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# Electromagnetic Shielding Effectiveness of Multifunctional Metal Composite Fabrics

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**Abstract** The growth of the electronic industry and the widespread use of electronic equipment in communications, computations, automations, biomedicine, space, and other purposes have led to many electromagnetic interference (EMI) problems as systems operate in close proximity. It is likely to become more severe in the future, unless proper EMI control methodology and techniques are used to meet the electromagnetic compatibility requirements. This article presents a comprehensive review of EMI shielding theory and materials. Furthermore, a method for fabricating a multifunctional metal composite fabric with electromagnetic (EM) shielding characteristics was successfully developed. The parameters influencing EM shielding properties of the metal composite fabrics were investigated. It was shown that the EM shielding effectiveness of the metal composite fabrics could be tailored by modifying the metal grid size and geometry.

**Key words** metal composite fabric, shielding effectiveness, stainless steel filament

A preparatory study for a multifunctional fabric with high values of electrical properties such as electromagnetic interference (EMI) shielding and electrical conductivity, comfort properties such as thermal insulation, and aesthetic properties has been carried out. Such metal composite fabric may be applied in smart clothing or in everyday clothing depending on the properties required. EMI shielding properties of the metal composite fabric are presented in this paper.

Wireless communication links have been used worldwide for many years as solutions for connectivity in point-to-point and point-to-multipoint applications. The most common wireless solutions include AM and FM radio, television broadcast stations, cellular phones, radar, and microwave systems. The electromagnetic spectrum contains an array of electromagnetic waves increasing in frequency from extremely low frequency and very low frequency (ELF/VLF), through radio frequency (RF) and microwaves to infrared (IR) light, visible light, ultraviolet (UV) light, X-rays, and gamma rays. Figure 1 is a graphical representation of the spectrum of electromagnetic waves and their applications. In recent years, electromagnetic (EM) waves in the 1–10 GHz range are broadly used in wireless communication tools and local area networks. In the future, the usable range of EM waves will tend to shift further to higher frequency regions with the development of information technology as well as electronic devices. As a consequence, the seriousness of problems such as EMI of electronic devices and health issues is ever rising.

The underlying reason for most of the interference problems we experience today is an undesirable consequence of the physics involved in the transmission of EM energy. EM

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Figures 1–5, 8 appear in color online: http://trj.sagepub.com

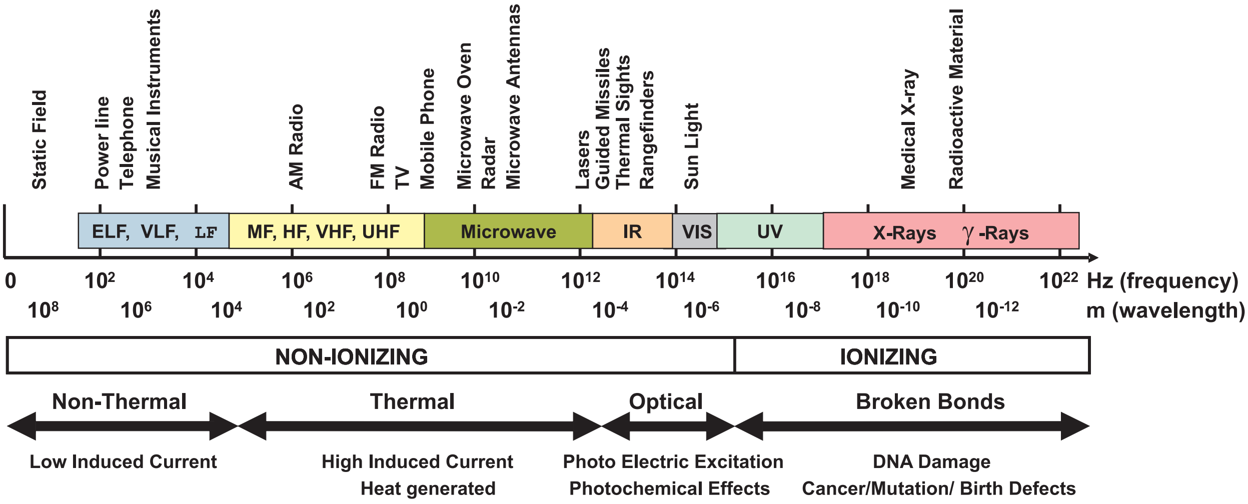


**Figure 1** A graphical representation of the spectrum of EM waves and their applications and effects.

energy is the only form of energy that can be used effectively to transmit intelligent signals over long distances in free space under controlled conditions. This characteristic of EM energy is referred to as EM wave propagation. However, even though most of the transmissions are achieved under controlled conditions, it is this transmitted energy that may create an interference producing phenomenon, a phenomenon that may affect the performance of many electronic devices. The term used to describe the ability of a device to generate or excite EM fields, intentionally or unintentionally, which can be received by other devices is propagated radiation. Unwanted reception of EM radiation may lead to EMI [1]. The most common type of EMI occurs in the RF range of the EM spectrum, from $10^4$ to $10^{12}$ Hz. This energy can be radiated by computer circuits, radio transmitters, fluorescent lamps, electric motors, overhead power lines, lightning, and many other sources. Shielding of EMI is becoming more critical due to the smaller size and faster operating speeds of these components, which make it more difficult to manage the EM pollution they create. Increased device frequencies cause proportionally decreased wavelengths that can penetrate very small openings in housings and containers. Thus, regulations on EM wave emission of electronic products are getting stricter around the globe [2–4].

Another important issue to be addressed with EM waves is their possible health effects on humans [5–9]. The World Health Organization (WHO) suggests that a wide range of environmental EM influences cause biological effects [10]. Although there is controversy on the dangerousness of EM fields on health and there is a lack of convincing biological evidence for such adverse health effects, humans should be adequately shielded from the growing amount of EM fields they are exposed to everyday. Current public concern also focuses on possible long-term health effects of EM field exposure. There is also increasing concern that EMI adversely affects the operation of biological devices such as pacemakers [11]. EMI between wireless electronic transmitting devices and medical equipment is a small, but growing problem in the healthcare industry that should not be ignored. The adverse health effects that EM waves may be capable of are also listed in Figure 1.

When an EM field is passed through an object, there are three phenomena that determine how the field strength is lost as it interacts with the object: absorption attenuation, attenuation due to reflection, and attenuation due to successive internal reflections (usually neglected) (Figure 2). As the wave impinges the surface of the object, it forces charges in the object to oscillate at the same frequency of the incident wave. This forced oscillating charge behaves as an antenna and results in reflection. The entire signal is not reradiated in the direction of the incident wave, resulting in measured signal loss. The field is emitted in many directions in a pattern associated with a signal charge oscillating antenna, and hence the field is scattered. As the charge is forced to vibrate in the medium, energy is lost in the form of heat. This mode of signal loss is known as attenuation due to absorption.

Thus, EM shields function on the basis of the above mentioned two major EM mechanisms: reflection from a conducting surface, and absorption in a conductive volume. An EM wave striking a metallic surface encounters both types of loss. Part of the wave is reflected, while the remainder is transmitted and attenuated as it passes through the media. The combined effect of these losses (reflection and absorption) determines the effectiveness of the shield.

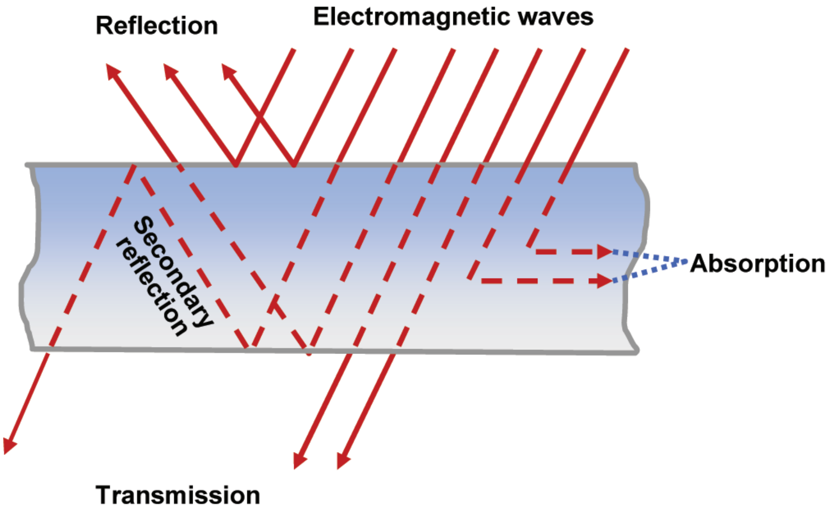


**Figure 2** Representation of shielding phenomena for EM waves passing through a homogeneous barrier.

Reflection from an EM shield results when the impedance of the wave in free space is different from the impedance of the EM wave in the barrier. This phenomenon is independent of the barrier thickness and is a function of the material's conductivity, magnetic permeability, and frequency. An EM wave consists of an electric component and a magnetic component perpendicular to each other and propagates at right angles to the plane containing the two components. As the wave impedance is different for magnetic fields (low impedance) and electric fields (high impedance), the barrier reflection follows a different characteristic for each wave type. Electrically conductive materials such as metals reflect EM fields to prevent them from escaping or penetrating the shield.

Absorption in an EM shield transforms EM energy into thermal energy. EM shields made of EM absorbers attenuate undesirable EM waves and substantially solve EMI. The absorption loss does not depend on the wave impedance of the impinging field, and thus it is not directly related to near- or far-field conditions of the system. The shield's effectiveness varies with frequency, shield geometry, positioning within the shield, type of field being attenuated, directions of incidence, and polarization. In general, the materials used for absorbing EM waves can be classified into two groups: (1) materials with high dielectric constant, such as $BaTio_3$, carbon particles, and (2) materials with high permeability, such as $Fe_3O_4$, ferrite materials [12]. Materials with high dielectric constant absorb the electric energy and convert it into thermal energy, while materials with high permeability convert the magnetic energy into thermal energy [13]. EM absorbers could be applied in many fields besides EMI suppression i.e. radar camouflage and stealth technology, microwave noise control, microwave antenna patterning, microwave curing and heating, and finite resistance paths [14, 15].

Traditional approach for EMI shielding relies on the use of metallic materials which supply excellent shielding effectiveness. However, the conventional metallic shields in the form of bulk sheets or meshes impose weight penalties, and metal plating coatings, powders or fibers in filled polymer composites or coatings suffer from poor wear or scratch resistance. Intrinsically conductive polymer composites (ICPs) have been replacing metals for various shielding applications in the electrical and electronic industries, especially for the electronic housing materials [16, 17]. However, ICPs, mostly polyaniline (PANI) and polypyrrole (PPY), have rigid characteristics owing to their chemical conformation of benzene rings [18]. Carbons are also used in EMI shielding applications, mainly as conductive fillers (fibers, particles, powders, filaments, tubes) in composite materials, due to their electrical conductivity, chemical resistance, and low density [19, 20].

Conductive woven or knitted fabrics, because of their structural order and ability to flex and conform to most desired shapes, offer a great opportunity to develop a new generation of multifunctional and interactive textiles. Conductive fabrics have been considered for EM shielding and electrostatic dissipation (ESD) applications in the defense, electrical, and electronics industries [21–23]. Such fabrics have desirable properties such as flexibility, electrostatic discharge, EMI protection, radio frequency interference protection, thermal expansion matching, and light weight.

The conductivity and EM shielding effectiveness of synthetic fabrics are improved using the following methods: (1) lamination of conducting layers onto the fabric surface, conductive coating, zinc arc spraying, ionic plating, vacuum metallization, sputtering and metal foil binding; (2) adding conductive fillers, such as conductive carbon black, carbon fiber, carbon nanotubes, metallized fiber, metal fiber (stainless steel, Al, Cu), metal powder and flake (Al, Cu, Ag, Ni) to the insulating material; and (3) incorporation of conductive fibers or yarns into the fabric [21]. As metallic fibers are closely spaced, continuous conductive paths can be established easily. However, due to the rigidity of the fibers, difficulties are found in the process of manufacturing on textile machinery.

The diameters of metal fibers utilized in previous studies for EM shielding conductive fabrics are too large (Φ: 0.08–0.15 mm) to be flexible enough to be applied in wearable clothing [22–24]. Cheng et al. [22] reported less shielding effectiveness for fabrics constructed with metal wires with larger diameters. A phenomenon called the *skin effect* also makes the finer metal filaments more favorable because, the higher the frequency of the EM wave, the smaller the penetration depth into the fiber. The electrical field of a plane wave drops exponentially with increasing depth into the conductor; the depth where the field drops to 1/*e* of the incident energy ‘*e*’ is called the fiber’s skin depth ‘δ’ and is defined by equation (1) [25]. Therefore, a smaller diameter fiber would be more efficient because a greater proportion of its volume (the skin volume) would be involved in attenuating the energy than for a larger diameter fiber.

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{1}$$

where δ is depth of penetration (m), *f* is frequency of incident energy (Hz), μ is magnetic permeability of the material (H/m), and σ is electrical conductivity of the material ($\Omega^{-1}m^{-1}$).

In this paper, we present the design and validation of a low cost metal composite fabric with EM shielding effectiveness, flexibility, and processibility. Film type shields show consistent effectiveness throughout the spectrum, but mesh type shields show different resonance peaks at different mesh sizes [26, 27]. Thus, EM shielding effectiveness of the metal composite fabric with different mesh sizes and geometry was studied and the correlation with frequencies was examined. The metal composite fabric has many potential applications, such as smart clothing, destaticizing people or equipment, RF protective suits, covers for sensitive electrical equipment, tents, curtains and tapestry, etc.

## Materials and Methods

### Materials

#### Fabrication of Metal Composite Yarns

Metal composite yarns, which were used in the construction of metal composite fabrics, were produced with commercially available metal filaments and polyester (PET) filaments. The characteristics of the metal filaments are listed in Table 1. With a PET filament (DTY semi-dull 75D/72f, Hualon Corp., Taiwan) as a core, the fine metal filament covered the PET filament in the Z-direction with 500 TPM, and another PET filament covered the previous metal covered PET yarn in the S-direction with 500 TPM, using a hollow spindle spinning machine for producing composite covered yarns. The characteristics of the resulting metal composite yarns are listed in Table 2.

**Table 1** Characteristics of metal filaments.

| Metal fiber | Silver plated copper (Cu) | Stainless steel (SS) |
|---|---|---|
| Linear density (denier) | $Cu_b$: non-coated 101 (Ø: 0.040 mm)<br>$Cu_c$: polyesterimide-coated 105 ($Ø_{Cu}$: 0.040 mm)<br>($Ø_{Cu+coating}$: 0.047 mm) | 70 (Ø: 0.035 mm) |
| Supplier (product name) | Elektrisola-Textile Wire, Switzerland<br>(TW-D, TW-O) | Bekaert, Belgium<br>(Bekinox® VN, 35/1x1 AISI 304L) |
| Density (kg/dm$^3$) | 8.9 | 8.0 |
| DC resistance (Ω/m) | $Cu_c$: 13.705 $Cu_b$: 13.373 | 735 |

**Table 2** Characteristics of composite yarns.

| Composite yarn, ID | Structure | Composition (wt%) | Linear density (denier) |
|---|---|---|---|
| $C_c$ | PET/Cu/PET covered yarn | PET : $Cu_c$ = 61.4 : 38.6 | 270 |
| $C_b$ |  | PET : $Cu_b$ = 62.4 : 37.6 | 266 |
| S | PET/SS/PET covered yarn | PET : S = 70.7 : 29.3 | 232 |
| P | PET/PET covered yarn | PET 100 | 162 |

**Table 3** Characteristics of metal composite fabrics.

| Composite yarn, ID[a] | Composition (warp × weft) | Openness (mm$^2$)[b] | Metal yarn density | | |
|---|---|---|---|---|---|
| | | | $V_f$[c] | $W_f$[d] | No. of metal composite yarns/cm |
| P | P × P | n.a. | 0 | 0 | 0 |
| $C_c$ | $C_c \times C_c$ | – | 1 | 0.386 | 25.2 |
| $C_b$ | $C_b \times C_b$ | – | 1 | 0.376 | 25.2 |
| S | S × S | – | 1 | 0.293 | 25.2 |
| PS 1/1 | (1S/1P) × (1S/1P) | 0.40 × 0.40 (0.16) | 0.50 | 0.147 | 12.5 × 12.5 |
| PS 1/2 | (1S/1P) × (1S/2P) | 0.40 × 0.79 (0.32) | 0.42 | 0.122 | 12.5 × 8.40 |
| PS 1/4 | (1S/1P) × (1S/4P) | 0.40 × 1.59 (0.64) | 0.35 | 0.103 | 12.5 × 5.04 |
| PS 1/8 | (1S/1P) × (1S/8P) | 0.40 × 3.18 (1.27) | 0.31 | 0.090 | 12.5 × 2.80 |
| PS 1/16 | (1S/1P) × (1S/16P) | 0.40 × 6.35 (2.54) | 0.28 | 0.082 | 12.5 × 1.48 |
| PS 2/2 | (1S/2P) × (1S/2P) | 0.79 × 0.79 (0.62) | 0.33 | 0.097 | 8.40 × 8.40 |
| PS 2/4 | (1S/2P) × (1S/4P) | 0.79 × 1.59 (1.26) | 0.27 | 0.078 | 8.40 × 5.04 |
| PS 2/8 | (1S/2P) × (1S/8P) | 0.79 × 3.18 (2.51) | 0.22 | 0.064 | 8.40 × 2.80 |
| PS 2/16 | (1S/2P) × (1S/16P) | 0.79 × 6.35 (5.02) | 0.20 | 0.057 | 8.40 × 1.48 |
| PS 4/4 | (1S/4P) × (1S/4P) | 1.59 × 1.59 (2.53) | 0.20 | 0.059 | 5.04 × 5.04 |
| PS 4/8 | (1S/4P) × (1S/8P) | 1.59 × 3.18 (5.06) | 0.16 | 0.046 | 5.04 × 2.80 |
| PS 4/16 | (1S/4P) × (1S/16P) | 1.59 × 6.35 (10.10) | 0.13 | 0.038 | 5.04 × 1.48 |

[a] Indicates the shape factor of openness; [b] warp opening (mm) × weft opening (mm), (open area, mm$^2$); [c] volume fraction of metal composite yarn, for PS m/n, $V_f = \{(m+1)+(n+1)\}/2(m+1)(n+1)$; [d] weight fraction of metal fiber $W_f = V_f \times$ (metal composition of metal composite yarn*) *from Table 2.

## Fabrication of Metal Composite Fabrics

Metal composite fabrics were constructed in a plain weave (25.2 × 25.2/cm$^2$) on an automatic sample rapier loom (SY1100, Korea). The metal composite yarns were inserted in certain intervals to obtain different open grid structures of metal within the fabrics, which resulted in different metal densities. The characteristics of the metal composite fabrics are shown in Table 3. The open grid structures of the metal yarns are represented in Figure 3.

## EM Shielding Effectiveness (EMSE) Measurement

EMSE of the metal composite fabrics was measured according to ASTM D 4935-99 [28], for planar materials using a plane-wave, far-field EM wave. The method is valid over a frequency range of 30 MHz to 1.5 GHz. A shielding effectiveness test fixture (Electro-Metrics, Inc., model EM-2107A) was used to hold the sample with a network analyzer (Agilent, N5230A) generating and receiving the EM signals

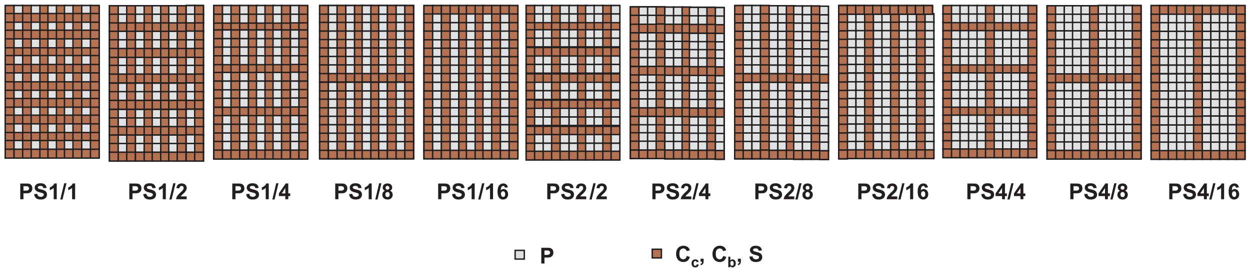


**Figure 3** Schematic diagram of open-grid structures formed in the woven fabrics (dark squares: metal composite yarns; light squares: PET yarns).

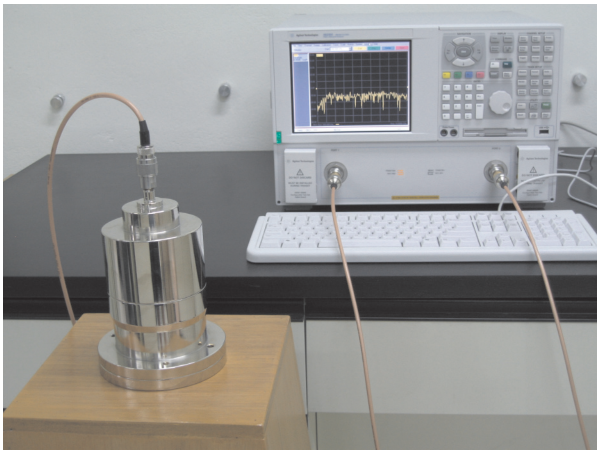
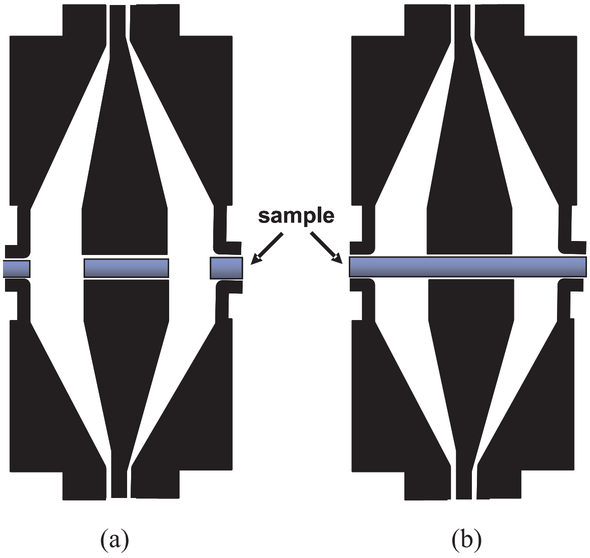


**Figure 4** Set up of EMSE testing apparatus.

(Figure 4). This standard determined the shielding effectiveness of the fabric using the insertion-loss method. The technique involved irradiating a flat, thin sample of the base material with an EM wave over the frequency range of interest, utilizing a coaxial transmission line with an interrupted inner conductor and a flanged outer conductor. A reference measurement for the empty cell was required for the shielding-effectiveness assessment (Figure 5(a)). The reference sample was placed between the flanges in the middle of the cell, covering only the flanges and the inner conductors. A load measurement was performed on a solid disk shape which had a diameter the same as that of the flange (Figure 5(b)). The reference and the load measurement were performed on the same material. The shielding effectiveness was determined from equation (2), which is the ratio of the incident field to that which passes through the material.

$$EMSE(dB) = 10\log\left(\frac{P_1}{P_2}\right) \tag{2}$$

where $P_1$ (watts) is received power with the fabric present and $P_2$ (watts) is received power without the fabric present. The input power used was 0 dBm, corresponding to 1 mW. The dynamic range (difference between the maximum and minimum signals measurable by the system) of the system was 80 dB.



(a) (b)

**Figure 5** A cross-section of the shielding effectiveness test fixture (a) reference sample in the jig and (b) load sample in the jig.

## Results and Discussion

### Effect of Metal Type

Copper ($C_b$), insulated copper ($C_c$), and stainless steel (S) were the three metals used in this study. Figure 6 shows the variation in EMSE for the three composite fabrics with incident frequency in the range 30–1500 MHz. Bare copper composite fabric had the highest shielding efficiency up to 800 MHz, whereas insulated copper composite fabric showed the best shielding efficiency over 800 MHz to 1.5 GHz.

The steel composite showed a drop in shielding efficiency around the 300–400 MHz region and copper showed a drop around 1GHz, which was related to resonance due to weave geometry and metal characteristics.

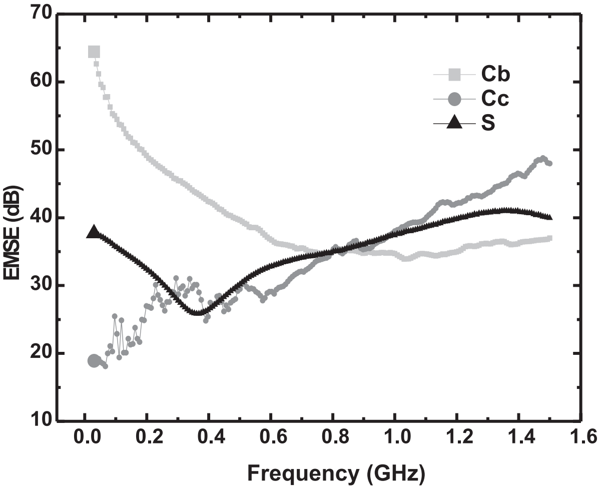


**Figure 6** Effect of metal type on EM shielding effectiveness.

Insulated copper composite fabric had a much lower shielding effect towards EM waves compared with bare copper up to 800 MHz. Although the DC resistance was similar for the two filaments (Table 1), in the case of insulated copper filaments, the insulating coating prevented conduction through the warp and weft metal filaments. Thus, the weave structure did not form an effective conduction mesh network, but rather a structure with conductivity in two directions. At higher frequencies (800–1500 MHz), capacitive coupling among the insulated copper filaments produced a conductive mesh network, increasing the shielding efficiency to a great extent.

## Effect of Metal Content and Grid Openness Open Grid Area

Even though the shielding effectiveness of mesh type EM shielding materials was obviously frequency dependent, the overall EMSE shielding effectiveness increased logarithmically with metal content (Figure 7(a)). Fabrics with smaller metal grids showed higher overall EMSE shielding effectiveness (Figure 7(b)). The results showed that the grid openness affected the EMSE more considerably compared to the metal content of the metal composite fabrics. In particular, when the openness was below 5 mm$^2$, a slight increase in openness dropped the EMSE to a great extent.

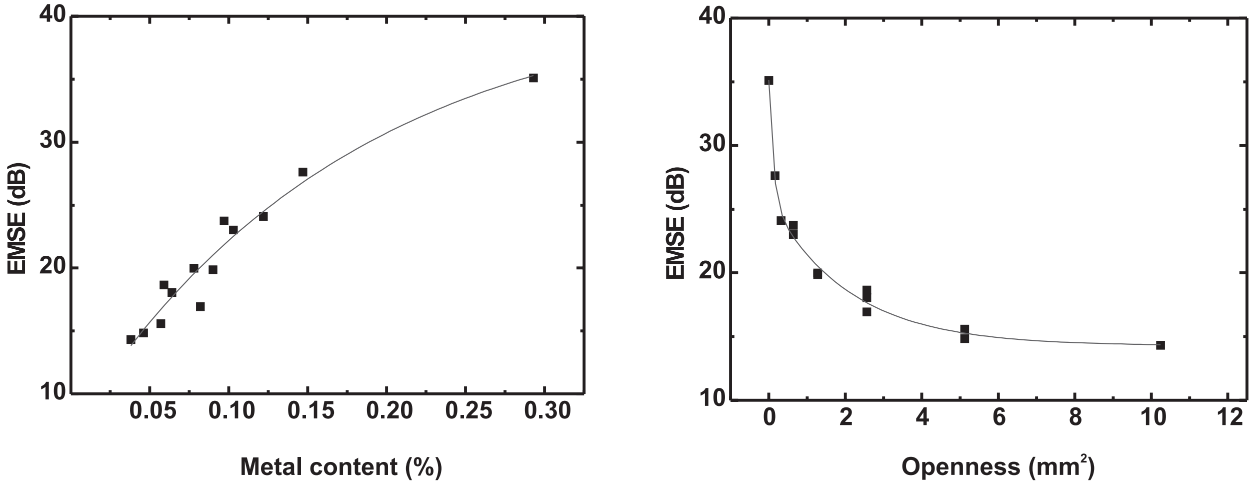
## Effect of Grid Openness

### Grid Openness Increased in One Direction

The common change in EMSE when the grid openness increased in only one direction was the decrease in the overall shielding effectiveness (Figure 8). However, it was noticeable that the fabrics with the same warp opening (Figures 8(a) and (b)) and the fabrics with the same weft opening (Figures 8(c) and (d)) showed different frequency dependent EMSE characteristics. This was due to the unique self resonance peaks of the metal mesh formed in the composite fabrics. For fabrics with the same warp opening (Figures 8(a) $d_{WA} \approx 0.40$ mm and (b) $d_{WA} \approx 0.79$ mm), the resonance peak intensities became stronger as the grid openness increased. This resulted in similar EMSE in the 600–800 MHz frequency region, although the longer opening caused the overall shielding effectiveness to drop. On the contrary, for fabrics with the same weft opening (Figures 8(c) $d_{WE} \approx 3.18$ mm and (d) $d_{WE} \approx 6.35$ mm), which was considerably longer than the warp openings, the resonance peak intensities became weaker as the grid openness increased. This resulted in similar EMSE among the fabrics in the lower frequency region (below 300 MHz when $d_{WE} \approx 3.18$ mm and below 200 MHz when $d_{WE} \approx 6.35$ mm) and around the 1 GHz region, but a comparably larger difference in EMSE in the medium frequency region (300–800 MHz when $d_{WE} \approx 3.18$ mm and 200–800 MHz when $d_{WE} \approx 6.35$ mm) and above the 1.1 GHz region. This suggested that the metal composite fabrics could be tailored by simply altering the open grid structure to achieve EM shielding properties against desired frequencies.

### Grid Openness Increased in Both Warp and Weft Directions

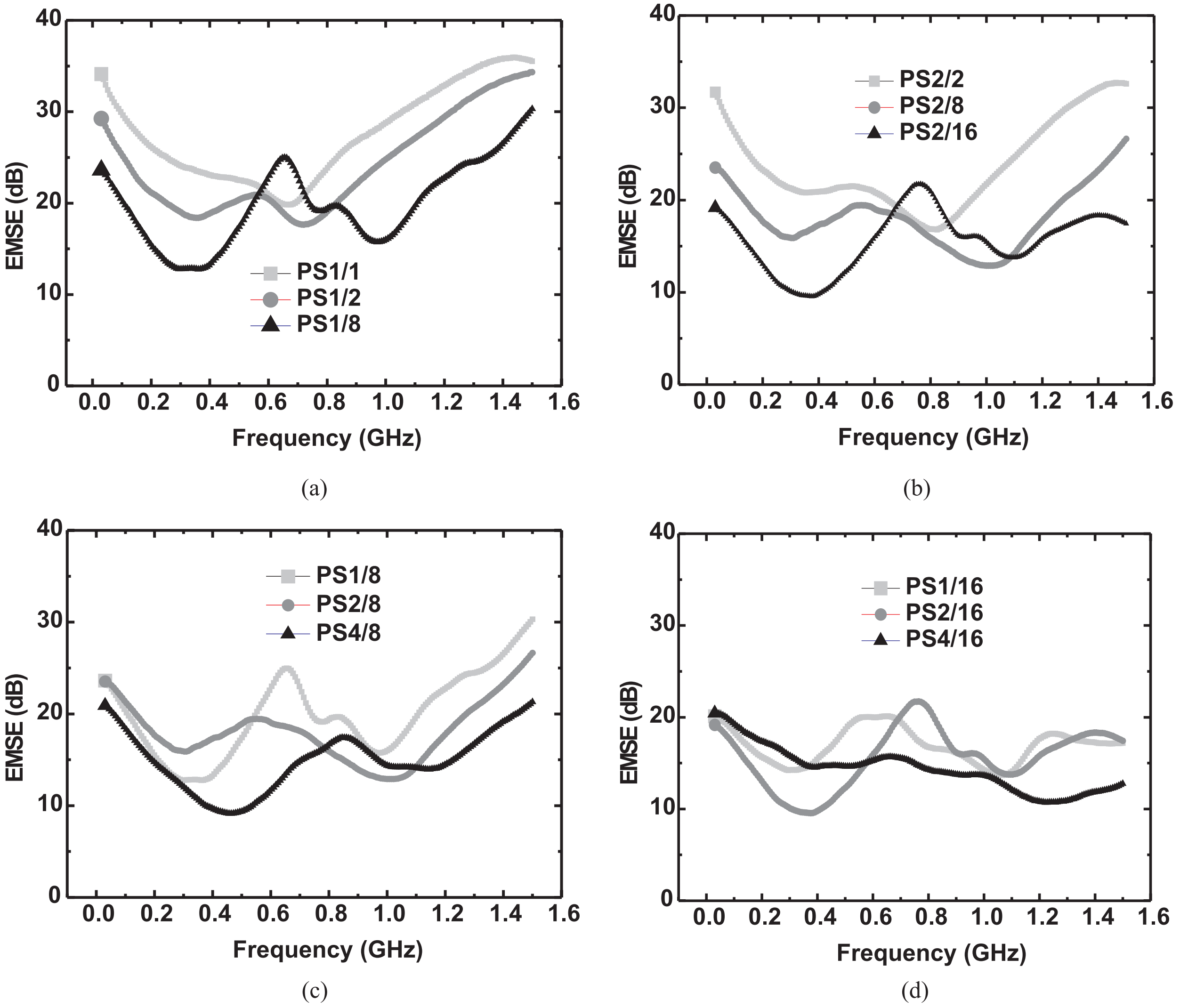
The EMSE of fabrics with grids increased in both the warp and weft directions is given in Figure 9. As expected from the results given above, decreased EMSE and shifted reso-



(a)

(b)

**Figure 7** Effect of metal content (a) and grid openness (b) on overall EM shielding effectiveness.



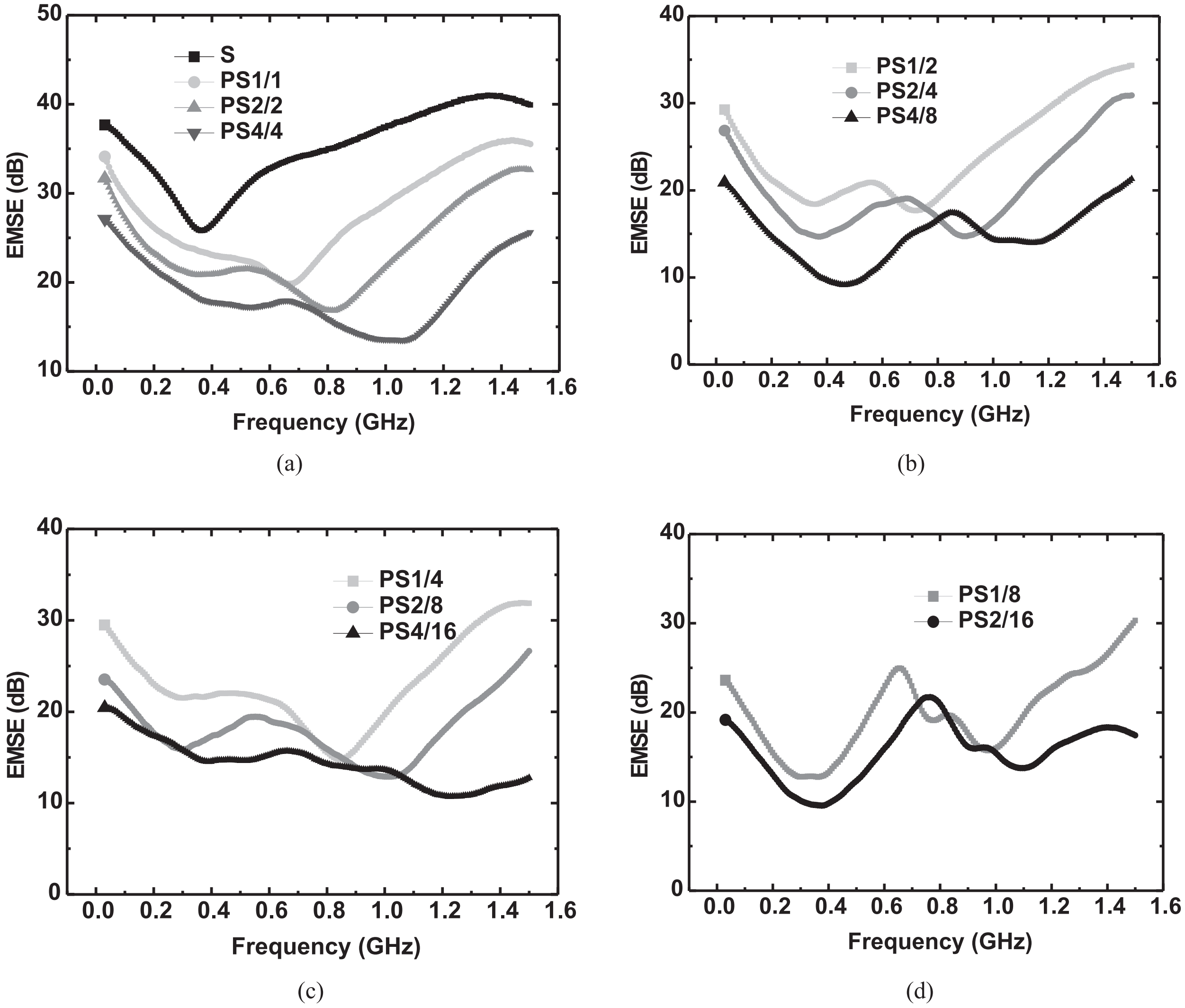
(a) (b) (c) (d)

**Figure 8** Effect of grid openness on EM shielding effectiveness (grid size increased in the weft or warp direction). Fabrics with the same warp opening ($d_{WA}$): (a) $d_{WA} \approx 0.40$ mm and (b) $d_{WA} \approx 0.79$ mm; fabrics with the same weft opening ($d_{WE}$): (c) $d_{WE} \approx 3.18$ mm and (d) $d_{WE} \approx 6.35$ mm.

nance peaks with increased grid size were clearly seen. In particular, the resonance peaks of the composite fabrics with aspect ratio of 1:8 (Figure 9(d)) were most intense, which also implied the strong frequency dependency of those fabrics.

## Effect of Shape Factor

Figure 10 presents EMSE of steel composite fabrics with identical metal grid openness, but different aspect ratios. The results showed that the geometry of the open grid affected the low, medium, and high frequency EMSE differently. Fabrics with same grid openness, but lower aspect ratios showed better shielding effectiveness against low and high frequencies despite their lower metal content. With the same openness of 0.63 mm$^2$, the fabric with the metal grid of 1:1 aspect ratio had higher shielding effectiveness against EM frequencies under 200 MHz and above 700 MHz than the fabric of 1:4 aspect ratio (Figure 10(a)). Likewise, with the same openness of 2.53 mm$^2$, the fabric with the metal grid with 1:1 and 1:4 aspect ratio had better EM shielding effectiveness under 400 MHz and above 1.2 GHz



(a)

(b)

(c)

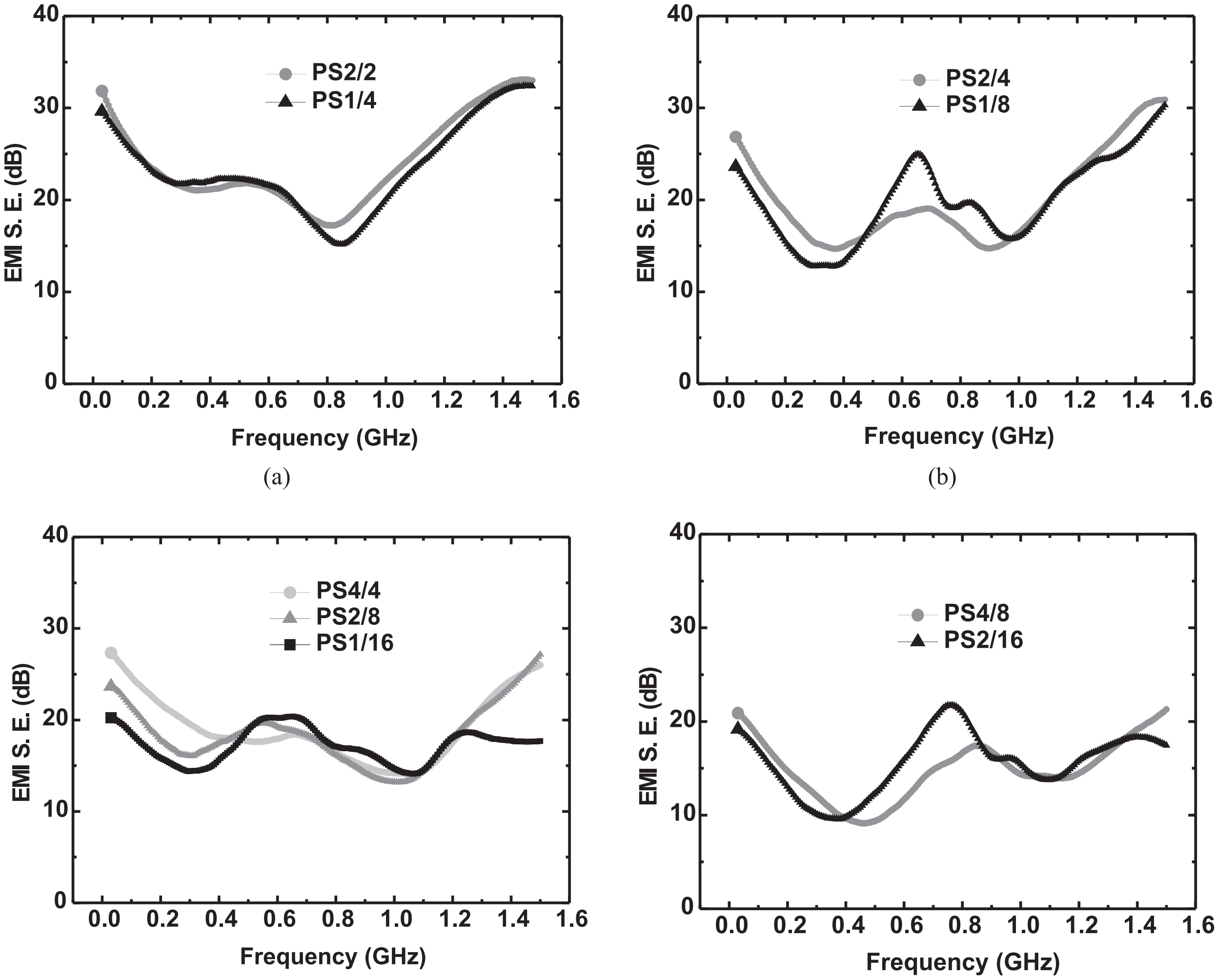
(d)

**Figure 9** Effect of grid openness (same aspect ratios) on EM shielding effectiveness (a) aspect ratio 1:1; (b) aspect ratio 1:2; (c) aspect ratio 1:4; and (d) aspect ratio 1:8.

than fabrics with 1:16 aspect ratio (Figure 10(c)). With the same openness of 1.26 mm$^2$ and 5.06 mm$^2$, the fabrics with the metal grid of 1:2 aspect ratio had higher EM shielding effectiveness under 400 MHz, than the fabric with 1:8 aspect ratio (Figures 10(b) and (d)). On the other hand, from the same figures, the fabrics with 1:8 aspect ratio metal grids had much higher EM shielding effectiveness between 500–1,000 MHz and 400–900 MHz, respectively, than the fabrics with 1:2 aspect ratio. Such a large increase of EMSE in this band region was not found with fabrics with the openness of 0.63 mm$^2$ and 2.53 mm$^2$ (Figures 10(a) and (c)).

## Conclusions

A method for fabricating a multifunctional metal composite fabric was successfully developed. Plane-wave shielding properties of the composite fabrics were measured between 30-1500 MHz using the coaxial transmission line method. The parameters influencing EM shielding properties of the composite fabrics were investigated. The overall EMSE shielding effectiveness increased with metal content, but different frequency dependence related to the aspect ratio of metal grid structure was discovered. For stainless steel composite fabrics with same grid openness, fabrics with



(a) (b) (c) (d)

**Figure 10** Effect of shape factor on the EM shielding effectiveness (a) openness ≈ 0.63 mm$^2$; (b) openness ≈ 1.26 mm$^2$; (c) openness ≈ 2.53 mm$^2$; and (d) openness ≈ 5.06 mm$^2$.

open grids of higher aspect ratios showed better EMSE in the medium frequency range, whereas fabrics with grids closer to a square shape showed the best EMSE in the low and high frequency ranges. It was shown that the EMSE of the metal composite fabrics could be tailored by modifying the metal grid size and geometry. The possible usage of the metal composite fabrics for EMSE was explored. Further studies will be carried out to investigate the thermal comfort and aesthetic properties.

## Acknowledgements

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## Literature Cited

1. American Society of Hospital Engineering in the American Hospital Association, Electromagnetic Interference: Causes and Concerns in the Health Care Environment, in “Healthcare Facilities Management Series” (1994).
2. Technology Report, Recent Developments in EMC Standards and Regulations, in “High Frequency Electronics,” pp. 36–38 (2004).
3. Watch Out for Latest Changes in Global EMC Regulations, Issue 12, Underwriters Laboratories Inc. (2004).
4. Editors of Conformity, EMC Regulations and Standards: Requirements for ITE, in “Conformity Annual Guide,” pp. 36–45 (2007).

5. King, R. W. P., Electrical Currents and Fields Induced in Cells in the Human Brain by Radiation from Hand-held Cellular Telephones, *J. Appl. Phys*. **87**, 893–900 (2000).
6. Gandhi, O. P., Electromagnetic Fields: Human Safety Issues, *Annu. Rev. Biomed. Eng.* **4**, 211–234 (2002).
7. Hocking, B., and Westerman, R., Neurological Effects of Radiofrequency Radiation, *Occup. Med. (Lond.)* **53**(2), 123–127 (2003).
8. Zamanian, A., and Hardiman, C., Electromagnetic Radiation and Human Health: A Review of Sources and Effects, High Frequency Electronics, in "Summit Technical Media," pp. 16–26 (2005).
9. Ericsson, Radio Waves and Health, Mobile Communications, Ericsson Brochure from 2006, Cited 2007 May 25, Available from: http//www.ericsson.com
10. World Health Organization Homepage on the Internet, World Health Organization 2007, Cited 2007 May 30, Available from: http//www.who.int/peh-emf/en/
11. Tan, K. S., Hinberg, I., and Wadhwani, J., Electromagnetic Interference in Medical Devices: Health Canada's Past and Current Perspectives and Activities, *IEEE Int. Symp. Electr. Comp.* **2**, 1283–1288 (2001).
12. Chung, D. D. L., Materials for Electromagnetic Interference Shielding, *J. Mater. Eng. Perform.* **9**(3), 350–354 (2000).
13. Motojima, S., Noda, Y., and Hoshida, S., Electromagnetic Wave Absorption Property of Carbon Microcoils in 12–110GHz Region, *J. Appl. Phys.* **94**(4), 2325–2330 (2003).
14. Kuhn, H. H., Adsorption at the Liquid/Solid Interface: Conductive Textiles Based on Polypyrrole, *Textile Chem. Color.* **29**, 17–21 (1997).
15. Deangelis, A., EM Absorptions in Fabrics: Radar Camouflage Systems, Smart Fabrics 2007, Washington DC, USA (2007).
16. Kuhn, H. H., Child, A. D., and Kimbrell, W. C., Toward Real Applications of Conductive Polymers, *Synth. Met*. **71**, 2139–2142 (1995).
17. Angelopoulos, M., Conducting Polymers in Microelectronics, *IBM J. Res. Dev*. **45**, 57–75 (2001).
18. MacDiarmid, A. G., Synthetic Metals: A Novel Role for Organic Polymers, *Synth. Met.* **125**, 11–22 (2001).
19. Chung, D. D. L., Electrical Applications of Carbon Materials, *J. Mater. Sci.* **39**, 2645–2661 (2004).
20. Wang, Y., and Jing, X., Intrinsically Conducting Polymers for Electromagnetic Interference Shielding, *Polym. Adv. Technol*. **16**, 344–351 (2005).
21. Chen, H. C., Lee, K. C., Lin, J. H., and Koch, M., Fabrication of Conductive Woven Fabric and Analysis of Electromagnetic Shielding via Measurement and Empirical Equation, *J. Mater. Process. Technol.* **184**, 124–130 (2007).
22. Cheng, K. B., Cheng, T. W., Nadaraj, R. N., Giri Dev, V. R., and Neelakandan, R., Electromagnetic Shielding Effectiveness of the Twill Copper Woven Fabrics, *J. Reinf. Plast. Comp.* **25**(7), 699–709 (2006).
23. Cheng, K. B., Lee, K. C., Ueng, T. H., and Mou, K. J., Electrical and Impact Properties of the Hybrid Knitted Inlaid Fabric Reinforced Polypropylene Composites, *Composites Part A* **33**, 1219–1226 (2002).
24. Chen, H. C., Lee, K. C., and Lin, J. H., Electromagnetic and Electrostatic Shielding Properties of Co-weaving-knitting Fabrics Reinforced Composites, *Composites Part A* **35**, 1249–1256 (2004).
25. Ramo, S., Whinnery, J. R., and Van Duzer, T., "Fields and Waves in Communication Electronics," 3rd Edn., John Wiley and Sons, New York, USA, pp. 149–153 (1994).
26. Cheng, K. B., Lee, M. L., Ramakrishna, S., and Ueng, T. H., Electromagnetic Shielding Effectiveness of Stainless Steel/Polyester Woven Fabrics, *Textile Res. J.* **71**(1), 42–49 (2001).
27. Su, C. I., and Chern, J. T., Effect of Stainless Steel-containing Fabrics on Electromagnetic Shielding Effectiveness, *Textile Res. J.* **74**(1), 51–54 (2004).
28. ASTM D 4935-99, "Test Method for Measuring the Electromagnetic Shielding Effectiveness of Planar Materials," American Society for Testing and Materials, West Conshohocken, PA, USA (1999).