Indian Journal of Fibre & Textile Research
Vol. 47, September 2022, pp. 362-374
DOI: 10.56042/ijftr.v47i3.52329

Role of coating add-on and substrate material on microwave and EMI shielding properties of coated fabric

Krishna Kumar Gupta[a], Ganga Datt Dhyani, Rakesh Kumar Yadav & Thako Hari Goswami
Defence Materials and Stores Research and Development Establishment Kanpur 208 013, India

Received 11 July 2021; revised received and accepted 5 January 2022

Role of coating add-on and nature of textile substrate have been studied on microwave and EMI shielding properties of coated cotton fabric. Coated fabric samples have been prepared with coating formulations containing carbon black and milled carbon fibre in polyurethane matrix, using cotton (non-conducting) and conducting fabric (warp: SS20%/PET80%, weft: SS 55% / PET 45%) substrate simultaneously. A high precision lab coating machine (Mathis Lab Coater, UK) has been used to produce coated fabric of uniform thickness (0.31- 0.67 mm). Coated fabrics are studied for microwave and EMI shielding properties in 8.2-18.0 GHz (X & Ku) frequency band in vertical and horizontal polarisation of electromagnetic wave. The microwave properties of coated fabric based on cotton substrate are found due to coating add-on only, as the cotton itself does not have any role to play. Cotton - based coated fabric with add-on of 257.7% exhibits 32-43% reflection, 22-39% transmission, 37-42% absorption and EMI shielding of 5.23-7.93 dB in 8.2- 18.0 GHz. On the other hand, microwave properties of coated fabric prepared on conducting substrates are found to produce synergetic effect of substrate material and coating add-on. Coated fabric on conducting substrate with add-on of 185.5% displays 92-82% reflection, 0.17-0.36% transmission, 7.20 - 26.310% absorption and EMI shielding of 23.98- 21.64 dB. Apart from this, coated fabrics are also prepared with gradual increase of coating add-on in order to understand the effect of ultimate coating add-on loading and to obtain optimum threshold combined effect of coating add-on and substrate materials. Sample with coating add-on of 237.9% acquires high surface conductivity (σ = 46.34 S/m) and low surface resistivity (34.25 Ω/□). Coated fabric offers 93.47-79.47% reflection, 6.39-22.07% absorption, <0.2% transmission, and EMI shielding of 28.86- 26.68 dB.

Keywords: Conducting fabric, Coated fabric, Cotton fabric, EMI shielding effectiveness, Microwave properties, Scattering parameters

1 Introduction

The extensive use of electrical and electronic appliances in the fields of defence, commerce, medical, industry, transmission and broadcasting, the useful spectrum of electromagnetic wave (em wave) has widened. These devices are emitting electromagnetic waves of high power, resulting into serious electromagnetic interference (EMI) in the operation of other electronic equipments in their vicinity[1,2] . Radar and microwave tower operators and service persons are vulnerable to high risk. Em wave adversely affects the human body by stopping regeneration of the DNA and RNA cells that cause fatal diseases, like cancer, disturbance in immune system, cellular damage and tissue repair reduction (refs 3-5). EMI shielding is a way to protect and control such unwanted electromagnetic radiations. Conducting polymer nano composites based on carbon nanotubes, carbon black, graphene, metal nano particles, carbon fibres, and magnetic nano particles have shown good shielding capacity. Polyaniline and polypyrrole conducting polymers are frequently used for making conductive textiles. Polyaniline containing 10 wt% offers electrical conductivity of 13.82 $\times 10^{-6}$ S/cm (refs 6-8). Electrically conductive nano composite fibres prepared with polyaniline, polyacrylonitrile and multi-walled carbon nano tubes with conductivity of 1.79 - 7.97 S/m offered reflection loss from -4.6 dB to -5.9 dB in 3.4 - 18.0 GHz (ref. 9).

Cotton fabric, carbon fabric and cotton–carbon fabric composite plates have provided better em performance in terms of reflection, transmission and absorption in frequency range of 3-18 GHz (ref. 10). Cotton fabric prepared by impregnation of polypyrrole displayed highest conductivity (~3.92 X 10^{-1} S/cm) and EMI shielding (−26 dB) (refs 11, 12). Cotton fabric coated with MWCNTs dispersed in perfluoro sulfonated polymer exhibited electromagnetic interference shielding of 9.0 dB

[a] Corresponding author.
E-mail: krishna62@rediffmail.com

(ref. 13). Rader absorbing structure materials based on MWCNT in 3 mm thickness offered reflection loss of −32 dB and −35 dB at frequencies of 10.6 GHz and 11.0 GHz respectively. Three-layered reinforced radar-absorbing structures on glass/epoxy composites containing polyaniline coated modified multi-walled carbon nanotubes in a thickness of 4 mm exhibited a reflection loss of –5 dB over the entire X-band and a reflection peak of –24.53 dB at 10.0 GHz (refs 14, 15). Multilayered coated fabric comprising of nickel-cobalt-ferrum-phosphorus/ polyaniline /polyimide (Ni-Co-Fe-P/PANI/PI) displayed electromagnetic shielding effectiveness of 40.5– 69.4 dB at X-band frequency range (ref. 16). Composite woven fabric in 1-4 layers prepared by cotton yarn, stainless steel/cotton complex yarn, and bamboo charcoal/ cotton complex yarn offered electromagnetic shielding of -11.87 dB at frequency of 900 MHz with a surface resistivity of 8×10^{-6} Ω/□ (ref. 17).

Electromagnetic shielding effectiveness of polyester fabric prepared by carbon black and graphite particles offered EMSE of 14.30 dB at 15 MHz for fabric printed with 40 % binder and 12.36 dB at frequency of 2190 and 2205 MHz for fabric printed with 10% binder concentration[10]. Vitalija *et al.*[18] prepared conductive textiles formulations by coating of conjugated polymer poly (3,4-ethylenedioxy thiophene)-polystyrene sulfonate (PEDOT-PSS), carbon black on polyester/cotton plain weave woven fabrics, and woven fabric by using PES/SS (80 : 20) blended yarn. PEDOT-PSS based coated fabric (229 gsm), with add-on of 6.3-7% offered shielding of 5-15 dB; carbon black based coated fabric (238 gsm) with add-on of 10-10.7% offered 5-10 dB; and PES/ SS metallised woven fabric (155 gsm) offered 7-35 dB in 2-10 GHz & 0-7 dB at 10-20 GHz. Cotton fabric (190 gsm), treated with poly(sodium 4-styrenesulfonate) and chitosan doped with graphene, acquire conductivity of 1.67×10^3 S/m and EMI shielding of 25-30 dB in 30 MHz -6 GHz (ref. 19).

Nonwoven composite fabric prepared by coating of nano particles of $BaFe_{12}O_{19}$/ multi-walled carbon nanotubes in silicon matrix, showed reflection loss of -7 dB at 9.5 GHz, absorption of -38.45 dB at 10.5 GHz at 1.5 mm thickness with bandwidth of 2.6 GHz in X and Ku- band[20]. Electromagnetic shielding effectiveness of needle-punched nonwoven fabric produced from silver-coated staple polyamide fibre (1.7 dtex) offered shielding of 36.53 dB in the frequency 15–3000 MHz (ref. 21). Fabric made of spun yarn containing cotton and steel fibres of diameter 6 -10 µm with warp and weft yarn density of 18 × 20 threads/cm, and yarn count of 38 - 40 tex, showed shielding of 20 to 40 dB at 10 GHz (ref. 22). Conducting woven fabric made of polysufonamide/ stainless steel core yarn in weft and PSA yarn in warp offered EMSE above 40 dB i.e., shielding of above 99.99 % against the incident waves at 2-3 GHz (ref. 23). Woven fabric prepared with stainless steel wire has exhibited 25-65 dB electromagnetic shielding effectiveness in horizontal and vertical polarization of em wave in the frequency range of 30 MHz - 9.93 GHz (refs 24, 25).

Work reported so far on microwave protection and EMI shielding is based on thick, heavy and multilayered structure that too is aimed for narrow frequency band of microwave. Microwave properties in single layer of fabric in wide frequency band of 8-18 GHz have not been reported so far. To overcome this, present work is focussed on the study of conductive coating formulations on conducting substrate to see the effect of substrate material and extent of coating- add on microwave and EMI shielding properties. This work includes preparation of coated fabric on cotton and inherent conducting fabric [warp: SS/PET (20:80), weft: SS/PET (55: 45)] using coating formulations containing carbon black and milled carbon fibre in PU matrix. Cumulative effect of coating add-on and nature of substrate materials on microwave properties is studied.

2 Materials and Methods

2.1 Materials

- **Basic Cotton Fabric**– It is non conductive light weight plain weave cotton fabric (gsm-60, EPI-68, PPI-51, thickness- 0.26 mm, warp-105 denier and weft-120 denier).
- **Basic Conducting Fabric** – It is light weight plain weave woven fabric having EPI-24, PPI-25, weight - 80 gsm and thickness- 0.27 mm. Fabric is prepared using following warp and weft:

Warp – SS20%/PET80% (w/w) blended yarn, 165 denier (linear resistance 8.52 KΩ/m) and polyester filament yarn 165 denier in alternate order.

Weft – SS 55% / PET 45% (w/w) blended yarn, 375 denier, and linear resistance of 750 Ω/m. Surface resistivity of fabric was 5.60 Ω/□. Visual image of basic fabrics is shown in Fig. 1.

- **Stainless Steel (SS) Fibre Configuration** – Staple length 55 mm, diameter 8 µm, denier 8.0, and tenacity 1.4 gpd. SEM image of SS fibre at k × 1.56 is shown in Fig. 2(a).

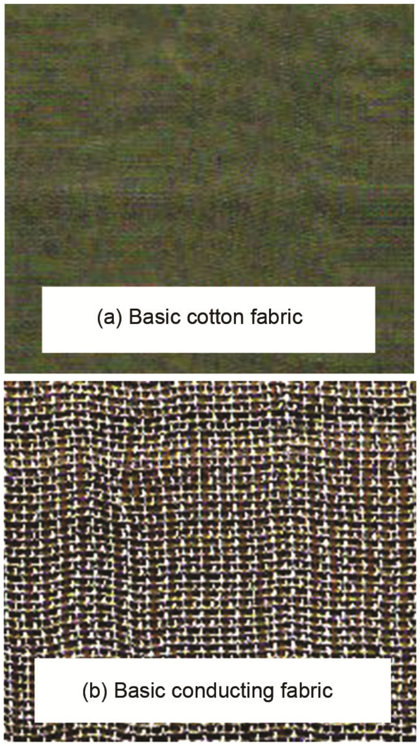

Fig. 1 — Visual image of (a) basic non- conducting cotton fabric and (b) basic conducting fabric

- **Carbon Black (Acetylene Black)** – Commercial grade carbon black[26], particle size 125-150 nm, bulk density 0.05-0.09 g/cc and electrical resistivity 0.25 ohm.cm, 50% compressed grade, procured from Sun Petrochemical, Mumbai and used as received. SEM micrograph of carbon black is shown in Fig. 2(b).
- **Milled Carbon Fibre** – Average fibre length 100 µm, mean fibre length 150 µm, diameter 7.0-7.2 µm, density 1.81 g/cm^3,bulk density 490 g/L, carbon content 95%, electrical resistivity 0.0016 Ω. cm, procured from Zoltek PX35 Milled Fibres and used as received[27]. SEM micrograph of milled carbon fibre is shown in Fig. 2(c).
- **Polyurethane Granular** – Aliphatic **e**mulsion grade polyurethane in bead form [Fig. 2(d)] used as a matrix for preparation of coating formulation. It is soluble in MEK.

2.2 Micrographs of SS Fibre, Carbon Black, and Milled Carbon Fibre

Micrographs of SS fibre, carbon black and milled carbon fibre were carried out using SEM equipment (Model No. EVO 50, CARL ZEISS, Low Vacuum

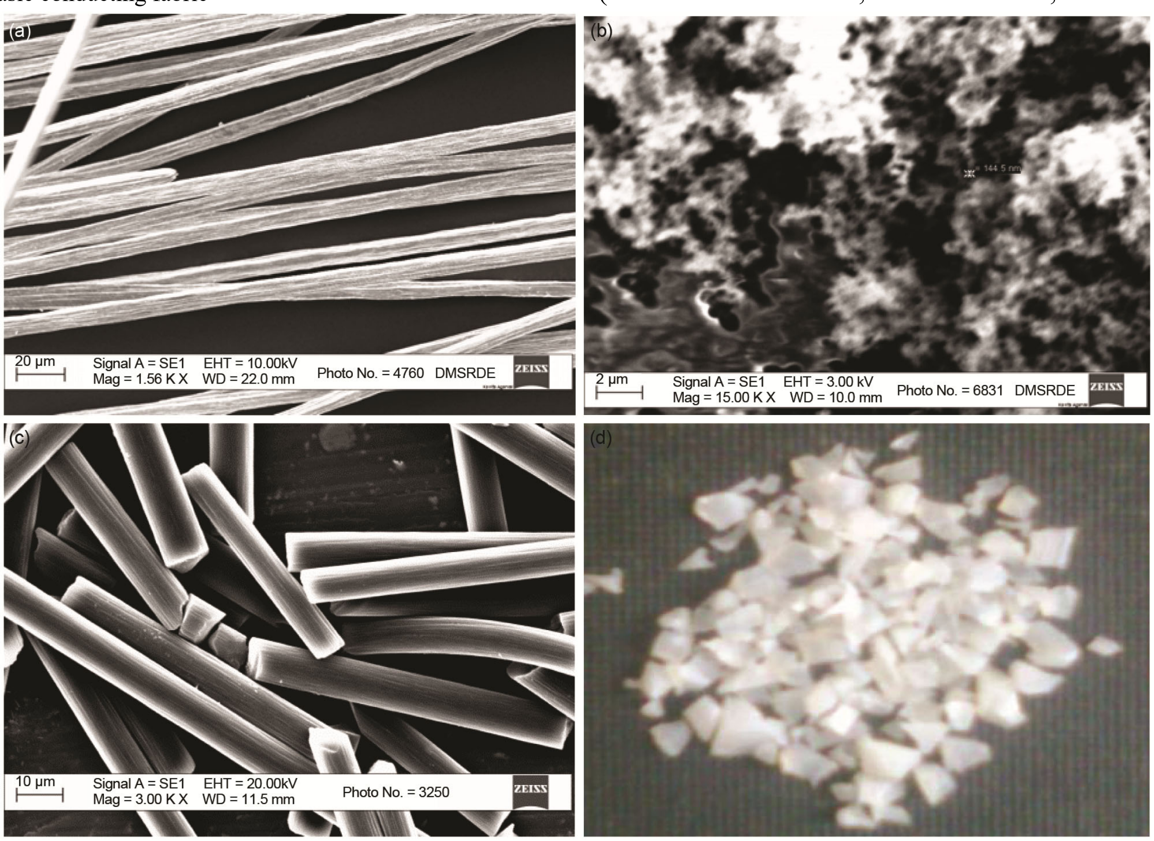

Fig. 2 — SEM micrographs (a) stainless steel fibre k × 1.56, (b) carbon black k × 15.0, (c) milled carbon fibre k × 3.0 and (d) PU chips/ grains

SEM). SEM image of carbon black at the magnification of k × 15.0 is shown in Fig. 2(b) and SEM micrograph of milled carbon fibre at the magnification of k × 3.0 is shown in Fig. 2(c).

2.3 Methods

2.3.1 Coating Formulation Scheme

Samples of coated fabric were prepared as per coating formulation given in Table 1. Experiments were performed in three sets, viz. Group A, Group B, and Group C. In each set, four samples are prepared. Four samples of coated fabric (NWF_1 to NWF_4) are prepared on cotton substrate and four samples (CWF_5 to CWF_8) on conducting fabric simultaneously with the same coating formulations. In Group A (NWF_1 to NWF_4), coating formulations based on carbon black and milled carbon fibre in PU were applied on basic cotton fabric (NWF, non conducting woven fabric). Simultaneously, in Group B (CWF_5 to CWF_8), same coating formulations were applied on conducting woven fabric (CWF, conducting fabric). Role of coating add-on and substrate material on microwave and EMI shielding properties was studied. Further, in Group C, four samples (CWF_9 to CWF_12) were prepared with increasing add -on content on conducting substrate to study combined effect of add- on and substrate materials on microwave properties.

2.3.2 Preparation of Coated Fabric Samples

Polyurethane solution of 20-30% was prepared in MEK. Carbon black and milled carbon fibre were wetted separately in MEK. One by one it was poured into freshly prepared PU solution under constant magnetic stirring for 30 min (600 rpm, at 40^0C) followed by sonication for 2 h (40 kHz, 40^0C) so that milled carbon fibre and carbon black are uniformly dispersed in PU solution. Viscosity of coating solution was kept in range of 1-10 Pa.s. Coating was carried out on both sides of fabric using Mathis Lab Coater, having mechanized knife-over roller coating head, and equipped with doctor blade and heating arrangements. In this process, the fabric was mounted in a coating tray/ frame with pre-tension of 4 - 5 kg. The coating was carried out with knife speed of 2.5 - 5.0 mts/ min., curing time of 5 min at 120^0C, fan speed of 1500 rpm followed by drying at 60- 80°C for 60- 90 min to evaporate the solvent.

Table 1 — Coating formulation scheme

Sample	Carbon black g	Carbon milled fibre, g	Polyura-thane, g	MEK mL
Group A (Cotton fabric)				
NWF_1	1	1	20	100
NWF_2	1	2	20	100
NWF_3	1	3	20	100
NWF_4	1	4	20	100
Group B (Conducting substrate)				
CWF_5	1	1	20	100
CWF_6	1	2	20	100
CWF_7	1	3	20	100
CWF_8	1	4	20	100
Group C (Conducting substrate with increasing add- on)				
CWF_9	1	2	30	300
CWF_10	2	4	30	300
CWF_11	3	6	30	300
CWF_12	4	8	30	300

MEK _ methyl ethyl ketone.

2.4 Physical Evaluation and Characterisation

2.4.1 Measurement of Physical Properties

The coated fabric samples were evaluated for various physical parameters, i.e. mass, add-on content, thickness and other physical parameters which are shown in Table 2. Coating add- on is the amount of coating mass deposited on the surface of fabric.

2.4.2 Evaluation of Surface Resistivity and Conductivity

Surface resistivity of coated fabrics was measured by using a Concentric Ring Probe Technique. Surface conductivity was calculated using surface resistivity and thickness of samples[28]. Specific resistance (resistivity) is given as $\rho = R\ A\ /L$, where R is the resistance of sample of thickness t, A is the cross - sectional area, and L is the length of sample. Here, thickness is considered very small as compared to other dimension. Conductivity is the reciprocal of resistivity, i.e. $\sigma = 1/\rho = L/R\ A$. For square sample, length and width are equal, $A = L \times L$. If thickness is t, conductivity (σ) $=1/\ (R \times t)$; using this relationship, conductivity was calculated. Linear resistance was also measured by digital multi meter DT830D at a probe distance of 15.0 cm. Surface resistivity, conductivity, and linear resistance are given in Table 3.

2.4.3 Measurement of Microwave Properties

Coated fabrics were evaluated for microwave properties in parallel and perpendicular mode. In parallel mode, E- field is parallel to conducting element embedded in the fabric and in perpendicular mode, E- field lies in perpendicular to conducting element in the

Table 2 — Mass, add-on content and thickness of coated fabric

Sample No.	Coated fabric mass, g (10cm×10cm)	Add-on, g (10cm×10cm)	Add-on %	Carbon content wt %	Milled carbon fibre content, wt %	Polyurethane content, wt %	Thickness mm (200g/cm^2)
NWF_1	1.380	0.780	130.0	4.53	4.53	90.90	0.31
NWF_2	1.633	1.033	172.2	4.34	8.69	86.93	0.34
NWF_3	1.821	1.221	203.5	4.16	12.49	83.34	0.34
NWF_4	2.145	1.545	257.5	3.99	15.98	79.97	0.35
CWF_5	2.257	1.457	182.1	4.52	4.52	90.90	0.61
CWF_6	2.158	1.358	169.8	4.34	8.69	86.95	0.60
CWF_7	2.387	1.587	198.4	4.16	12.49	83.32	0.62
CWF_8	2.284	1.484	185.5	3.99	15.99	79.99	0.58
CWF_9	1.480	0.679	84.9	2.94	6.03	91.01	0.48
CWF_10	1.776	0.976	122.0	5.55	11.10	83.34	0.52
CWF_11	2.809	2.009	251.1	7.66	15.38	76.89	0.67
CWF_12	2.703	1.903	237.9	9.51	19.02	71.41	0.63

Table 3 — Surface resistivity, conductivity and linear resistance of coated fabrics

Sample marked	Surface resistivity	Surface conductivity (σ), S/m	Linear resistance of coated fabric	
			Warp direction	Weft direction
NWF_1	5.33 kΩ/□	0.605	115.0 kΩ	156.0 kΩ
NWF_2	4.46 kΩ/□	0.658	62.3 kΩ	89.9 kΩ
NWF_3	3.56 kΩ/□	0.825	59.9 kΩ	29.0 kΩ
NWF_4	781.0 Ω/□	3.658	4.6 kΩ	4.8 kΩ
CWF_5	2.24 kΩ/□	1.074	22.0 kΩ	63.0 kΩ
CWF_6	90.65 Ω/□	18.38	0.96 kΩ	2.20 kΩ
CWF_7	86.95 Ω/□	18.54	1.27 kΩ	1.68 kΩ
CWF_8	56.45 Ω/□	30.54	0.75 kΩ	1.12 kΩ
CWF_9	1.04 kΩ/□	1.993	26.0 kΩ	29.0 kΩ
CWF_10	189.70 Ω/□	10.13	2.5 kΩ	2.5 kΩ
CWF_11	142.75 Ω/□	10.45	378.0 Ω	602.0 Ω
CWF_12	34.25 Ω/□	46.34	225.0 Ω	299.0 Ω

fabric. Electromagnetic wave propagates perpendicular to both E-field and conducting element. Microwave properties were measured in terms of scattering parameters, i.e., S_{11} and S_{21} by HVS Free Space Microwave Measurement System. It consists of transmit and receive dielectric horn lens antennas, and Vector Network Analyzer (Agilent, E8364B). The study was carried out in frequency range of X & Ku-band (8.2-18.0 GHz) in vertical and horizontal polarization of electromagnetic waves. The measurement of X-band and Ku-band was done in separate set –up (horn antennas). Hence, continuation in the graphs has broken in some of the samples at juncture points of X & Ku-bands (Figs 3 & 4). Plane polarized wave is emitted from transmit antenna, E-field being in vertical direction, H- field in horizontal direction and em wave propagates in perpendicular to both[29]. In this method, S_{11} and S_{21} scattering parameters of a planar fabric samples were measured for normal incident of plane em wave in frequency of 8.2- 18.0 GHz. These are shown in Table 4. Reflection, transmission and absorption/ scattering were worked out using following relationships with the help of S_{11} and S_{21} scattering parameters:

$$\% \text{ Reflection} = 10^{-S_{11}/10} \times 100 \quad ...(1)$$

$$\% \text{ Transmission} = 10^{-S_{21}/10} \times 100 \quad ...(2)$$

$$\% \text{ Absorption/Scattering} = 100 - (\% \text{ Reflection} + \% \text{ Transmission}) \quad ...(3)$$

Here, parallel mode refers to the state when warp is parallel to E-field of microwave and perpendicular mode denotes when warp is perpendicular to E- field and weft becomes parallel to E- field. Scattering parameters S_{21} when measured in dB, itself represents the EMI shielding effectiveness. The scattering parameters shown in the Table 4 are given in range from 8.2 GHz to 12.4 GHz in X-band and from 12.0 GHz to 18.0 GHz in Ku-band. Reflection, transmission, and absorption/ scattering are illustrated through Figs 3 & 4.

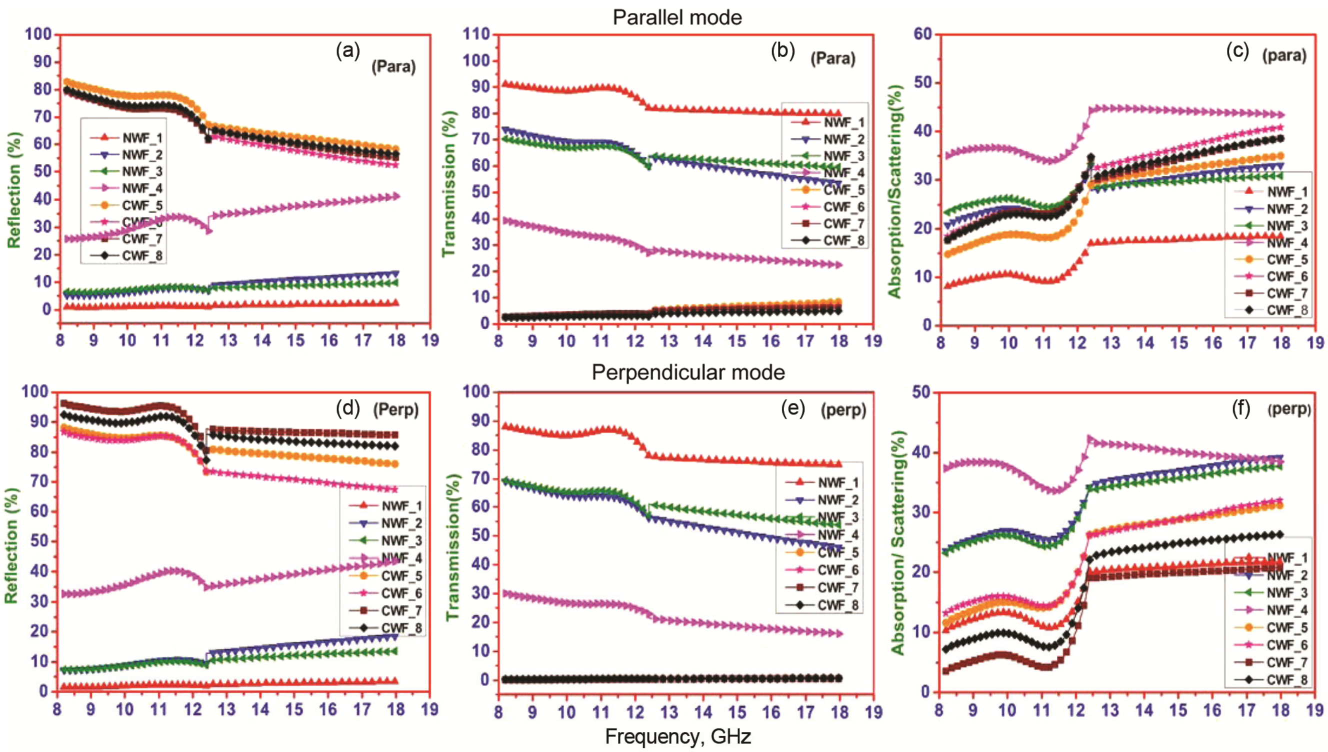

Fig. 3 — Reflection, transmission, absorption/ scattering of cotton substrate samples (NWF_1 to NWF_4), and conducting substrate samples (CWF_5 to CWF_8) in frequency 8.2 - 18.0 GHz in parallel and perpendicular modes

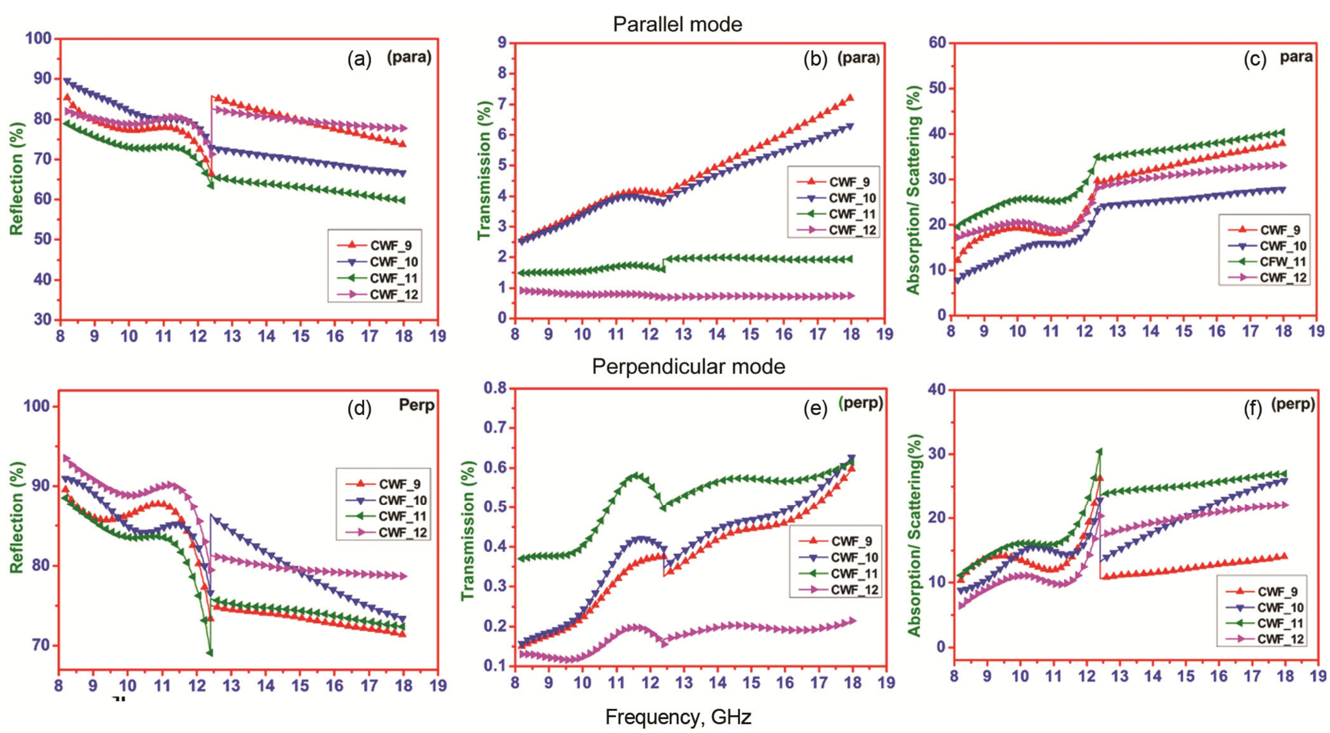

Fig. 4 — Reflection, transmission, absorption/ scattering of conducting substrate samples (CWF_9 to CWF_12) in frequency 8.2 - 18.0 GHz in parallel and perpendicular modes

Table 4 — Scattering parameters (in dB) of coated fabrics in X-bands and Ku bands

Sample	Parallel mode		Perpendicular mode	
	S_{11}	S_{21}	S_{11}	S_{21}
X- Band (8.2-12.4 GHz)				
NWF_1	(-20.66)- (-20.22)	(-0.40)- (-0.85)	(-18.00)- (-17.25)	(-0.55)- (-1.08)
NWF_2	(-12.86)- (-11.58)	(-1.30)- (-2.22)	(-11.33)- (-10.27)	(-1.60)- (-2.49)
NWF_3	(-11.99)- (-11.60)	(-1.52)- (-2.23)	(-11.33)- (-10.49)	(-1.58)- (-2.44)
NWF_4	(-5.90)- (-5.42)	(-4.04)- (-5.67)	(-4.86)- (-4.58)	(-5.23)- (-6.40)
CWF_5	(-0.81)- (-1.73)	(-15.99)- (-14.13)	(-0.54)- (-1.34)	(-27.38)- (-23.42)
CWF_6	(-1.02)- (-2.08)	(-15.88)- (-14.32)	(-0.62)- (-1.33)	(-27.34)- (-25.59)
CWF_7	(-0.98)- (-2.09)	(-15.73)- (-14.21)	(-0.16)- (-0.93)	(-27.66)- (-24.31)
CWF_8	(-0.97)- (-2.05)	(-16.21)- (-15.31)	(-0.33)- (-1.11)	(-25.63)- (-23.59)
CWF_9	(-0.69)- (-1.78)	(-15.92)- (-13.92)	(-0.48)- (-1.34)	(-28.24)- (-24.25)
CWF_10	(-0.47)- (-1.36)	(-15.97)- (-14.19)	(-0.40)- (-1.15)	(-28.00)- (-24.01)
CWF_11	(-1.02)- (-1.97)	(-18.31)- (-17.97)	(-0.53)- (-1.60)	(-24.32)- (-23.03)
CWF_12	(-0.29)- (-0.99)	(-20.40)- (-21.64)	(-0.86)- (-1.47)	(-28.86)- (-28.08)
Conducting substrate	(-1.26)- (-2.04)	(-16.38)- (-14.18)	(-0.73)- (-2.84)	(-27.65)- (-23.83)
Cotton substrate	(-34.29)- (-33.12)	(-0.02)- (-0.12)	(-36.67)- (-36.43)	(-0.01)- (-0.11)
Ku- Band (12.0-18.0 GHz)				
NWF_1	(-18.44)- (-16.56)	(-0.57)- (-0.68)	(-16.31)- (-14.64)	(-0.77)- (-0.92)
NWF_2	(-10.57)- (-8.73)	(-1.97)- (-2.71)	(-8.92)- (-7.28)	(-2.47)- (-3.36)
NWF_3	(-11.03)- (-10.14)	(-1.94)- (-2.25)	(-9.85)- (-8.69)	(-2.14)- (-2.69)
NWF_4	(-4.69)- (-3.85)	(-5.46)- (-6.48)	(-3.77)- (-2.96)	(-6.67)- (-7.93)
CWF_5	(-1.33)- (-1.89)	(-12.80)- (-10.76)	(-0.89)- (-1.19)	(-23.68)- (-21.15)
CWF_6	(-1.98)- (-2.81)	(-13.27)- (-11.63)	(-0.93)- (-1.28)	(-24.76)- (-22.59)
CWF_7	(-1.83)- (-2.58)	(-13.19)- (-12.01)	(-0.56)- (-0.67)	(-24.77)- (-22.64)
CWF_8	(-1.81)- (-2.48)	(-14.12)- (-13.05)	(-0.65)- (-0.86)	(-23.32)- (-21.64)
CWF_9	(-0.66)- (-1.33)	(-12.71)- (-10.70)	(-0.04)- (-0.20)	(-24.86)- (-22.21)
CWF_10	(-3.09)- (-3.70)	(-12.96)- (-11.24)	(-0.63)- (-1.34)	(-24.60)- (-22.00)
CWF_11	(-1.81)- (-2.23)	(-17.12)- (-17.13)	(-1.19)- (-1.40)	(-22.98)- (-22.11)
CWF_12	(-0.89)- (-1.04)	(-21.14)- (-21.87)	(-0.82)- (-1.09)	(-27.74)- (-26.68)
Conducting substrate	(-1.41)- (-2.27)	(-12.78)- (-10.42)	(-2.92)- (-5.30)	(-23.98)- (-21.89)
Cotton substrate	(-36.41)- (-36.11)	(-0.08)- (-0.09)	(-38.87)- (-39.88)	(-0.07)- (-0.08)

3 Results and Discussion

3.1 Physical Properties of Coated Fabrics

The coated fabrics were evaluated for physical properties, viz. mass, add-on content, and thickness. For Group A samples (NWF_1 to NWF_4), mass lies in the range of 138.0-214.5 gsm, add on increases from 78.0 gsm to 154.5 gsm, carbon content from 4.53% to 3.99%, milled carbon fibre content from 4.53% to 15.98%, and thickness from 0.31 mm to 0.35 mm. For Group B samples (CWF_5 to CWF_8), mass lies in the range of 225.7-228.4 gsm, add-on increases from 145.7 gsm to 148.4 gsm, carbon content from 4.52% to 3.99%, milled carbon fibre content from 4.52% to 15.99%, and thickness from 0.58 mm- 0.62 mm. For Group C samples (CWF_9 to CWF_12), mass lies in the range of 148.0-270.3 gsm, add-on increases from 67.9 gsm to 190.3 gsm, carbon content from 2.94% to 9.51%, milled carbon fibre content from 6.03% to 19.02% and thickness from 0.48 mm to 0.67 mm. In Group A & B samples, same coating formulations are applied, and it is found that on cotton substrate add- on has increased significantly from 78.0 gsm to 154.5 gsm while on conducting substrate the add-on remains almost constant at 145.7-148.4 gsm. This is because cotton fabric is hygroscopic and closely woven, coating material is absorbed by it. For Goup B samples, substrate material is highly porous and synthetic, coating mass is deposited on yarn only, add-on is almost same and the space between yarns is unfilled. In the Group C samples, when coating concentration is increased, the space between yarns is gradually filled by the coating mass from sample CWF_9 to CWF_12, with increase of coating material add- on from 67.9 gsm to 190.3

gsm. It is observed that carbon black and milled carbon fibre fillers are uniformly distributed and as the concentration of filler materials increases, the density of filler particles increases. The uniform dispersion of these fillers has provided consistent microwave properties in vertical and horizontal polarisation of wave.

3.2 Surface Resistivity and Conductivity

From Table 3, it is seen that as the coating material add-on increases, the surface resistance decreases and, in turn, conductivity increases. For samples NWF_1 to NWF_4, surface resistivity decreases from 5.33kΩ/□ to 781 Ω/□ and conductivity increases from 0.605 S/m to 3.658 S/m. For samples CWF_5 to CWF_8, same coating formulations are applied on conducting substrate, surface resistivity has reduced from 2.246 kΩ/□ to 56.45 Ω/□ and conductivity is increased from 1.074 S/m to 30.54 S/m. This is because, the substrate fabric is inherently conducting. Further, for samples CWF_9 to CWF_12 prepared with increasing coating add-on content on conducting substrate, the surface resistivity has further decreased from 1.045 kΩ/□ to 34.25 Ω/□ and conductivity is increased to a very high level from 1.9936 S/m to 46.34 S/m. Sample CWF_12 is found to be the best having highest conducting surface. Shen *et al.*[30] produced electromagnetic shielding polyester fabrics using carboxymethyl chitosan-palladium complexes as activation solution, followed by electroless nickel plating. Surface resistance of 125 mΩ/□ was obtained when Pd^{2+} concentration was 1.5 g/L. This fabric showed electromagnetic shielding of 40-60 dB in frequency range of 1-3000 MHz. Similarly, surface resistance of fabric with six depositions of Nafion-MWCNTs (378.0 Ω/□) is found much lower than that of Nylon/CNT textiles (31 MΩ/□) and that of MWCNTs/BTCA coated cotton fabric (2.0 KΩ/□) (ref. 31).

3.3 Microwave Properties of Basic Textile Substrates

3.3.1 Basic Cotton Substrate

Basic cotton fabric is non-conducting, it does not have any role on microwave properties and almost entire em wave is transmitted uninterrupted. Basic cotton fabric has 0.03-0.04% reflection, 99.33-97.09% transmission, 0.62-2.85% absorption in X-band; and 0.02-0.24% reflection, 98.18-97.87% transmission, 1.795- 2.09% absorption in Ku-band. EMI shielding effectiveness is very poor in X-band [(-0.01)-(-0.11) dB in perpendicular and (0.02)-(-0.12) dB in parallel mode], and in Ku-band, it is (-0.07) -(-0.08) dB in perpendicular mode and (0.08) - (- 0.09) dB in parallel mode. To see the role of coating add on, cotton fabric has been taken.

3.3.2 Basic Conducting Textile Substrate

Basic fabric is inherently conducting, and hence it displays reflecting behaviour. It has reflection of 74.77 - 62.40% in parallel and 84.50-51.94% in perpendicular mode in X-band; and in Ku-band, reflection is 50.96-29.48% in parallel, and 72.24-59.26% in perpendicular mode. Transmission is less in X-band; in parallel mode, transmission is 2.55-4.04%, and in perpendicular mode, it is 0.14- 0.37%. In Ku-band, in parallel mode, the transmission is 4.04-7.21%, and in perpendicular mode, it is 0.32-0.60%. EMI shielding effectiveness is high. It is (-27.65) - (-23.83) dB in perpendicular and (-16.38) - (-14.18) dB in parallel mode in X-band; and in Ku-band, it is (-23.98) - (-21.89) dB in perpendicular and (-12.78) - (-10.42) dB in parallel mode. Here, basic fabric itself has shown adequate EMI shielding properties. To see the effect of substrate material, conductive substrate has been taken.

3.4 Role of Coating Add-on on Cotton Substrate

Four samples of coated fabric marked NWF_1 to NWF_4 (Group A) are prepared on cotton substrate. Since microwave properties are acquired by the coated fabric by deposition of coating mass only, it is isotropic; it does not depend on parallel and perpendicular polarisation of em wave. For samples NWF_1 to NWF_4, as the proportion of milled carbon fibre increases, its surface resistivity remarkably decreases from 5.33 kΩ/□ to 781Ω/□ and conversely, surface conductivity increases from 0.605 S/m to 3.65 S/m.

As add-on increases from 78.0 gsm to 154.5 gsm (carbon content 3.99 - 4.53 wt%, and milled fibre content 4.53-15.98 wt%) from sample NWF_1 to NWF_4 (Table 2), reflection increases from 1.58-1.88% to 32.63-34.83% in X-band and from 2.33-3.43% to 34. 94- 43.46% in Ku-band. Shorter waves are more reflecting. Absorption increases from 10.31-20.16% to 37.40-42.30% in X-band and from 19.91-21.70% to 41.54-38.46% in Ku-band. Transmission decreases from 88.10- 77.95% to 29.95-22.86% in X-band and from 77.74-74.86% to 21.51-16.07% in Ku-band (Fig. 3). EMI shielding depends on transmission. The lower is the transmission the higher will be the EMI shielding. From samples NWF_1 to NWF_4, transmission decreases and consequently EMI shielding increases from 1.0815 to 6.4075 dB in X-band, and from 0.9223 to 7.9398 dB in Ku-band (Table 4). Microwave properties displayed by the coated fabric on cotton substrate are comparatively lower as compared to samples prepared on conducting substrate materials.

3.5 Effect of Conducting Substrate Material

Samples CWF_5 to CWF_8 (Group B) are prepared as per experimental plan given in Table 1, using the add-on in the range of 145.7-148.4 gsm. Carbon content and milled carbon fibre content are shown in Table 2. Initially, for sample CWF_5, carbon and milled fibre contents are equal (4.52%), while from samples CWF_5 to CWF_8, carbon content is same (4.52 wt %) but milled carbon fibre content increases from 4.52 wt% to 15.99 wt%. Reflection, absorption, transmission and EMI shielding are shown in Fig.3 and Table 4. The substrate material exhilarates the overall functional performance of coated fabric.

3.5.1 Reflection

In perpendicular mode, E-field of em wave becomes perpendicular to warp and parallel to weft yarn. Since weft is more conducting, its effect on microwave properties is significantly more than in warp yarn. In X-band, reflection increases from 84.50- 51.94% (basic fabric) to 92.51- 77.42%) (CWF_8) in perpendicular mode. For parallel mode, it increases from 74.77- 62.40% (basic fabric) to 79.84- 62.31% (CWF_8). For Ku-band, in parallel mode, reflection increases from 50.96-29.48% (basic fabric) to 65.80-56.47% (CWF_8). In perpendicular mode, it increases from 72.24-59.26% (basic fabric) to 86.02- 82.0% (CWF_8). Overall reflections of perpendicular mode are higher than those of parallel mode (Fig. 3).

3.5.2 Absorption/ Scattering

In the basic fabric, absorption is due to scattering, and in the coated fabric the absorption is due to combined effect of scattering of basic fabric and absorption of coating ingredients. There is no trend for absorption. In X-band, in parallel mode, absorption is 14.66- 29.03%, 18.47- 34.46%, 17.64 - 34.52% & 17.76-34.74%, and in perpendicular mode, it is 11.61- 26.18%, 13.18- 26.24%, 3.59-19.07 & 7.20-22.13% for samples CWF_5 to CWF_8 respectively. In Ku-band, in parallel mode, absorption is 29.28- 34.94%, 31.94- 40.84%, 29.63- 38.57% & 30.32- 38.57%, and in perpendicular mode, it is 26.22- 31.23%, 26.04- 32.01%, 18.90- 20.79% & 22.51-26.31% for samples CWF_5 to CWF_8 respectively (Fig.3).

3.5.3 Transmission

Basic and coated fabrics are highly conducting, and therefore reflections are very high, which culminates to least transmission. In perpendicular mode, transmission is lower in entire X- & Ku – band. Since basic fabric contains conducting yarn in warp and weft both, the transmission is less in both vertical and horizontal polarisation of electromagnetic wave. In X-band, transmission of coated fabric ranges from 2.51-3.85% to 2.39-2.93% in parallel mode and from 0.18- 0.45% to 0.27-0.43% in perpendicular mode for samples CWF_5 to CWF_8. In Ku-band, it is reduced to a range of 0.42-0.76% to 0.46-0.68% in perpendicular mode and from 5.23-8.37% to 3.87- 4.94% in parallel mode (Fig. 3).

3.5.4 EMI Shielding Effectiveness

EMI shielding depends on conducting ingredients in the coating mass, nature of substrate materials, and level of blockage offered to the propagation of em wave. The higher is the blockage, the lower will be the transmission of wave and, in turn, it will offer higher EMI shielding effectiveness. X- Band longer waves are reflecting more than Ku- band shorter waves. Ku-band shorter waves have more depth of penetration than longer X-band wave; its EMI shielding is comparatively lower. In parallel mode, maximum EMI shielding of 16.21 dB in X- band and 14.12 dB in Ku- band has been observed. In perpendicular mode, weft yarn being higher conductive yarn, has more reflection, and this enhances EMI shielding effectiveness. In perpendicular, EMI is higher (27.66 dB) in X- band than in Ku-band (24.77 dB) (Table 4).

3.6 Microwave Properties with Maximum Limit of Coating Add-on Content

Four samples CWF_9 to CWF_12 (Group C) are prepared on conducting substrate with increasing add-on content to study the synergic effect of increase of add-on content and nature of substrate on microwave properties as per coating plan given in Table 1. These are aimed to study microwave properties of coated fabric to the extent of coating add- on limit. These samples have shown synergetic effect of coating material and conducting substrate. For samples CWF_9 to CWF_12, carbon content increases from 2.94% to 9.51%, and milled carbon fibre content from

6.03% to 19.02%. This overall increases the coating add- on from 67.9 gsm to 190.3 gsm (Table 2). With increase of add-on content, microwave properties are further increased. In the basic fabric when E- field is parallel to weft, reflection is higher and than E- field becomes parallel to warp. The same trend has also been revealed in coated fabric samples CWF_9 to CWF_12. It is also unveiled that with increase of add-on content, surface resistivity has tremendously decreased from 1.045 kΩ/□ to 34.25 Ω/□, and conversely surface conductivity increases from 1.993 S/m to 46.34 S/m (Table 3). Reflection, transmission, absorption and EMI shielding of coated fabrics are illustrated in Fig. 4 and Table 4. It is found that sample CWF_12 with coating add-on of 190.3 gsm shows 93.47-78.66% reflection, 6.39-20.37% absorption, <0.2% transmission, and EMI shielding of 28.86- 26.68 dB in X & Ku- band (8.2-18.0 GHz).

3.6.1 Reflection

Samples CWF_9 to CWF_12 have displayed high reflections in both parallel and perpendicular modes. In weft direction, reflection is higher due to higher conductive weft yarn in the basic fabric. Reflection increases from 89.52-73.38% to 93.47-79.47% in X-band, and from 75.04-71.32% to 81.31-78.66% in Ku-band in perpendicular mode; and in parallel mode, reflection lies in the range from 85.26-66.26% to 81.87-71.25% in X-band and from 85.79-73.56% to 82.63- 77.71% in Ku-band (Fig. 4).

3.6.2 Absorption

Initially, basic fabric has shown scattering rather than absorption. When coating is applied to the basic fabric, scattering and absorption both take place. Overall result is combination of scattering and absorption both. Therefore, there is no trend of absorption of coated fabrics. For X-band in parallel mode, absorption increases from 12.18 - 29.67% to 17.21 – 28.05% from samples CWF_9 to CWF_12. In perpendicular mode, first it reduces from 10.32-26.23% to 8.82-22.96% from sample CWF_9 to CWF_10, and thereafter, it increases to 11.12-30.41% from sample CWF_10 to CWF_11. In Ku-band, in parallel mode, absorption decreases from 28.85- 37.92% to 23.96- 27.82% from sample CWF_9 to CWF_10, and then it increases to 34.23- 40.31% from sample CWF_10 to CWF_11. This variation of absorption is due to the combined phenomenon of scattering and absorption. In perpendicular mode, absorption increases from 10.63- 14.07% to 17.20-22.07% (Fig. 4).

3.6.3 Transmission

From samples CWF_9 to CWF_12 in parallel mode (X- band), transmission decreases from 2.55-4.04% to 0.91-0.68%, and in perpendicular mode, it is <1.0%. In Ku-band, transmission reduces from 4.04-7.21% to 0.68- 0.73% in parallel mode and in perpendicular mode, it is <1.0% (Fig. 4). Overall, transmission is very less.

3.6.4 EMI Shielding Effectiveness

Overall, EMI shielding depends on transmission of wave; if wave is completely blocked, the highest will be the EMI shielding. Coated fabric based on conducting substrate, offers higher EMI shielding. Basic fabric itself is reflecting, when coating material is applied, EMI shielding has further increased. EMI shielding is given in Table 4 (S_{21} parameters). From samples CWF_9 to CWF_12, with the increase of add-on, EMI shielding increases from (-15.92)-(-13.92) dB to (-20.40)- (-21.64) dB and from (-12.71)- (-10.70) dB to (-21.14) - (-21.87) dB in X and Ku- band respectively in parallel mode. In perpendicular mode, it increases from (-28.24) -(-24.25) dB to (-28.86)-(-28.08) dB in X- band and from (-24.86)- (-22.21) dB to (-27.74) - (-26.68) dB in Ku- band. In perpendicular mode, EMI shielding effectiveness is higher. Sample CWF_12 is found to be the best amongst all, showing highest microwave properties due combined effect of conducting substrate and coating add-on.

3.7 Comprehensive Study of Microwave Properties of Coated Fabrics

A comprehensive presentation of microwave properties, i.e. reflection, absorption and EMI shielding effectiveness of representative samples from each group (NWF_1 & NWF_4 from Group A; CWF_5 & CWF_8 from Group B; and CWF_9 & CWF_12 from Group C) in parallel and perpendicular modes of polarisation of em wave are summarised in Table 5.

It is observed that cotton substrate with add -on level of 78-154 gsm acquires microwave properties and offers 32.63-43.46% reflection, 34.91-44.63% absorption and 5.23-7.93 dB EMI shielding in frequency range 8.2- 18.0 GHz. When same coating formulations are applied on conducting substrate with coating add-on of 145.7-148.4 gsm, coated fabric shows 92.51-82.00% reflection against 84.50-59.26%

Table 5 — Comprehensive microwave test results of coated fabrics

Parameters	Group A				Group B				Group C			
	NWF_1 (78.0 gsm)		NWF_4 (154.5 gsm)		CWF_5 (145.7 gsm)		CWF_8 (148.4 gsm)		CWF_9 (67.9 gsm)		CWF_12 (190.3 gsm)	
	Parallel	Perp.	Parallel	Perp.	Parallel	Perp.	Parallel	Perp.	Parallel	Perp.	Parallel	Perp.
Reflectance, %												
X-Band	0.85-0.95	1.58-1.88	25.67-28.69	32.63-34.83	82.81-67.10	88.20-73.36	79.84-62.31	92.51-77.42	85.26-66.27	89.52-73.38	81.87-71.25	93.47-79.47
Ku-Band	1.43-2.20	2.33-3.43	33.92-41.15	34.94-43.46	67.10-58.30	81.34-76.00	65.80-56.47	86.02-82.00	85.79-73.56	75.04-71.32	82.63-77.71	81.31-78.66
Absorption, %												
X-Band	8.05-6.99	10.31-20.16	34.91-44.25	37.40-42.30	14.66-29.03	11.61-26.18	17.76-34.74	7.20-22.13	12.18-29.67	10.32-26.23	17.21-28.05	6.39-20.37
Ku-Band	16.87-18.36	19.91-21.70	44.63-43.37	41.54-38.46	29.28-34.94	26.22-31.23	30.32-38.57	22.51-26.31	28.85-37.92	10.63-14.07	28.20-33.07	17.20-22.07
EMI Shielding, dB												
X-Band	(-0.40)-(-0.85)	(-0.55)-(-1.08)	(-4.04)-(-5.67)	(-5.23)-(-6.40)	(-15.99)-(-14.13)	(-27.38)-(-23.42)	(-16.21)-(-15.31)	(-25.63)-(-23.59)	(-15.92)-(-13..92)	(-28.24)-(-24.25)	(-20.40)-(-21.64)	(-28.86)-(-28.08)
Ku-Band	(-0.57)-(-0.68)	(-0.77)-(-0.92)	(-5.46)-(-6.48)	(-6.67)-(-7.93)	(-12.80)-(-10.76)	(-23.68)-(-21.15)	(-14.12)-(-13.05)	(-23.32)-(21.64)	(-12.71)-(-10.70)	(-24.86)-(-22.21)	(-21.14)-(-21.87)	(-27.74)-(-26.68)

reflection of basic fabric and EMI shielding to a tune of 25.63-21.64 dB against 27.65- -21.89 dB EMI of basic fabric. It appears that with this add- on, there is a mild increase in microwave properties. Here, substrate conducting fabric is playing a prominent role rather than coating materials. However, when coating formulations are changed and coating add- on is increased to a thresh hold level of ~ 200 gsm, there is synergic effect of coating material and nature of conducting fabric on microwave properties. A significant increase in reflection (93.47-77.71%) and EMI shielding (-28.86 to -26.68 dB) have been observed in the frequency range 8.2-18.0 GHz. For coated fabric based on conducting substrate in perpendicular mode, microwave properties are much higher than in parallel mode. This is because, higher conducting yarn is laid in weft direction in the basic fabric.

3.8 Mechanical Properties of Coated Fabric

To study flexibility, sturdiness and robustness of coating materials adhered on textile substrate, and mechanical properties of coated fabrics are evaluated. Flexibility and robustness of coated fabric are examined in terms of bending length and flexing test.

3.8.1 Bending Length

This is the length of fabric that bends under its own weight to a definite extent to touch the datum line. It is a measure of the stiffness that determines drape quality. Softness and flexibility of coated fabric are tested in Shirley Stiffness Tester. Bending length is expressed as, c = l. f (θ); where l is the length that bends up to datum line and f (θ) = (Cos (θ/2) / 8 tan θ)$^{1/2}$ for θ = 41.5º, f (θ) = 0.5. Bending modulus is used to compare the stiffness of the material of different thickness. It is expressed as $q = 12\ G \times 10^{-6} / g^3$ kg/cm^2; where g is the thickness in cm and G is flexural rigidity ($G = w.c^3.10^3$ mg/cm, w = weight in g/cm^2) (ref. 32). Cotton based coated fabric is soft and flexible, its bending length is less (Table 6). Samples NWF_4 and CWF_11 have highest add-on. These samples are comparatively stiffer, and their bending lengths are highest. For sample NWF_1, coatings add -on is least. This sample is highly flexible, and its bending length and bending modulus are less.

Table 6 — Bending length and bending modulus of coated fabric

Sample	Bending length (l) mm	Bending modulus (q) kg/cm^2
NWF_1	21	6.43
NWF_2	27	13.65
NWF_3	29	16.94
NWF_4	32	24.53
CWF_5	43	11.01
CWF_6	42	11.06
CWF_7	36	6.98
CWF_8	40	11.21
CWF_9	35	7.88
CWF_10	33	6.18
CWF_11	55	21.98
CWF_12	40	10.36

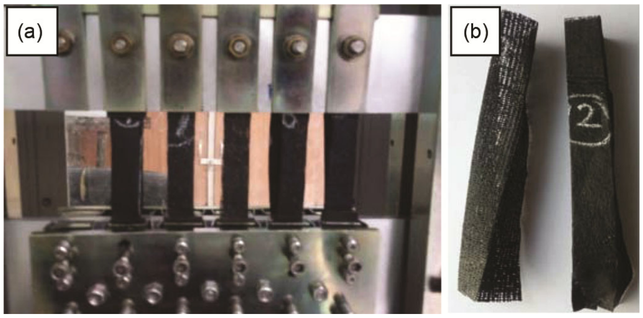

Fig. 5 — (a) Samples mounted in Dematia Flex Tester, and (b) tested sample of coated fabric

3.8.2 Flexing Test

Durability and robustness of coated fabrics are tested in Dematia Flex Tester (IS: 7016 part 4) [Fig. 5(a)]. Three-fold sample of size 4.5 cm × 12.5 cm was mounted between reciprocating jaws. Sample is run for 1, 00,000 cycles and after that no marks of cracks of coating, flexing, de-lamination of coating, or wrinkles are observed. The tested samples are shown in Fig. 5(b). It is seen that coated fabric is highly flexible, showing strong adherence of coating which can withstand frequent folding and unfolding operations. Thus, coated fabrics have sufficient flexibility and durability. This shows that the coating is strongly adhered to the basic fabric.

4 Conclusion

In this study, coatings based on conducting ingredients have been performed on cotton and inherent conducting fabric substrates simultaneously. Coated fabrics are evaluated for microwave properties. It is found that microwave properties on cotton fabric are of restricted nature, and it is found most suitable for radar camouflage, while coated fabric on conducting substrate is highly reflecting and transmission is almost negligible. It is found appropriate candidate for EMI shielding purpose in frequency band of 8.2-18.0 GHz. Cotton coated fabric with add-on of ~150 gsm and thickness of 0.35 mm has offered 40-50% reflection, 33-36% absorption, and 16-21% transmission with EMI shielding of 6-8 dB. Similar coating formulations are also applied on conducting fabric to investigate the combined effect of substrate materials and coating formulations. With this add-on, there is moderate increase in microwave properties; here substrate conducting fabric is playing a dominant role. Further, to study the role of coating mass, samples of coated fabric have also been prepared to the maximum limit of coating viscosity with add- on of ~200 gsm on conducting substrate. With this add-on level, it is found that microwave properties are synergized owing to conducting nature of substrate fabric. EMI shielding of high order has been achieved in single layer light weight coated fabric. Coated fabric (0.63 mm thickness) offers very high reflection of 80-90%, moderate absorption of 6-20% and very low transmission with EMI shielding of 20-29 dB in X -band and 21-28 dB in Ku-band. Thus, it is conferred that coating add-on and nature of substrate material in conjunction play a prominent role in achieving the overall microwave performance.

Acknowledgement

Authors express their sincere thank to Mr Rudresh Kumar, Scientist E and Mr Sumit Kumar Scientist D, DMSRDE, Kanpur for extending their support in evaluation of microwave properties and interpretation of results. Thanks are also due to Mrs Priyanka Katiyar, Scientist E, Mr Lallan Sah, Technical Officer C, and Mr Dev Singh Technical Officer B, Directorate of Technical Textiles, DMSRDE, Kanpur for their support in physical and chemical evaluation of coated fabric samples.

References

1 Yang Y, Wang J, Liu Z & Wang Z, *J Ind Text*, 50 (2021) 830.
2 Rajendrakumar K & Thilagavathi G, J *Ind Text*, 42(2013) 400.
3 Powar A & Hulle A, *J Text Sci Eng*, 8 (2018) 1.
4 Nam I W, Lee H K & J H Jang, *Composites: Part A*, 42 (2011) 1110.
5 Erdumlu N & Saricam C, *J Ind Text*, 46 (2016) 1084.
6 Guzaitienė J B & Zuravliov S V, *Advanced Materials for Electromagnetic Shielding: Fundamentals, Properties, and Applications* (Wiley Publication, Manhattan), 2018, 219.
7 https://en.wikipedia.org/wiki/Electromagnetic_shielding (accessed on 20.02.2021)
8 Chauhan V K, Singh B & Singh J P, *Indian J Fibre Text Res,* 45 (2020) 215.
9 Zhang Z, Zhang F, Jiang X, Liu Y, Guo Z & Leng J, *Fiber Polym*, 15 (2014) 2290.
10 Gültekin B C, Gültekin N D, Atak O & Şimşek R, *Fiber Polym*, 19 (2018) 313.
11 Yildiz Z, Usta I & Güngör A, *Fibres Text East Eur*, 98 (2013) 32.
12 Gahlout P & Choudhary V, *Compos [B] Eng,* 175 (2019) 107093.
13 Zou L, Lan C, Li X, Zhang S, Qiu Y & M Ying, *Fiber Polym,* 16 (2015) 2158.
14 Ramji K , Murthy K K , Naidu M K & Haritha T , *Proceedings*, *11th International Conference on Recent Trends in Mechanical Engineering* (Springer) 2019, 409.
15 Haritha T , Ramji K, Subrahmanyam C H, Krushnamurthy K & Nagasree P S, *Plast Rubber Compos*, 50 (2021) 180.
16 Wang Y, Wang W, Ding X & Yu D, *Chem Eng J*, 380 (2020) 122553.

17 Lou C W & Lin J H, *Fiber Polym*, 12 (2011) 514.
18 Rubezien V, Baltusnikaite J, Varnaite S, Sankauskaite A, Abraitiene A & Matuzas J, *J Electrostat*, 75 (2015) 90.
19 Tian M, Du M, Qu L, Chen S, Zhu S & Han G, *RSC Adv*, **7** (2017) 42641.
20 Afzali A, Mottaghitalab V & Afghahi S S S, *J Ind Text,* 47 (2017) 1867.
21 Ozen M S, Sancak E, Soin N & Shah T H, *J Text Inst,* 107 (2015) 912.
22 Dordevic Z (Beograd, Yugoslavia), *US Pat* 5,103,504A (1992).
23 Peng H K, Wang Y T, Li T T, Lou C W, Wang X X & Lin J H, *Fiber Polym*, 21 (2020) 775.
24 Bahadir S K, Mitilineos S, Smeonidis, Kivanc U, Sahin S, Vassiliadis, Kalaoglu F, Goustouridis D, Stathopoulos N & Savvaidis S P, *J Electron Mater*, 49 (2020) 1579.
25 Ortlek H G, Saracoglu O G, Saritas O & Bilgin S, *Fiber Polym*, 13 (2012) 63.
26 https://en.wikipedia.org/wiki/Electroconductive_carbon_black (accessed on 16.02.2021).
27 http://zoltek.com/products/px35/milled-fiber/ (accessed on 16.02.2021).
28 William A, Maryniak, Uehara T & Maciej A, Trek Application Note number 1005, *ASTM Standard D 257-99 for Surface resistivity measurement* (Trek Inc), 2000.
29 Ghodgaonkar D K, Varadan V V & Varadan V K, *IEEE Transact Instrument Measurement,* 39 (1990) 387.
30 Shen Y, Zhang1H F, Wang L M, Xu L H & Ding Y, *Fiber Polym*, 15 (2014) 1414.
31 Zou L, Lan C, Li X, Zhang S, Qiu & Ying M, *Fiber Polym,* 16 (2015) 2158.
32 Booth J E, *Principle of Textile Testing* (Butterworth & Co. Ltd London), 1970, 283.