deposited on fabrics were not dispersed and the impedance measurements were only slightly different from those which we got initially. We performed four-probe dc measurements, on inkjet-printed SWNT films with different film thicknesses as shown in Fig. 1. With each successive inkjet printing, the nanotube film thickness (*t*) increased, thereby increasing the conductivity from 54 S/m (*t* = 5 μm) to 720 S/m (*t* = 35 μm). The improved conductivity can be attributed to the better percolation of the deposited SWNTs which improves the number of electrical pathways. The impedance was measured with the impedance analyzer connected to a probe station, which has two sharp needles located at the margins of the CNT pattern. As the dimensions of the structure are much more than the length of the CNTs, so the measured current is due to the formation of a random network of conducting CNTs. The important properties of the CNT- polymer ink are that it is conductive when dried onto substrates (fabric, papers, etc.) relatively indelible, compatible with printing facilities, and the tubes stretches across cracks in ink, form ordered array as shown in Fig. 2.

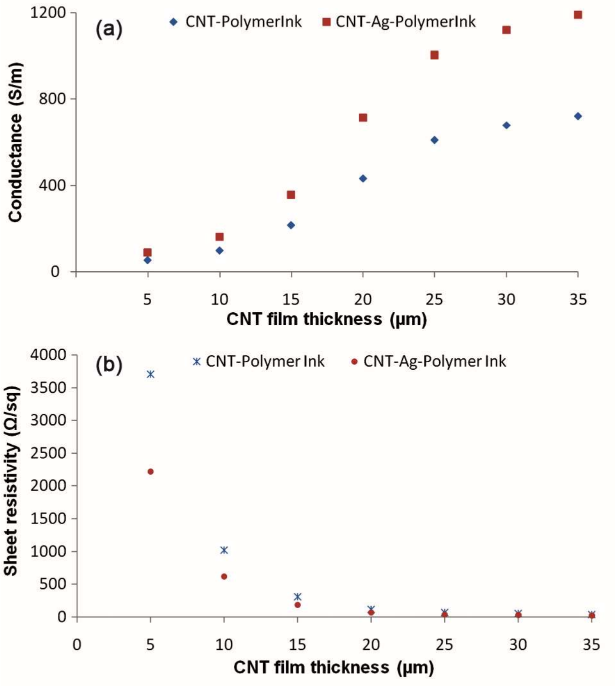

Fig. 1 — Variation of conductance and sheet resistance of printed SWNT films on cotton substrates as a function of film thickness

3 Design and Modelling

Design of conformable four patch array has been fabricated as shown in Fig. 3 on a cotton and songket fabric surface using CNT polymer ink as a highly conducting material. Antenna design has been carried out in the 2.2-3.2 GHz band. The antenna is made up from textile materials, where silvery-grey portion is

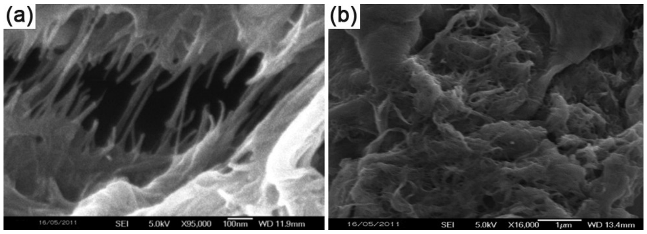

Fig. 2 — SEM image of SWCNT-polymer ink dried onto (a) Cotton, (b) songket fabric

highly conductive CNT polymer and rest is cotton/Songket fabric. We used a microstrip feed that not only guarantees a flat structure, but also allows the assembly of electronic components directly on the fabric in antenna proximity. Prior to the antenna design, we carried out systematic investigations regarding the electrical performance of the deployed materials, i.e., the multi layer textile substrate and the CNT ink. The thickness of the substrate was varied in a range of 1.5 mm to 2.2 mm for bandwidth and efficiency optimization.

The conducting ground plane and the antenna consist of a CNT-polymer composite, which is 0.43 mm thin and flexible.

The multi-layer substrate shown in Fig. 4 was modelled in order to ensure a well-defined substrate thickness and to keep the antenna conformal when it is bent. Micro-strip antenna dimensions were calculated using transmission line model. The Mstrip40 computational electromagnetic software package[30-35] was used to analyze the behaviour of the micro-strip antenna. To interconnect the antennas with the instruments, a silver paste is used for electrically contacts to 50 and 75 Ω microstrip feed line on both the side of fabric substrate. The program utilizes the method of moments technique[34,35] to compute the radiation pattern and impedance of the antenna. The conducting ground plane and the antenna consist of a CNT-polymer composite, which is 0.43 mm thin and flexible. It allows for changes in the dimensions of the antennas, the shape of the antenna and the feed, the dielectric properties of the substrate (losses can be included), and the conductivity of the conductors.

We have used three set of conductivity[31,32], i.e., 5.8×10^7 S/m (conductivity of copper), 720 S/m (conductivity of CNT-Polymer ink) and 1190 S/m (conductivity of CNT-Ag ink).

4 Results and Discussion

According to simulation, the changes in antenna's resonant length detune frequency band dependence on thickness of fabric. The thickness of the fabric has a great influence on the antenna bandwidth. Fabrics have nearly the same permittivity; therefore, the thickness generally determines the bandwidth. It is possible to design well-matched input impedance for all fabric substrates. As it can be seen from Fig. 5, the simulated bandwidths at 2.3 GHz are 1.92% for the cotton and 1.73% for the songket fabric respectively

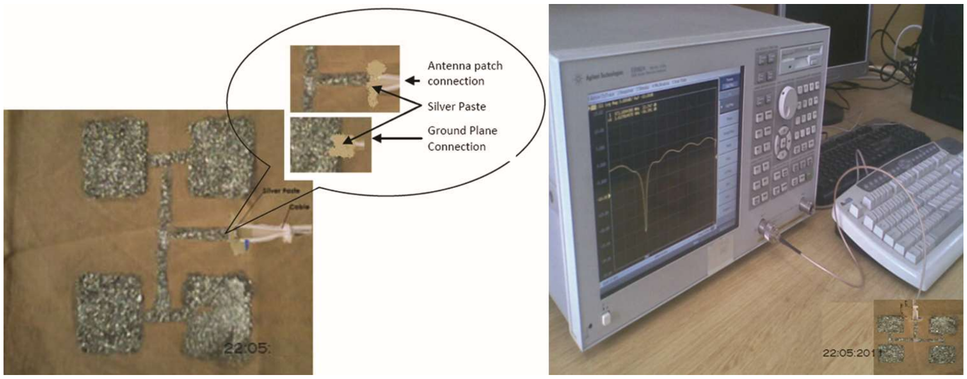

Fig. 3 — Patch antenna array printed on cotton fabric and experimental setup

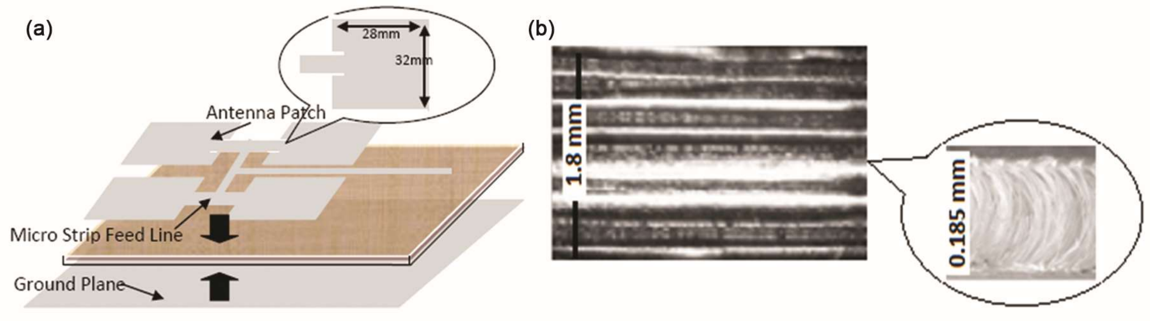

Fig. 4 — (a) Patch antenna with micro-strip feed-line and (b) cross section view of multilayer cotton fabric substrate

when CNT polymer ink is used while it is 2.35% for the cotton and 2.12% for the songket fabric for copper tape. It is because the copper tape was tightly attached to the surface of cotton fabrics, and did not detach due to the smooth and firm surface, while in case of songket, the copper tape did not fasten itself properly and stoutly. In case of CNT-polymer ink it sticks firmly tightly attached with both cotton and songket fabric and thus results in small change in antenna resonant frequency. The bandwidths of the antenna remain too narrow because of fabrics thickness. Simulation results show that thickness affects the bandwidth as predicted (Table 2). It is because the effective permittivity, ϵ_{eff} is given by[35]:

$$\epsilon_{\text{eff}} = \left[\frac{\epsilon_r+1}{2}\right] + \left[\frac{\epsilon_r-1}{2}\right]\left[1+\frac{12h}{w}\right]^{-1/2} \quad \dots (1)$$

where h is the height of the substrate. The patch length determines the resonant frequency and is a critical parameter in design because of the inherent narrow bandwidth of the patch.

The design value[29] for L is given by:

$$L = \left[c/\left(2f_r\sqrt{\epsilon_{\text{eff}}}\right)\right] - 2\Delta L \quad \dots (2)$$

where, ΔL is additional line length on either ends of the patch length, due to the effect of fringing fields, f_r is resonant frequency and c is the velocity of electromagnetic wave.

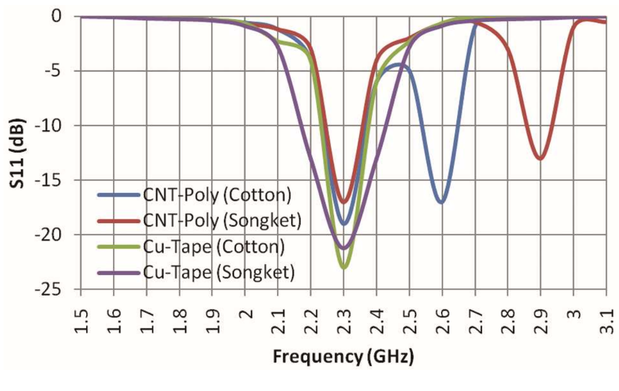

Fig. 5 — Simulation results of using different fabrics with CNT ink and copper tape and their return losses

The antenna with cotton substrate fabric had wider bandwidth. In addition, the distance between the radiating patch and the ground plane should remain constant in order to maintain antenna's electrical characteristics. In order to characterize the antennas a network analyzer was used to measure the input return loss of the antennas as a function of frequency. The simulated and measured return loss and voltage standing wave ratio (VSWR) response for cotton and songket fabric are shown in Figs 6 and 7, respectively. Both the antennas were measured under similar conditions. It can be seen from the graph that in case of cotton and songket substrate materials, the measured results agree very well with simulations and the target frequency 2.3 GHz is reasonably well met. The reason behind it is that the CNT-Polymer ink sticks well and tightly attached to the surface of both the fabrics. Further when we used different values of conductivity, we find that the radiation pattern in the E-plane and the H-plane did not show any significant differences for conductivity down to about 7.2×10^2 S/m (as shown in Fig. 8). At 720 S/m, there appears to be some differences in the radiation pattern, but these are not significant. The antenna impedance did vary significantly. At the high conductivities, the antenna impedance was mostly inductive. The effects of conductivity on the antenna efficiency and gain is also studied which have been shown in Fig. 9. As these parameters are very prone to be affected by losses in the antenna, the parts apart from conductors were chosen as lossless, but there are still very minor losses present due to dielectric layer.

However, as the conductivity is decreased the impedance became more resistive. It appears that the conduction losses increase significantly around 1000 S/m. All these results indicate the importance of proper fabric selection and conductive ink that sticks to the surface tightly. Therefore, the desired requirements for particular application need to be

Table 2 — Effect of substrate thickness on antenna performence

Substrate	Thickness (mm)	Effective permittivity ϵ_{eff}	Simulated			Measured		
			Frequency (GHz)	Return losses	Band width (MHz)	Frequency (GHz)	Return losses	Band width (MHz)
Cotton	1.5	1.45	2.3	-10.1	200	2	-10.2	248
	1.8	1.44	2.3	-20.3	170	2	-21.4	208
	2.2	1.43	2.3	-18.2	141	2	-19.8	170
Songket	1.5	1.54	2.3	-8.0	240	2	-8.2	268
	1.8	1.53	2.3	-12.3	203	2	-13.2	221
	2.2	1.52	2.3	-16.9	166	2	-18.1	174

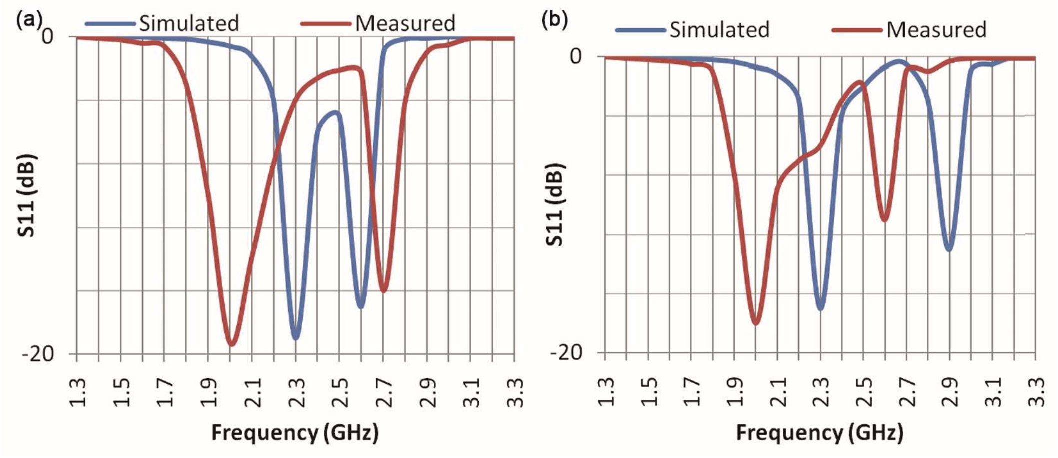

Fig. 6 — A comparison of simulated and measured return loss result for (a) cotton and (b) songket

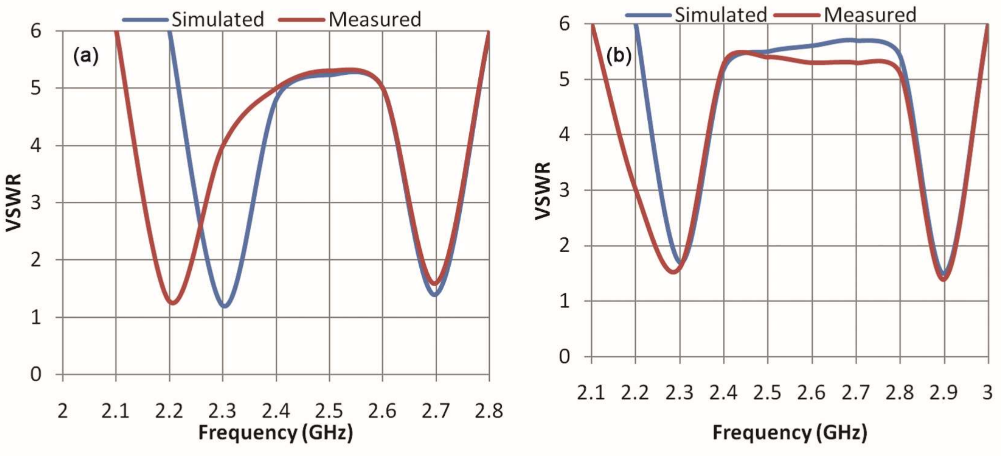

Fig. 7 — VSWR response for (a) cotton and (b) songket fabric

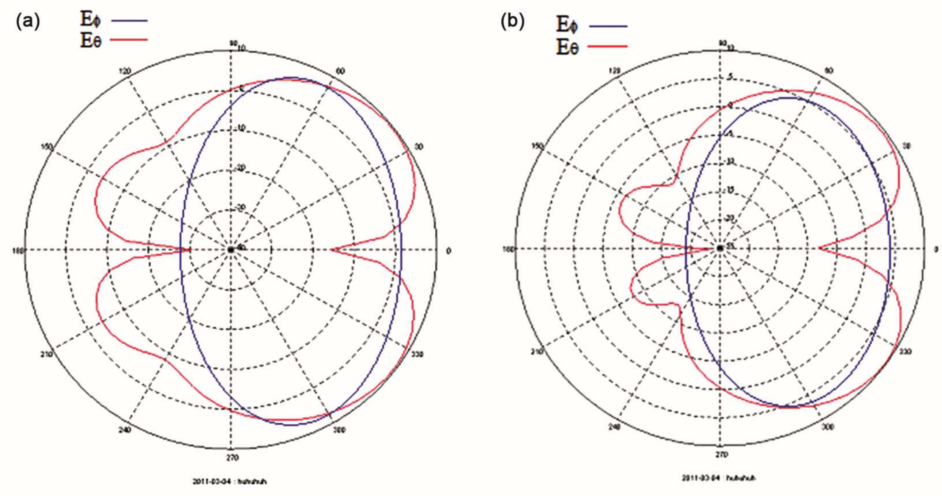

Fig. 8 – Antenna pattern for (a) $\sigma = 5.8\times10^7$ S/m and (b) $\sigma = 6.2\times10^2$ S/m

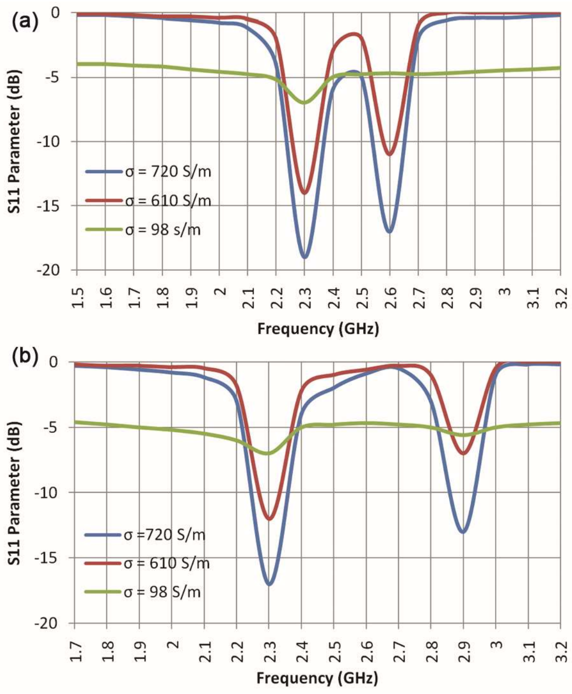

Fig. 9 — S_{11} parameters for loss conductors for three antennas for (a) cotton, and (b) songket substrate

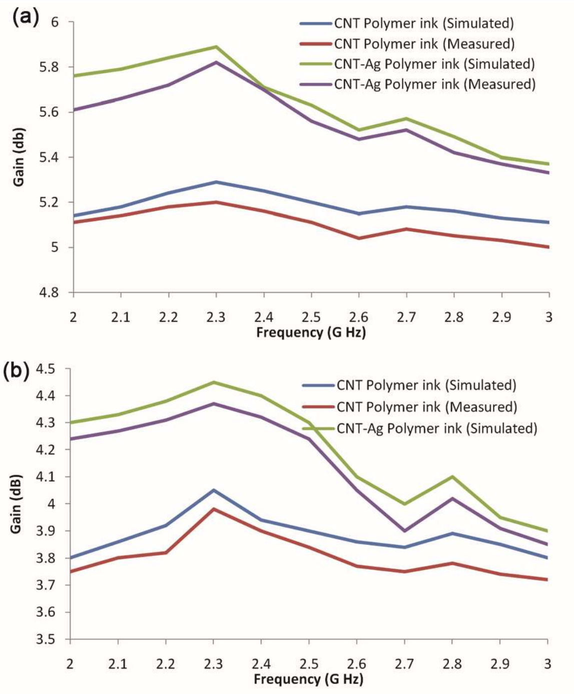

Fig. 10 — Gain versus frequency for (a) cotton and (b) songket substrate based antennas

Table 3 — Antenna gain and its efficiency at 2.3 GHz on different fabric substrate with different conductive inks

Fabric	Ink	Simulated gain (dB)	Measured gain (dB)	Simulated efficiency (%)	Measured efficiency (%)
Cotton	CNT-Polymer ink	5.29	5.20	81	78
	CNT-Ag-Polymer ink	5.89	5.82	83	81
Songket	CNT-Polymer ink	4.05	3.98	80	79
	CNT-Ag-Polymer ink	4.45	4.37	84	82

properly considered, and a suitable fabric need to be selected to meet these requirements. The current flow and the radiation characteristics of all fabric antennas were also studied. Both fabric antennas had similar features of the current flow and 3D far field radiation pattern simulated for the cotton and songket fabric antennas respectively. On the other hand, conductive materials affected the antenna gain, in the same way as the bandwidth is affected. Cotton and songket substrate fabrics had similar gain values. The results illustrated in Table 3 and Fig. 10, which indicates the importance of electronic properties of ink and proper fabric selection.

5 Conclusions

Future utilization of flexible electronics will necessitate applications of textile based antennas. In addition, well-known methods for patch antennas are readily applicable for fabric antennas, which help in fabricating and designing of better antennas. This paper has presented the development, manufacture, and measurement of antennas that are integrated into clothing. Two antenna designs were considered and the study focused on investigation of suitability of using different fabrics for wearable application. The results indicate the importance of proper fabric selection. Further because of, unique electronic property of CNT, it is a potential choice for metal less polymer-CNT nanocomposite antennas.

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