Chapter

Electromagnetic Function Textiles

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Abstract

This chapter is about the electromagnetic (EM) functional textiles. There are three parts including the EM properties of the textiles, the EM functional textile materials, and the application of the EM functional textiles. In the first part, we outline the textile materials including the fibers, yarns, and fabrics and their EM properties. Generally, textiles are poor in EM properties such as low conductivity and low dielectric and magnetic properties. In the second part, EM functional textiles are defined and the manufacture method is stated. The EM functional fibers and yarns and fabrics can be got by various methods; the EM properties can be improved to a high level. In the third part, several typical EM functional textiles are introduced. These textiles are antistatic textiles, EM shielding textiles, EM scattering textiles, and two-dimensional and three-dimensional frequency selective textiles. The principle, the processing methods, the properties of the static electro or EM shielding or EM scattering or frequency selection, and so on are described one by one in detail.

Keywords: antistatic textiles, EM shielding textiles, EM scattering textiles, frequency selective textiles

1. Electromagnetic properties of textile materials

1.1 The outline of textile materials

The textile materials include various raw fiber materials which are used in textile and various products processed from textile fibers, such as the one-dimensional yarn, thread, rope, and so on; two-dimensional and shape-based fabrics, textile nets, flakes, and so on; and three-dimensional and form-based clothing, braids, utensils, and its reinforced composites. The basic textile processing process is shown in **Figure 1**.

As shown in **Table 1**, the textile materials are essentially different from traditional engineering materials; moreover, textile materials are flexible, easy to change their shape, and generally light weight; these characters can largely compensate the defects of engineering materials. According to the form, textile materials can be divided into fibers, yarns, flat fabrics, and three-dimensional fabrics. The fibers are spun to form the yarns, which are then weaved into the fabrics by weaving technology or knitting technology. In addition, the nonwoven fabrics are formed directly by winding the fibers.

1.1.1 Fiber

The shape of fibers is flexible and elongate, with length (**Figure 2**) and diameter ratio (**Figure 3**) of more than 10^3. Theoretically speaking, the fibers have round and

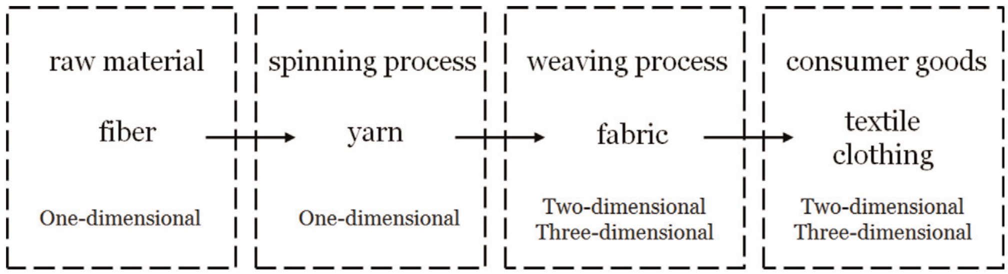

Figure 1.
Basic process of textile processing.

Traditional engineering materials	Transitional material	Textile materials
Rigidity	Flexible	Flexible
Homogeneous state	Solid state	Discontinuous state
Dense, non-permeable	Dense or porous	Porous
Smooth surface	Soft, fillable loose structure	Surface texture
No buckling state	Flexion or non-buckling	Multiple buckling state

Table 1.
The difference between textile materials and traditional engineering materials.

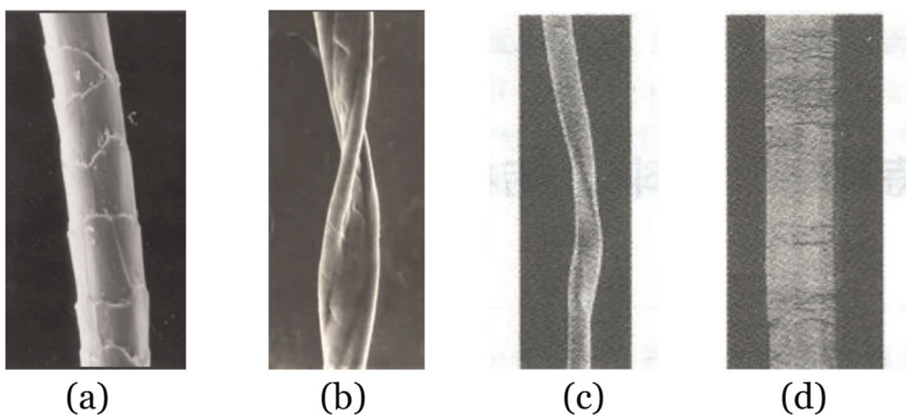

Figure 2.
The longitudinal morphology of natural fibers. (a) Wool fiber; (b) Cotton fiber; (c) Silk fiber; (d) Hemp fiber.

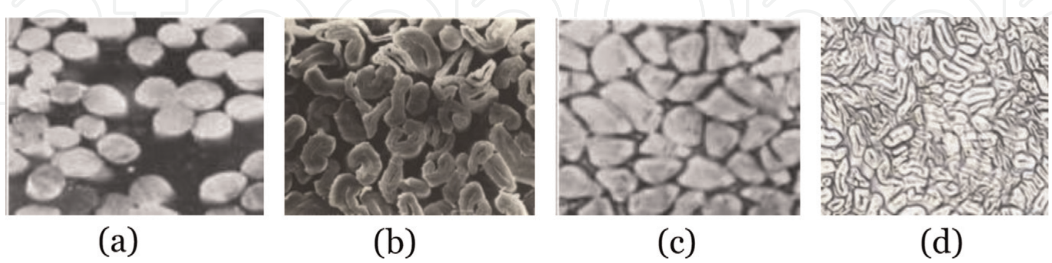

Figure 3.
The cross-sectional morphology of natural fibers. (a) Wool fiber; (b) Cotton fiber; (c) Silk fiber; (d) Hemp fiber.

slender bodies with the continuous homogeneous internal structure. But actually, they have a wide variety of cross-sectional shapes, and section shape changing along the length, heterogeneous internal structure, with the porosity form. According to the source of the fibers, they can be divided into natural fibers and chemical fibers. Fibers such as cotton, hemp, silk, and wool are the natural fibers with the longest history.

1.1.2 Yarn

The yarn is an elongated body having a certain strength and toughness, in which the fibers are arranged in parallel and are cohered or entangled by twisting or other methods. The yarn is an intermediate product of textile processing. A number of short fibers or filaments are arranged in an approximately parallel state and twisted in the axial direction to form an elongated object having a certain strength and linear density, which is called the "yarn." The strand of two or more single yarns is called the "thread" (**Figure 4**).

1.1.3 Fabric

A two-dimensional object having thin thickness, large length, and wide width formed by interweaving and interlacing textile fibers and yarns by a certain method is the flat fabric. There are a variety of fabrics (as shown in **Figure 5**); they could have various materials, forms, colors, structures, and formation methods.

According to the forming methods, the fabrics can be divided into woven fabric, knitted fabric, and nonwoven fabric. The woven fabric is composed by warp and weft yarns arranged perpendicularly to each other according to some organization rules. The knitted fabric is formed by the yarns bent into a loop. Nonwoven fabrics are reinforced by oriented or randomly arranged fiber webs.

1.2 Electromagnetic properties of textile materials

Traditional textile materials are mostly dielectric materials and are important electrical insulation materials. The electromagnetic properties of textile materials include electrical conductivity, dielectric properties, electrostatic and magnetic properties.

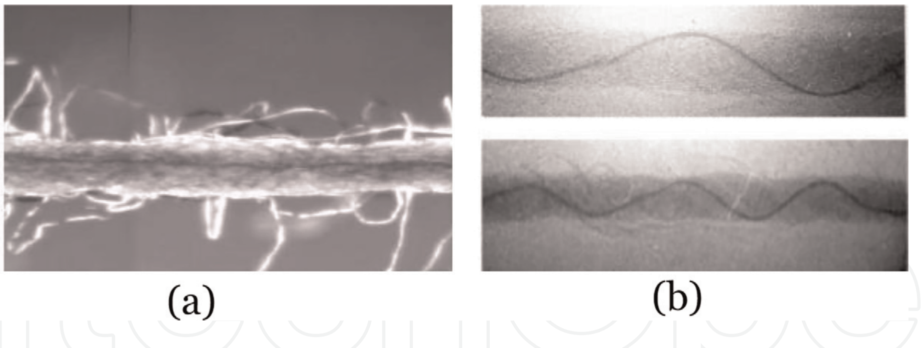

Figure 4.
The morphology of one kind of the yarn. (a) The appearance of the yarn and (b) The distribution of fibers in the yarn.

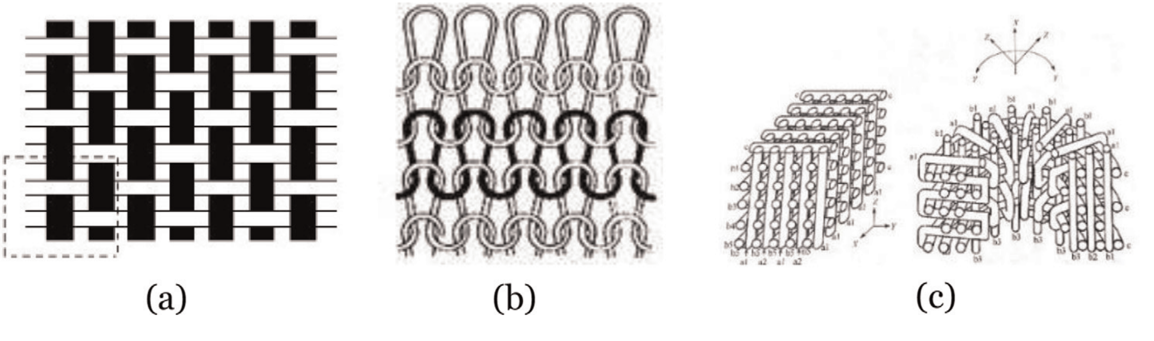

Figure 5.
The type of the fabric. (a) Woven fabric; (b) Knitted fabric and (c) Nonwoven fabric.

1.2.1 Conductive properties

The electrical conductivity of textile materials is expressed as specific resistance. There are usually three representations: volume specific resistance, mass specific resistance and surface specific resistance (**Table 2**).

According to the law of resistance, the resistance R of the conductor is proportional to the length L of the conductor, inversely proportional to the cross-sectional area S, and related to material properties. That is,

$$R = \rho_V \cdot \frac{L}{S} \tag{1}$$

where ρ_V is the resistivity or volume specific resistance and its unit is Ω cm, and it is the physical expression that indicates the electrical conductivity of a material.

For textile materials, the cross-sectional area or volume is not easy to measure; so, we usually use the mass specific resistance ρ_m rather than the volume specific resistance ρ_V to indicate the conductivity of textile materials, especially for the fibers and yarns.

$$\rho_m = d \cdot \rho_V \tag{2}$$

where ρ_m represents the mass specific resistance, and the unit is Ω cm/cm^2. d is the density of the material in 1 g/cm^3. In actual measurement, the moisture content of the fiber or the relative humidity of the air has a great influence on its electrical resistance. The dried textile fibers have extremely poor electrical conductivity, and their mass specific resistance is generally bigger than 10^{12} Ω cm/cm^2. For most textile materials, there is an approximate relationship between the moisture content M and the mass specific resistance ρ_m of the textile materials in the range of 30–90% relative humidity:

$$\lg\rho_m = -n\lg M + \lg K \tag{3}$$

where n and K are experimental constants.

Type of fiber	lg ρ_m	n	lg K
Cotton	6.8	11.4	16.6
Ramie	7.5	12.3	18.6
Silk	9.8	17.6	26.6
Wool	8.4	15.8	26.2
Washed wool	9.9	14.7	26.6
Viscose fiber	7.0	11.6	19.6
Acetate fiber	11.7	10.6	20.1
Acrylic	8.7	—	—
Acrylic (degreasing)	14	—	—
Polyester	8.0	—	—
Polyester (degreasing)	14	—	—

Table 2.
Mass specific resistance of textile materials.

1.2.2 Dielectric properties

1.2.2.1 Dielectric constant

The dielectric constant of dried fiber is 2–5 at the frequent of 50 or 60 Hz. The dielectric constant of the liquid water is 20 and the adsorbed water is 80. The dielectric constants of common textile fibers measured at the frequency of 1 kHz and the relative humidity of 65% are shown in **Table 3**.

As the relative dielectric constant of water is several tens of times larger than that of the dry textile material, the dielectric constant of the fiber is different when the moisture regain or moisture content of the textile material is different. The presence of frequency, temperature, and impurities also changes the dielectric constant of the materials.

1.2.2.2 Dielectric loss

A physical process in which a dielectric converts a portion of electrical energy into thermal energy under the action of an electric field is known as dielectric loss. The magnitude of the dielectric loss is related to the applied electric field frequency, electric field strength, fiber constant, and dielectric loss angle. In unit time, the heat energy P produced per unit volume of fiber is

$$P = 0.556f \cdot E^2 \cdot \varepsilon_r \cdot \tan\delta \cdot 10^{-12} \tag{4}$$

where P is the power consumed by the electric field (W/cm^3); f is the frequency of the applied electric field (Hz); E is the external electric field strength (V/cm); and $\tan\delta$ is the tangent of the dielectric loss angle δ.

The dielectric constant of dry textile material generally is 2–5, for which $\tan\delta$ is equal to 0.02–0.05. The dielectric constant of water is 20–80, for which $\tan\delta$ is 0.15–1.2. Therefore, the higher the moisture content of the textile material, the larger than $\tan\delta$.

1.2.3 Electrostatic performance

The specific resistance of textile materials with dielectric properties is generally high, especially for synthetic fibers with low hygroscopicity, such as polyester and acrylic fibers. Under normal atmospheric conditions, the mass specific resistance is

Fiber	Dielectric constant (ε)	Fiber	Dielectric constant (ε)
Cotton	18	Acetate	4.0
Wool	5.5	Nylon staple fiber	3.7
Viscose fiber	8.4	Nylon yarn	4.0
Viscose wire	15	Polyester staple fiber (deoiled)	2.3
Acetate staple fiber	3.5	Polyester staple fiber	4.2
Acrylic staple fiber (deoiled)	2.8	—	—

The high moisture regain of cotton and viscose leads to its high dielectric constant.

Table 3.
The dielectric constant of common textile fibers.

as high as 10^{13} Ω cm/cm^2 or more. In textile processing, the contact and friction between fibers or between fibers and machine parts tends to trigger charge transfer and static electricity generation. During the production process, static electricity will cause fiber hairiness, hairiness increase, filament winding mechanism, breakage, etc. In the course of the taking process, static electricity will cause clothes to stick and absorb dust.

Although the phenomenon of static electricity leads to many hazards during textile processing, the electrostatic properties of textile materials can also benefit to some processing technology, such as electrospinning and electrostatic flocking.

1.2.4 Magnetic properties

Ordinary textile materials are anti-magnets, which are negative. The magnetic susceptibility of some textile materials is shown in **Table 4**.

The magnetic properties of textile materials are not as much as those of electrical properties, but they are gradually being valued by people to develop various types of magnetic fibers and textiles. For example, magnetic powders such as iron, cobalt, nickel, and ferrite are added to a spinning solution, and fibers having magnetic properties are obtained by wet spinning.

2. Electromagnetic functional textile materials

Common textile materials have dielectric properties and electrostatic phenomena, but the electromagnetic parameter of them has not reached the order of magnitude of metals or semiconductors. Therefore, they generally do not own any electromagnetic function.

2.1 The definition of electromagnetic textile materials

Electromagnetic textile materials are a new type of functional textile materials obtained from fibers or yarns with good electrical and magnetic properties through textile processing technology or by applying the materials with metallic properties to common textile material. Meanwhile, electromagnetic textile materials have unique structure of textile materials and the electromagnetic properties of the metal materials [1, 2].

2.2 Preparation of electromagnetic materials

Ordinary fibers are generally made of nonconductive and non-magnetic polymer materials. To obtain the functionalization of textile materials, special materials must be introduced during the preparation process. Textile materials include fibers,

Material	Magnetic susceptibility (χ)	Material	Magnetic susceptibility (χ)
Ethylene	-10.3×10^{-6}	Polyester	-6.53×10^{-6}
Polypropylene	-10.1×10^{-6}	Nylon 66	-9.55×10^{-6}
Fluorine	-47.8×10^{-6}		

Table 4.
Magnetic susceptibility of some fibers.

yarns, and fabrics. Therefore, electromagnetic functionalization of fibers, yarns, and fabrics can be achieved by spinning, weaving, and finishing.

In the spinning process for fibers, metal fibers, carbon/graphite fibers, or intrinsically conductive polymer materials having intrinsic electromagnetic function may be used to take place of the ordinary fiber materials in whole or in part. It is possible to add the powder having electromagnetic properties to the spinning solution in the blending way during the spinning process.

In the spinning process for yarns, electromagnetic fibers such as metal fibers and magnetic fibers can be added to the ordinary fibers through different ways to combine, producing the electromagnetic yarn. Metal fibers have low elongation and poor toughness; so, they are not suitable to be used alone for weaving. They are often used to form the yarn containing metal fiber with ordinary textile fibers by blending, enveloping, etc.

In the weaving process, electromagnetically functionalized yarns can be directly woven. The common yarns can be interlaced into fabrics with the electromagnetically functionalized yarns.

The finishing process is suitable for fibers, yarns, and fabrics. For the fiber or the yarn that has been formed and does not have electromagnetic function, the surface of it may be coated with a metal coating or magnetic powder by electroless plating, electroplating, magnetron sputtering, or other ways. For ordinary fabrics without electromagnet properties, the surface can be treated by finishing, such as the electroplating, electroless plating, or embroidery to make it electromagnetic.

3. The application of electromagnetic textile materials

3.1 Antistatic textile materials

The electrostatic phenomenon of cellulose fibers in the processing process is not obvious; but the electrostatic interference of protein fibers is pretty serious. Although the wool fiber has high equilibrium moisture regain, its mass specific resistance is the highest in the natural fiber. The resistivity of synthetic fibers such as polyester, nylon, acrylic, and polypropylene, which are generally high in moisture regain, is as high as 10^{14} Ω cm, and the accumulation of electrostatic charge is obvious.

3.1.1 Electrostatic mechanism

The material is excited by various energies, causing the electrons to escape from the nucleus. The electrons overcome the binding of the nucleus, and the minimum energy required to escape from the surface of the material is called the work function. Different materials or the same material in different states have different work function. The generation and accumulation of electric charge causes the substance to carry static electricity, and the one that acquires the electron exhibits the negative electric property, and the one that loses the electron exhibits the positive electric property, which generate the electrostatic phenomenon.

The resistivity of conventional textile materials is up to 10^{10} Ω cm or more, and the generated charge is not easily dissipated, resulting in very serious electrostatic phenomenon. Therefore, the antistatic properties of textile materials have become an important property having a great influence on the processing of textile materials and the use of textiles.

3.1.2 Antistatic technology for textile materials

The antistatic technology of textile materials includes the preparation of antistatic fibers, the preparation of conductive yarns, and the conductive treatment of textiles.

3.1.2.1 The preparation of antistatic fibers

For textile materials with higher mass specific resistance, surfactants are often added to fibers in fiber factories, which absorb water molecules from the environment and reduce static interference in the yarns. The hydrophobic end of the surfactant molecule is adsorbed on the surface of the fiber; the hydrophilic group is pointed to the outer space [3]. Then, the fiber forms the polar surface and adsorbs water molecules in the air. The surface resistivity of the fiber is reduced, and the charge dissipation is accelerated. The method is simple and easy to make; however, the antistatic effect is poor in durability, and the surfactant is volatile and less resistant to washing.

In order to prepare relatively durable antistatic fiber, the methods are following: (1) Adding the surfactant to a fiber-forming polymer during blend spinning; (2) adding the hydrophilic group by block copolymerization; and (3) adding the hydrophilic group by graft modification in a fiber-forming polymer. These can make the fibers obtain durable hygroscopicity and antistatic properties.

In addition, there are also another methods, including fixing the surfactant to the surface of the fiber with a binder and crosslinking the surfactant on the surface of the fiber to form a film. The effect is similar to applying an antistatic varnish onto the surface of the plastic.

Antistatic fibers are usually blended with ordinary fibers, and a higher content of antistatic fibers is required to achieve a more feasible antistatic effect. The specific ratio between antistatic fibers and ordinary fibers should be based on the resistivity of the ordinary fibers used, the final use environment, and requirements of the products.

3.1.2.2 The preparation of conductive fibers

The electrical resistivity of the conductive fiber is smaller than that of the antistatic fiber, and it has a more significant antistatic effect. And during the blend fabrics with the same antistatic effects, the amount of conductive fiber added is much smaller than that of the antistatic fiber [4]. As long as a few thousandths to a few percent of the conductive yarn is added, the fabric can attain antistatic requirements. So with the widespread use of organic conductive fibers [5, 6], the field of application of antistatic fibers has been gradually reduced.

3.2 Electromagnetic shielding textile materials

3.2.1 Shielding effectiveness

Electromagnetic shielding is a technical measure to prevent or suppress the transmission of electromagnetic energy by using a shield. The shield used can weaken the electromagnetic field strength generated by the field source in the electromagnetic space protection zone. There are two main purposes for shielding: one is to limit the field source electromagnetic energy leaking out from the area that needs protection and the other is to prevent the external electromagnetic field energy entering into the area protected.

The shielding effectiveness equals to the ratio of electric field strength E_0 when a point in space is unshielded to the electric field strength E_S of the field after shielding, or the ratio of the magnetic field strength H_0 to the magnetic field strength H_S of the field after shielding, or the ratio of the power P_0 to the P_S of the field after shielding. The shielding effectiveness (SE) can be expressed as follows:

$$SE_E = 20\lg\frac{|E_0|}{|E_S|}, or\ SE_H = 20\lg\frac{|H_0|}{|H_S|}, or\ SE = 10\lg\frac{|P_0|}{|P_S|} \tag{5}$$

Arching method is usually used to measure shielding effectiveness. The schematic diagram is shown in **Figure 6**, which can characterize the shielding effectiveness by measuring the power of the receiving antennas and transmitting antennas.

3.2.2 Conductive grid structure of electromagnetic shielding fabrics

Woven fabric is composed of warp and weft yarns interlaced vertically with each other according to a certain regularity. It is well known that ordinary fiber yarns are transparent to the EM wave, while yarn containing metal fibers is conductive. As metal fiber yarns are closely spaced, continuous conductive paths can be established easily. For an electromagnetic shielding fabric composed of metal fiber yarns or coated with a metal layer or a functional layer, it has a remarkable and typical mesh structure [7], as shown in **Figure 7**. **Figure 7(a)** is a schematic view of the structure of the metal fiber-containing yarn fabric and **Figure 7(b)** is a structural model diagram of the metal fiber yarn extracted in **Figure 7(a)**. The geometric parameters in the figure correspond to the parameters in the fabric: h is the buckling wave height, similar to the thickness of the fabrics in the data; l is the length of the organization cycle; and a is the arrangement cycle spacing of the metal yarns in the fabric.

3.2.2.1 The metallic yarn grid model

The metal fiber yarn fabric is considered as a periodic grid structure model composed of conductive yarns [8], as shown in **Figure 8**. Assume that one parallel periodic array is composed of the warp yarn (as shown in **Figure 8(b)**) and the

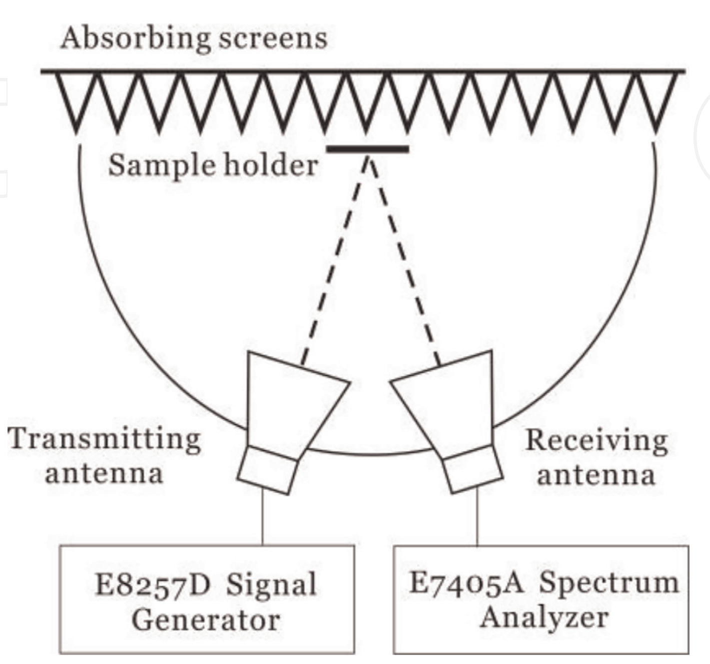

Figure 6.
Schematic diagram of arching measuring method for shielding effectiveness.

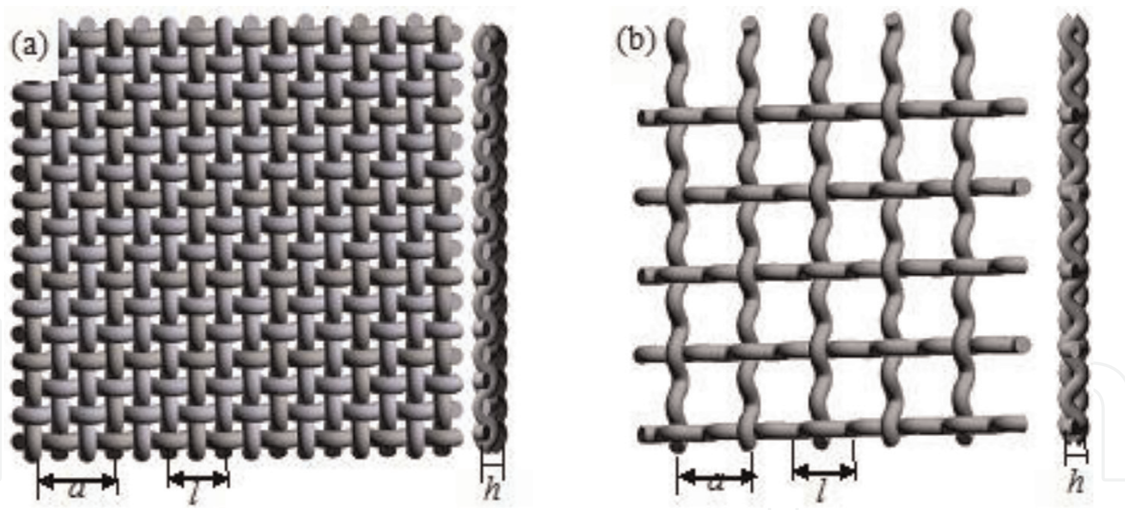

Figure 7.
The grid structure of electromagnetic shielding fabric. (a) Typical mesh structure (b) The structure of the metal fiber-containing yarn fabric.

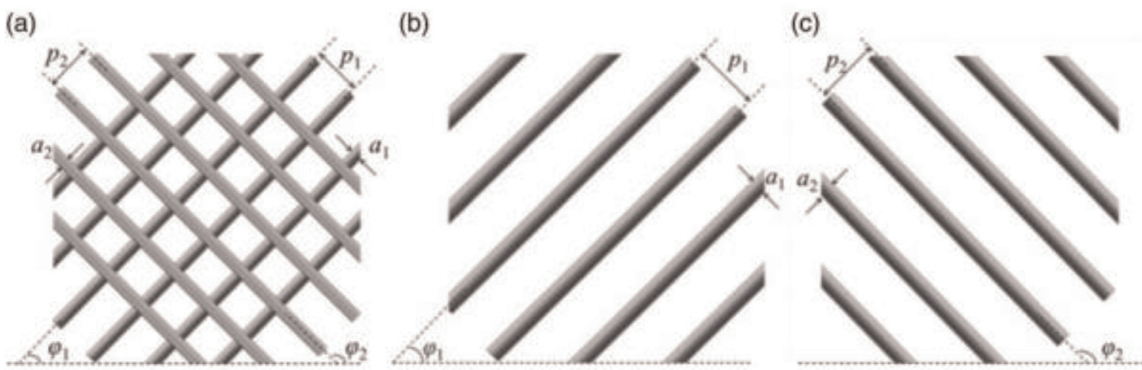

Figure 8.
Grid structure model. (a) Grid structure; (b) Period parallel array 1 and (c) Period parallel array 2.

other is composed of the weft yarn (as shown in **Figure 8(c)**). The two wire arrays are directly cascaded at a certain orientation angle. The contact impedances between the wires of the two arrays are assumed to be negligible, due to the *EM* coupling between the two grid arrays. In particular, the grid structure model is only composed of metal fiber yarns, that is, the effect of ordinary yarns in fabric is not considered.

The two parallel periodic arrays (as shown in **Figure 1**) have wire orientation ψ_1, ψ_2, and (°); spacing p_1 and p_2 (m); and wire diameter a_1 and a_2 (m), respectively. In most fabric structures, the grid is anisotropic and asymmetric, namely, $\psi_1 \neq \psi_2$, $p_1 \neq p_2$, and $a_1 \neq a_2$.

3.2.2.2 Shielding effectiveness of the grid model

The periodic grid is regarded as a stratified medium made of two periodic parallel arrays at a certain angle. The transmission matrix was established, and the *SE* for different polarization incident waves was calculated by analyzing the propagation of *EM* fields passing through the wire mesh. It can be used for the calculation of the *SE* of isotropic and anisotropic metal wire mesh structures for different polarization.

The grid is excited by a plane wave having normal incidence, and the incident *EM* wave can be decomposed into TM_Z (transverse magnetic: the magnetic field component only in the plane perpendicular to the propagation direction) and TE_Z (transverse electric: the electric field component only in the plane perpendicular to the propagation direction) polarized waves, that is, the vertical polarization wave and the horizontal polarization wave, respectively, as shown in **Figure 9**.

ε_0 and μ_0 are the dielectric constant and absolute permeability of free space, respectively. Assume that the metallic yarns are lossy and characterized by the per-unit-length impedance Z_w (unit: Ω/m). The skin depth is given by

$$\delta = \sqrt{\frac{1}{\pi f \mu_0 \mu_r \sigma}} \tag{6}$$

where δ is the skin depth (m); μ_0 is permeability of the vacuum (H/m); μ_r is relative permeability of the conductive yarns; σ is electrical conductivity (S/m); and f is frequency (Hz).

As shown in **Figure 10**, the global coordinate system (x, y, z) and the local one (ξ, ψ, ζ) are introduced. The ζ-axis is parallel to the wires of the array; the x-axis is parallel to the ξ-axis, and they are perpendicular to the plane of the periodic parallel array, which has yarn orientation ψ, spacing p, and yarn diameter a.

Assuming that the diameters of the metallic yarns and periodic spacing are small compared to the wavelength, then the parallel array can be modeled by a homogeneous thin anisotropic sheet with thickness a. Under the condition of the *EM* wave having normal incidence, the following relations can be written among the propagating field components expressed in the local coordinate system and averaged over the wire array period, on each side of the sheet.

$$E_\zeta(a) = E_\zeta(0) \tag{7}$$

$$E_\psi(a) = E_\psi(0) \tag{8}$$

$$H_\zeta(a) = H_\zeta(0) \tag{9}$$

$$H_\psi(a) = H_\psi(0) + J \tag{10}$$

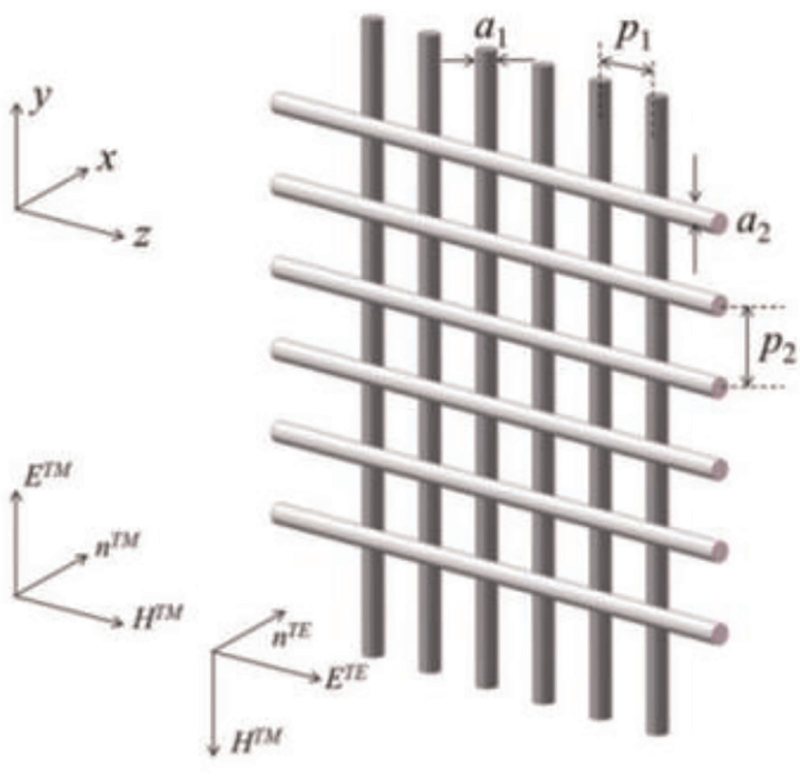

Figure 9.
*Schematic wire mesh illuminated by a plane wave with normal incidence and transverse magnetic (*TM*) or transverse electric (*TE*) polarization.*

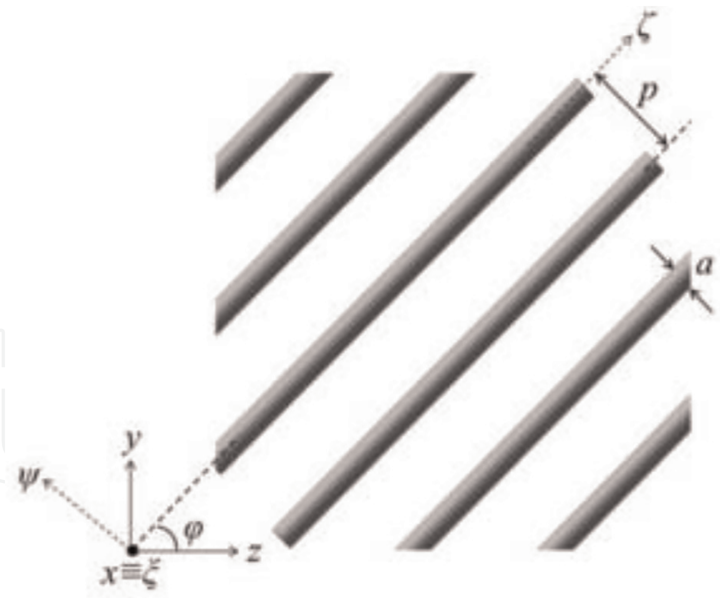

Figure 10.
The periodic array in the local coordinate system and the global coordinate system.

in which J is the current density (A/m^2) flowing inside the wire and all quantities are considered to be averaged over the wire array period. The current density J can be related to the tangential average electric field components along the wires. According to the following impedance condition,

$$E_\zeta(0) = Z_S J \tag{11}$$

in which the expressions of impedance Z_S for the periodic array are given by

$$Z_S = \left[Z_W p9 + j\alpha\sqrt{\mu/\varepsilon}\right] \tag{12}$$

where μ (H/m) and ε (F/m) are the magnetic permeability and dielectric constant of the substrate, respectively; α is a parameter that depends on the geometry structure of the periodic array and on the wavelength in the substrate λ_W (m).

$$\alpha = (p/\lambda_W)\log\left(p/(a\cdot\pi)\right) \tag{13}$$

Combining Eqs. (10) and (11) yield

$$H_\psi(a) = H_\psi(0) + E_\zeta(0)/Z_S \tag{14}$$

According to Eqs. (7)–(9) and (14), the boundary condition describing the relation among the *EM* field components tangential to the conductive grid is obtained, and its matrix expression is

$$\begin{bmatrix} E_\zeta(a) \\ E_\psi(a) \\ H_\zeta(a) \\ H_\psi(a) \end{bmatrix} = [\Phi_{loc}] \begin{bmatrix} E_\zeta(0) \\ E_\psi(0) \\ H_\zeta(0) \\ H_\psi(0) \end{bmatrix} \tag{15}$$

in which $[\Phi_{loc}]$ is the transformation matrix of the parallel array in the local coordinate system as follows:

$$[\Phi_{loc}] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1/Z_S & 0 & 0 & 1 \end{bmatrix} \tag{16}$$

In the global coordinate system, the transformation matrix of the parallel array $[\Phi]$ is given by

$$[\Phi] = [R]^{-1}[\Phi_{loc}][R] \tag{17}$$

in which the transformation matrix $[R]$ from the global coordinate system to the local coordinate system is as follows:

$$[R] = \begin{bmatrix} \sin\varphi & \cos\varphi & 0 & 0 \\ -\cos\varphi & \sin\varphi & 0 & 0 \\ 0 & 0 & \sin\varphi & \cos\varphi \\ 0 & 0 & -\cos\varphi & \sin\varphi \end{bmatrix} \tag{18}$$

The grid array transmission matrix $[\Phi]$is

$$[\Phi] = \begin{bmatrix} [U] & [0] \\ [Y_T] & [U] \end{bmatrix} \tag{19}$$

where $[U]$ and $[0]$ are the bi-dimensional unit and null matrices, respectively, and $[Y_T]$ is the effective shunt admittance of the parallel array; its matrix expression is

$$[Y_T] = \frac{1}{Z_S}\begin{bmatrix} -\sin\varphi\cos\varphi & -\cos^2\varphi \\ \sin^2\varphi & \sin\varphi\cos\varphi \end{bmatrix} \tag{20}$$

The total thickness of the wire grid is $a_M = a_1 + a_2$; the orientations of two parallel arrays are ψ_1 and ψ_2, respectively, and the effective shunt admittances are $[Y_{T1}]$ and $[Y_{T2}]$, respectively. The transmission matrix of the grid is the product of two parallel array transmission matrixes $[\Phi_1]$ and $[\Phi_2]$ as shown below:

$$[\Phi_M] = [\Phi_2][\Phi_1] = \begin{bmatrix} [U] & [0] \\ [Y_M] & [U] \end{bmatrix} \tag{21}$$

in which the effective shunt admittance $[Y_M]$ of the grid is

$$[Y_M] = [Y_{T1}] + [Y_{T2}] \tag{22}$$

Therefore, the matrix of the boundary condition for the metal grid is given as

$$\begin{bmatrix} [E_z(a_M)] \\ [E_y(a_M)] \\ [H_z(a_M)] \\ [H_y(a_M)] \end{bmatrix} = [\Phi_M]\begin{bmatrix} [E_z(0)] \\ [E_y(0)] \\ [H_z(0)] \\ [H_y(0)] \end{bmatrix} \tag{23}$$

The shielding factors of the metal grid of against TM_z and TE_z polarized waves with normal incidence are F_{TM} and F_{TE}, respectively, shown as:

$$F_{TM} = \left|E^{TM,i}\right|^2 / \left|E^{TM}(a_M)\right|^2 \tag{24}$$

$$F_{TE} = \left|E^{TE,i}\right|^2 / \left|E^{TE}(a_M)\right|^2 \tag{25}$$

in which $\left|E^{TM,i}\right|$ and $\left|E^{TE,i}\right|$ are the amplitude of the incident electric field for the TM_z and TE_z polarized plane waves, respectively. $\left|E^{TM}(a_M)\right|$ and $\left|E^{TE}(a_M)\right|$ are the amplitude of the corresponding transmitted electrical field. $[\eta_0]$ is the free space wave impedance and $\left[E^i\right]$ is the vector of the incident electric field.

The electric field component on the back faces of the grid expressed in matrix form is given by

$$[E(a_M)] = 2\eta_0^{-1}\left[Z_{eq}\right]\left[E^i\right] \tag{26}$$

in which

$$\left[Z_{eq}\right] = \left\{[Y_M] + 2[\eta_0]^{-1}\right\}^{-1} \tag{27}$$

In the case where the incident wave is the TM_z polarized wave, set $\left[E^i\right] = [0E^y{}_i]_t$. Therefore, the amplitude of the transmitted field is

$$\left|E^{TM}(a_M)\right| = 2\eta_0^{-1}\left\{\left|Z_{eq}(1,2)\right|^2 + \left|Z_{eq}(2,2)\right|^2\right\}^{1/2}\left[E_y^i\right] \tag{28}$$

Similarly, for a TE_z polarized incident wave, set $\left[E^i\right] = [E^y{}_i, 0]_t$. Therefore, the amplitude of the transmitted field is

$$\left|E^{TE}(a_M)\right| = 2\eta_0^{-1}\left\{\left|Z_{eq}(1,1)\right|^2 + \left|Z_{eq}(2,1)\right|^2\right\}^{1/2}\left[E_z^i\right] \tag{29}$$

The shielding factors are, respectively

$$F_{TM} = \frac{\eta_0^2}{4}\left\{\left|Z_{eq}(1,2)\right|^2 + \left|Z_{eq}(2,2)\right|^2\right\}^{-1} \tag{30}$$

$$F_{TE} = \frac{\eta_0^2}{4}\left\{\left|Z_{eq}(1,1)\right|^2 + \left|Z_{eq}(2,1)\right|^2\right\}^{-1} \tag{31}$$

The SE against TM_z and TE_z polarized incident waves are, respectively

$$SE^{TM} = 10\lg F_{TM} \tag{32}$$

$$SE^{TE} = 10\lg F_{TE} \tag{33}$$

For isotropic material, the transmitted EM power due to incident TM_z or TE_z polarized plane waves is equal. Namely

$$\left|E^{TM}(a_M)\right| = \left|E^{TE}(a_M)\right| = |E(a_M)| \tag{34}$$

For anisotropic materials, the total incident and transmitted power are computed as the average of the two polarizations

$$P^i = \left[\left|E^{TM,i}\right|^2 + \left|E^{TE,i}\right|^2\right] / (4\eta_0) \tag{35}$$

$$P = |E(a_M)|^2/(2\eta_0) \tag{36}$$

From Eq. (6), we obtain

$$SE = 10\lg\left(\frac{F_{TM} + F_{TE}}{2}\right) \tag{37}$$

For the grid that is isotropic in the (y, z) plane, the *SE* against the two polarized waves is coincident. It results in

$$SE = SE^{TM} = SE^{TE} \tag{38}$$

3.2.3 Influencing factors for electromagnetic shielding effectiveness

In combination with the mesh structure of the electromagnetic shielding fabric, the key factors affecting the electromagnetic shielding effectiveness *SE* are the structural parameters and material parameters of fabric [9, 10]. Some key 1parameters are as following: the periodic spacing of metal yarns, the conductivity of the yarns (decided by the type of yarns, the type of metal fibers, the content of metal fibers), the diameters of the yarns, the arrangement method, the connection of intersections, the direction of incidence of electromagnetic field, and the frequency.

3.2.3.1 The influence of structural parameters on shielding effectiveness

3.2.3.1.1 The influence of periodic spacing on SE

Samples in which copper filaments are arranged in parallel at different intervals have different *SE*. As shown in **Figure 11**, the arrangement periodic intervals of copper filaments are 1, 2, 3, 4, and 5 mm, respectively. The *SE* of 10–14 GHz is 17–20, 7–12, 5–10, 2–5, and 2–4 dB, respectively. It can be seen that as the periodic spacing increases, the shielding effectiveness is significantly reduced.

Metal yarn arrangement interval has an important effect on *SE* of fabrics. The metal yarn periodic spacing is related to these parameters such as fabric density and

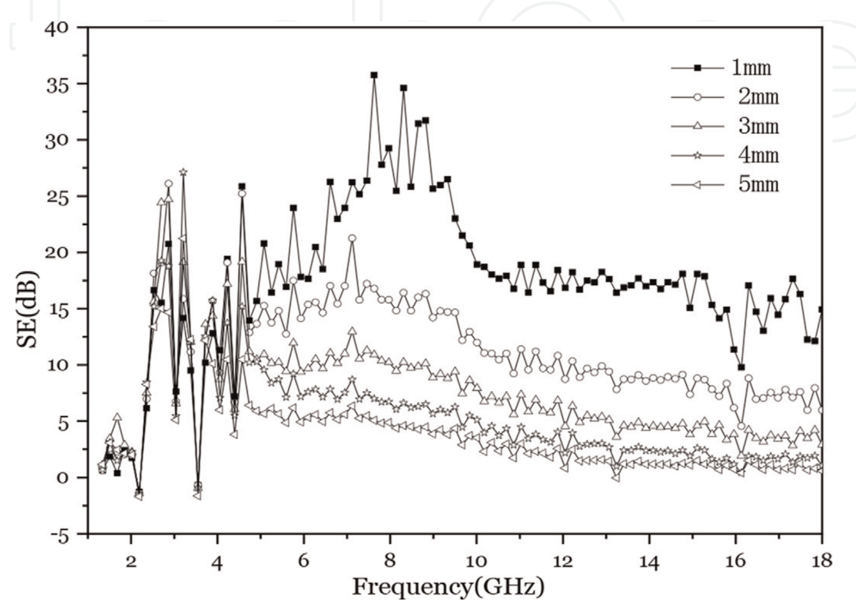

Figure 11.
The shielding effectiveness at different intervals.

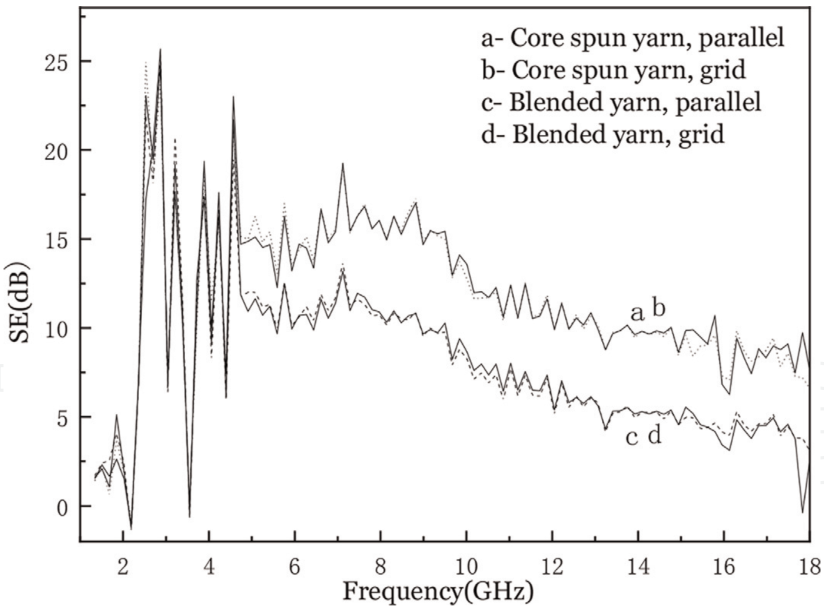

Figure 12.
The shielding effectiveness of metal fiber yarns in parallel and grid arrangement.

tightness. And as the fabric tightness and density increase, the spacing of the metal fibers reduces, the electromagnetic wave transmission decreases, and the *SE* increases.

3.2.3.1.2 The influence of the way of arrangement on SE

The woven fabric is interwoven from the yarns of two systems that are perpendicular to each other. Therefore, it is possible to introduce functional fibers into the parallel structure in only one system, or functional yarns are introduced to both systems to form a grid structure.

The stainless steel core spun yarn and the blended yarn were arranged in parallel as a sample with a spacing of 2 mm, and the distance of the grid structure sample is 2 mm in both vertical and horizontal directions. The shielding effectiveness is shown in **Figure 12**. It can be seen that the *SE* of the yarn model of the parallel arrangement structure is the same to the grid arrangement structure, and as the frequency increases, the *SE* gradually decreases.

3.2.3.1.3 The influence of intersection conduction on SE

Separating the yarns of the horizontal and vertical systems in the sample with a thin insulating plate is seen as a nonconducting state. The bare copper wire is arranged in two states with conduction and nonconduction at the intersection, and the periodic intervals of the grid samples are 1, 2, 3, 4, and 5 mm, respectively, the shielding effectiveness is shown in **Figure 13**. It can be seen that under the same periodic spacing, the shielding effectiveness curves of the copper wire mesh model samples almost coincide in the two states of conduction and nonconduction.

3.2.3.2 Effect of material parameters on shielding effectiveness

The material parameters mainly include the way of forming the metal yarns, the material of the metal fibers, and the content of the metal fibers.

3.2.3.2.1 The effect of the method of forming yarns on SE

Metal monofilaments can be used to make fabrics after they have been formed into yarns by a certain yarn forming method. For metal filaments, core yarns and twisted yarns are the common yarns. However, for metal staple fibers, blended

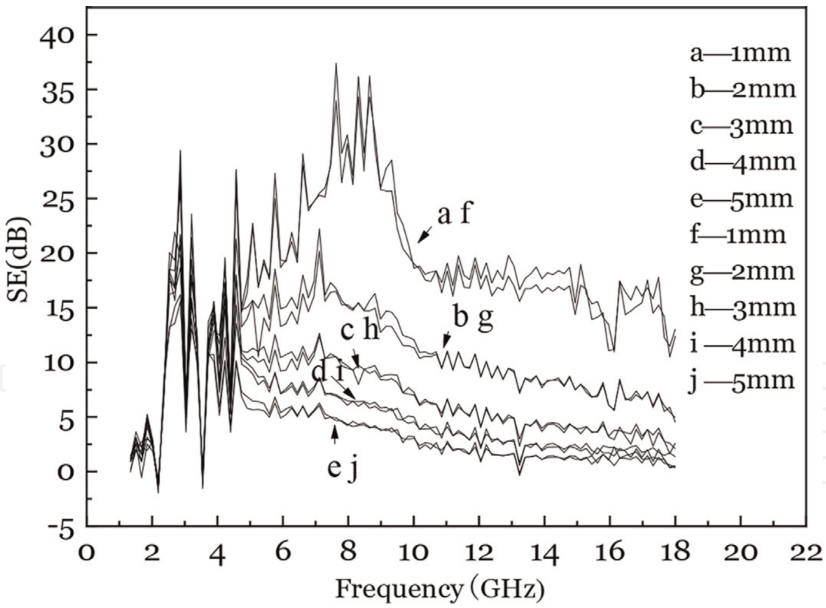

Figure 13.
The shielding effectiveness of metal fiber yarns in parallel and grid arrangement.

yarns are the commonly used yarn. The type of yarns affects the electromagnetic parameters of the yarns and fabrics, resulting in the difference in *SE*.

Stainless steel filaments, core-spun yarns, blended yarns, and twisted yarns composed of stainless steel/cotton with a stainless steel content of 30% are arranged in a grid sample with a periodic spacing of 2 mm. The *SE* is shown in **Figure 14**. At the same spacing, the blended yarns have the best shielding effectiveness, while the shielding effectiveness of stainless steel filaments, core spun yarns, and twisted yarns are equivalent. At the frequency of 8–16 GHz, the *SE* of the former is about 7 dB higher than that of the latter, and both decrease with increasing frequency.

3.2.3.2.2 The effect of the material of the metal fibers on SE

The metal fibers used in the fabric are different, and the different electrical conductivity of the metal may affect the electrical resistivity of the yarns and the

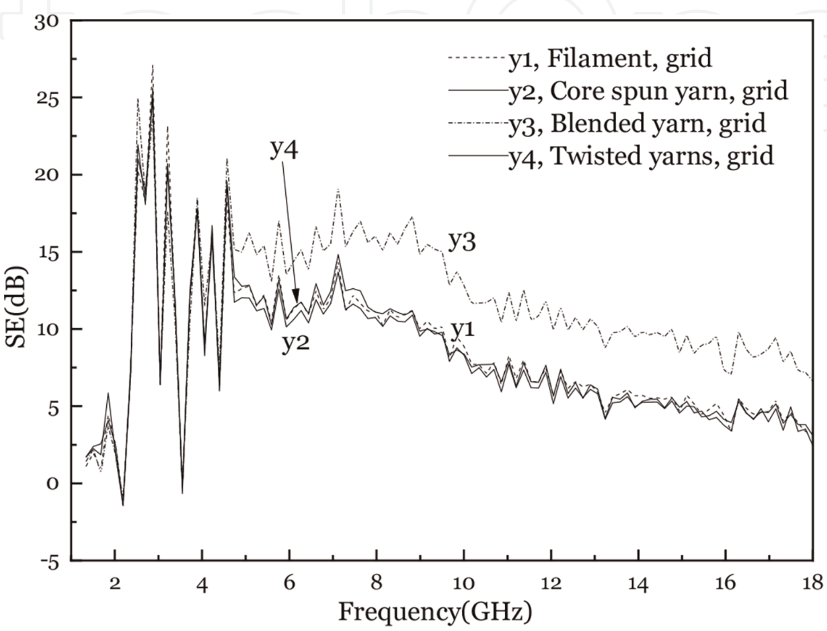

Figure 14.
The shielding effectiveness of different types of yarns.

fabrics. For example, the electrical conductivity of copper fiber is 5.8×10^7 S/m, and the electrical conductivity of aluminum is 3.54×10^7 S/m. When the metal fiber content, linear density, and fabric specification parameters are the same, the *SE* of copper fiber fabrics are better than that of aluminum fiber fabrics.

The five grid samples with completely nonconducting period of 2 mm is shown in **Figure 15**, for which each grid sample of five different materials consisting of stainless steel bare wire (the diameter is 35 μm), core spun yarn and blended yarn of stainless steel/cotton (containing the stainless steel content of 30%), silver-plated nylon filament (the diameter is 50 μm), and bare copper wire (the diameter is 80 μm). The *SE* of the samples made of, respectively, stainless steel blended yarns, silver-plated filaments, and bare copper wires are substantially equal and higher that of the samples of core spun yarn and stainless steel bare wire.

3.2.3.2.3 The effect of metal fiber content on SE

The two blended yarns with the stainless steel content of 20 and 30% are woven in both warp and weft directions, and the *SE* of the obtained sample in the range of 1–18 GHz are shown in **Figure 16**. It can be seen that except for the frequency range of 10 and 12–14 GHz, the *SE* of the fabric with 30% stainless steel content is 5 dB higher than that of the fabric with 20% stainless steel content, and the difference of *SE* in other frequency bands is unobvious. The content of stainless steel fibers has a certain effect on the shielding effectiveness of the fabric, but after reaching a certain level, the difference is not significant.

It is assumed that the fibers are evenly distributed in the yarn. As the content of the metal fibers increases, the shielding effectiveness of the fabrics will increase, but when it is increased to a certain extent, the bending stiffness and flexural modulus of the yarns will increase, and the porosity among fibers during the fabric will increase. So the *SE* of the fabrics becomes slow down or even lower. Considering the cost, the content of stainless steel is generally 20–30% for fabrics containing stainless steel fibers.

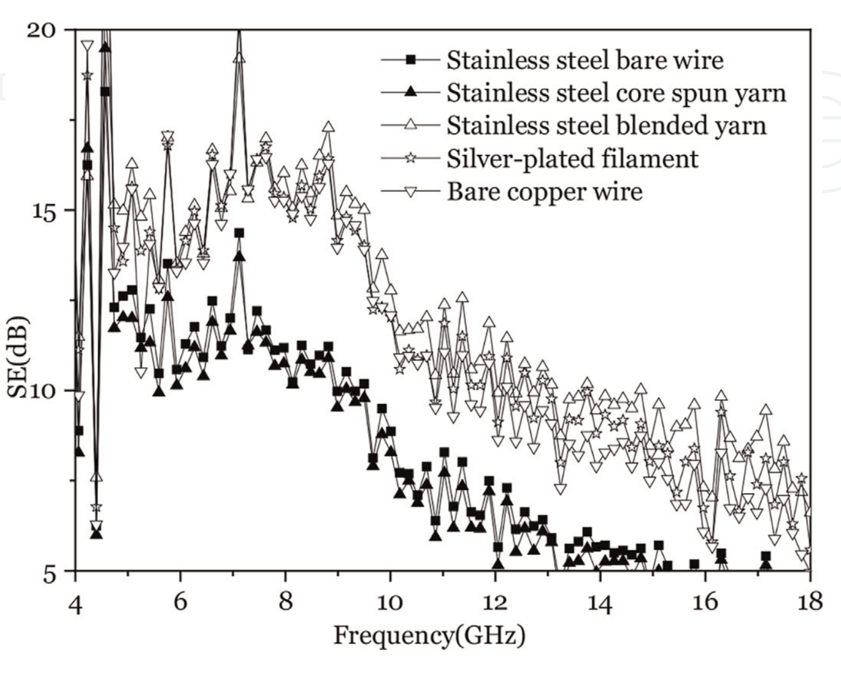

Figure 15.
Shielding effectiveness of different materials with grid period spacing of 2 mm in order.

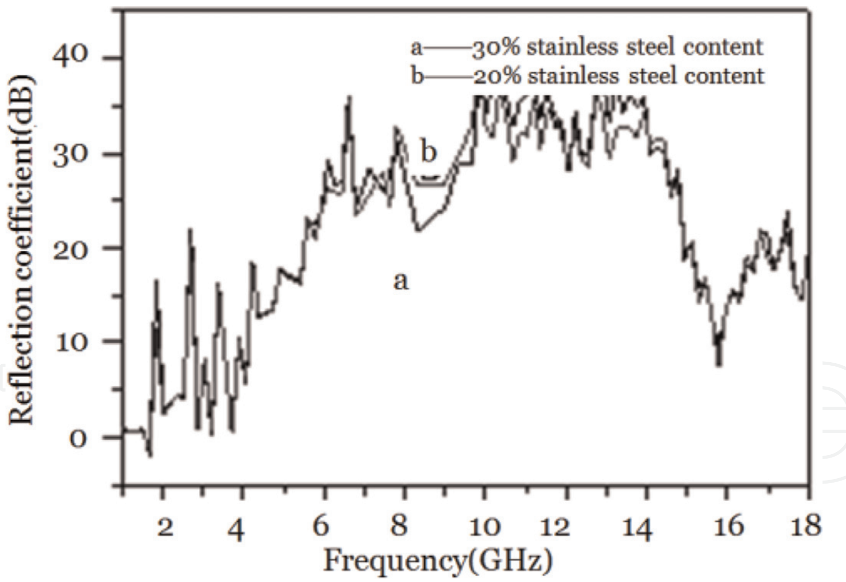

Figure 16.
The shielding effectiveness of the fabrics with different content of stainless steel.

3.3 Electromagnetic scattering fabrics

3.3.1 The mechanism of electromagnetic scattering fabrics

When electromagnetic waves radiate into the macroscopic object, which will causing induced electric charges and currents of the object, then the electromagnetic wave radiated into the object will be scattered into various directions. This process is called electromagnetic scattering [11, 12]. The electromagnetic scattering fabric is an electromagnetic functional material with the specific design structure, which makes the electromagnetic waves incident on the target are no longer reflected back along the way of the reflection of mirror, but radiated out into different directions. Thereby, it can reduce the radiated electromagnetic waves in the direction of propagation, and can make the human body and military targets invisible for certain direction Radar.

The textile technology is relatively mature in the preparation of three-dimensional structural fabrics. Thus, it is very feasible to design the three-dimensional structure of metallized fabrics which have good scattering properties for incident electromagnetic waves.

3.3.1.1 The electromagnetic wave scattering characteristics of linear column unit structures

As shown in **Figure 17**, the composite materials of the three-dimensional periodic structure can be simplified into two-phase dielectric materials when studying the transmission process of electromagnetic waves in the three-dimensional structure.

When a simple harmonic uniform plane wave is incident on the three-dimensional structure, the three-dimensional coordinate system *XYZ* shown in **Figure 18** is selected. The *XOY* plane of the coordinate system coincides with the lower surface of the object, and the *Z* axis is perpendicular to the interface of the upper and lower surfaces. Electromagnetic waves are incident from the upper surface with the incident angle θ, and reflected waves and transmitted waves are generated at the interface of the upper surface. The transmitted waves enter the

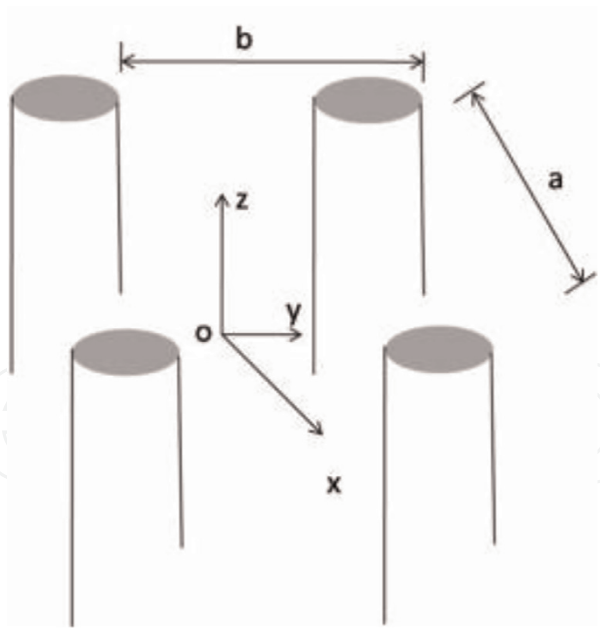

Figure 17.
Dielectric column periodic three-dimensional structure.

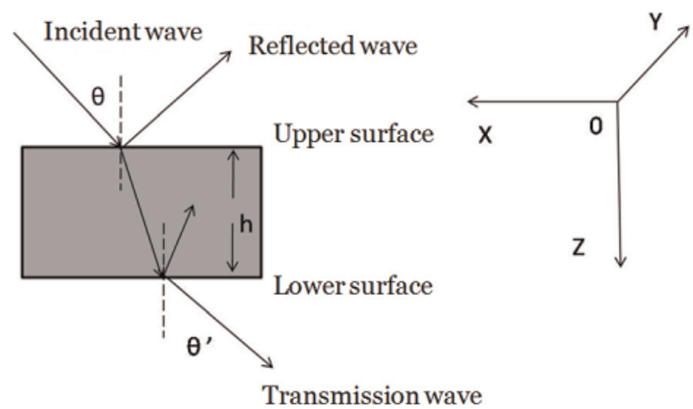

Figure 18.
The schematic diagram of electromagnetic wave incident three-dimensional structure.

periodic three-dimensional structure, and after being attenuated in the three-dimensional structure, the reflected waves and the transmitted waves are again generated at the lower surface interface.

3.3.1.2 The electromagnetic wave scattering characteristics of the concave-convex element structure

Electromagnetic waves are reflected at the interface of different medium, which conforms to the law of reflection, as shown in **Figure 19**. The concave-convex natural surfaces can be broken down into a series of planar elements with small-sized geometries, which is called roughness. The roughness of the scattering surface is very important in the surface scattering.

If the surface is smooth, the incident energy would form two plane waves after interacting with the surface. One is a surface-reflected wave whose angle with the normal is the same as the angle of incidence, and the direction is opposite, as shown in **Figure 20**. The other is refracted or transmitted waves with downward surface.

If the surface is rough, the incident energy interacts with the surface and then radiates and shoots in all directions, becoming a scattering field, as shown in **Figure 21**.

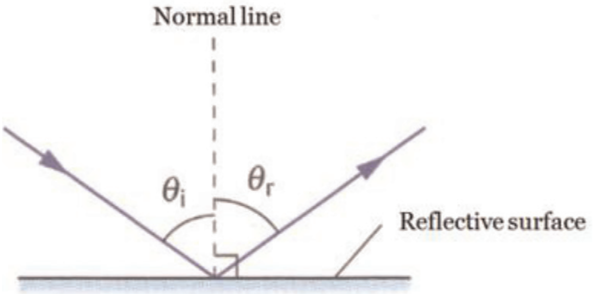

Figure 19.
The law of electromagnetic wave reflection.

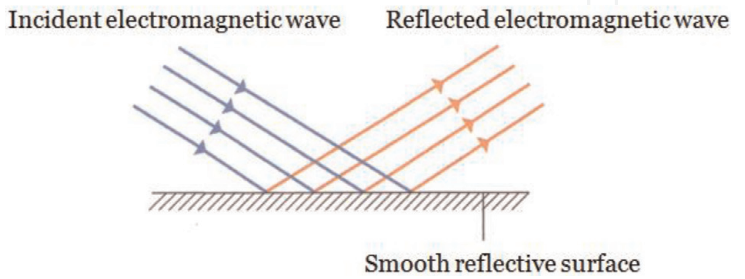

Figure 20.
The reflection of electromagnetic waves on smooth reflective surfaces.

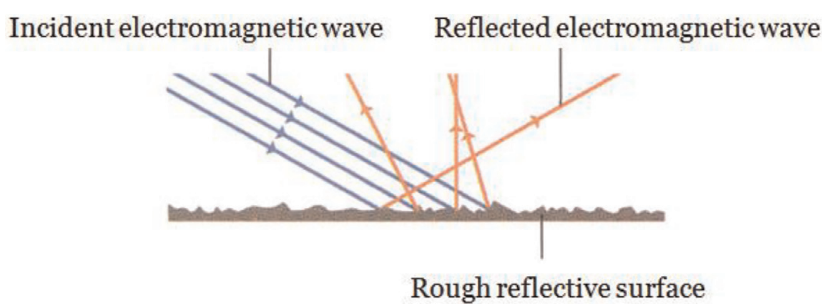

Figure 21.
The reflection of electromagnetic waves on rough reflective surfaces.

3.3.2 The scattering properties of electromagnetically functional textile materials

3.3.2.1 Velvet structure fabrics

The fibers having electromagnetic properties are scattered as the fluff of the fabric on the surface, or are consolidated as a U-shaped structural unit on the fabric to form the fluff, and thereby a velvet structure fabrics with good radar wave scattering property is obtained.

The woven velvet fabric for decoration and its reflection coefficient is displayed in **Figure 22**. It can be seen from the test results that the tested structural unit achieves attenuation of 5 dB in the bandwidth of 10 GHz, and the peak value reaches −30 dB. This is mainly due to the angle between the metal fluff of the structural unit and the plane of the sample. When electromagnetic waves are incident onto the sample, those metal fluffs with a certain angle in the plane have a certain scattering of the incident electromagnetic waves, which reduces the energy received by the receiving antenna, so that the reflection coefficient is reduced.

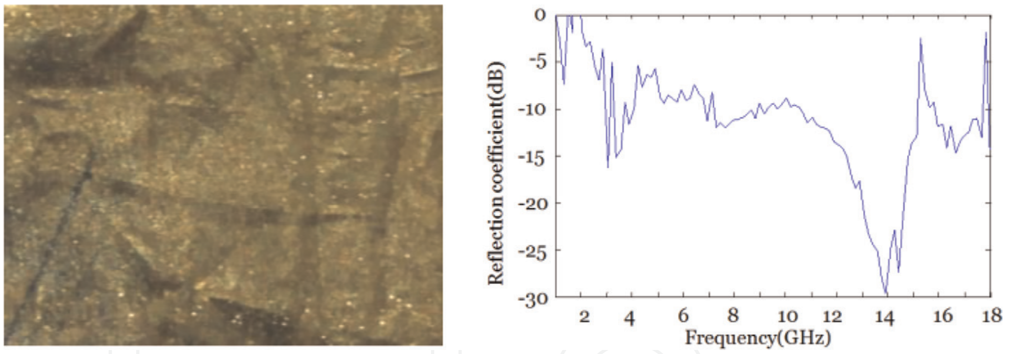

Figure 22.
The woven velvet fabric for decoration and its reflection coefficient.

3.3.2.2 The three-dimensional spacer fabrics

The silver fiber spacer fabric is prepared on the warp knitting machine, of which the silver-plated filaments with a fineness of 83dtex are used in the middle layer, and the upper and lower surfaces are all made of polyester fibers, as shown in **Figure 23**. The silver-plated fibers make the radar waves absorption, reflection, and multiple reflections happen in the intermediate layer.

The silver-plated fiber spacer fabric has a significant resonance peak, which should be related to the thickness of the intermediate layer of the fabric, and indicates that the shielding effect on the radar wave is not mainly due to the reflection radar wave mechanism. The reflectivity of silver-plated fiber spacer fabric is generally inferior to that of velvet fabrics, but its resonance peak can reach −30 dB, and when the reflection coefficient is below −5 dB, it has a wide bandwidth, even up to 18 GHz.

3.3.2.3 Cut flower structure fabrics

The cut fabrics are obtained by cutting fabrics containing metal fibers or metallized fibers into different shapes. The planar fabrics are formed into the three-dimensional structure through some support, and the cut flower units of fabrics become scattering units for radar waves, which are a kind of flexible, lightweight, wide-band radar stealth fabric.

The stainless steel/polyester/cotton blend fabric with a stainless steel content of 20% is cut as shown in **Figure 24**. The reflection coefficient of the fabric in the

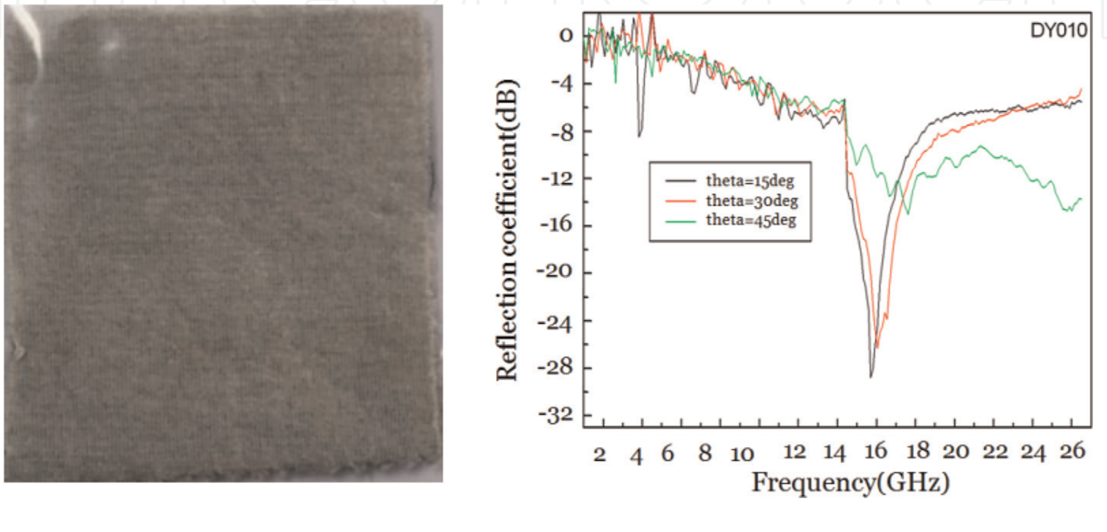

Figure 23.
The silver-plated fiber spacer fabric and its reflection coefficient.

Figure 24.
Cut flower structure fabric. (a) Three-dimensional cut flower fabric and (b) Flat cut flower fabric.

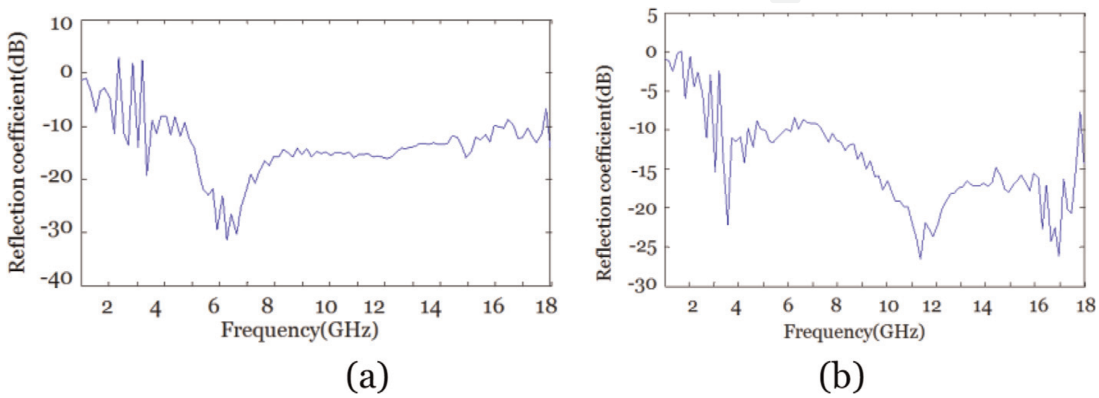

Figure 25.
The reflection coefficient of cut flower structure fabric. (a) The reflection coefficient of three-dimensional cut flower fabric and (b) The reflection coefficient of flat cut flower fabric.

three-dimensional state and the state in which the fabric is flattened is as shown in **Figure 25**.

From the test results, it can be found that the reflection coefficient of the flat structural unit and the uneven structural unit are very large in a wide frequency range, and the coefficient of the uneven cut flower fabric can reach −10 dB at 2 GHz, and the flat cut flower fabric is −5 dB. In the test results, mainly because of the antenna used in the test, the results of the test in the frequency bands less than 3 GHz and greater than 17 GHz are not regular enough. The irregularity of the structural unit produces a strong scattering for electromagnetic waves, making the reflection coefficient smaller. However, the main difference in the structural unit of unevenness and flatness is the difference in the position of the resonance peak that appears. This is because when the mesh structure becomes flat, the size of the unit structure becomes small, so that the resonance peak shifts toward the higher frequency.

3.3.2.4 Uneven surface structure fabrics

By adopting the method of embedding the heat shrinkable yarns, the textured structure containing metal fibers or metallized fibers can be obtained, which imparts good electromagnetic wave scattering properties to the fabric.

The stainless steel fibers and the cotton fibers in a ratio of 40/60 were blended into a yarn of 116dtex linear density, and high heat-shrinkage polyester yarns with a shrinkage ratio of 53.7% in the boiling water and a linear density of 167dtex are embedded in the warp and weft directions. Mixed yarns and polyester yarns are

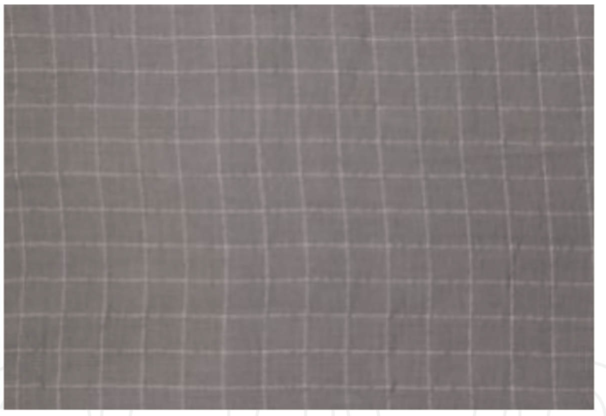

Figure 26.
The original plain weave.

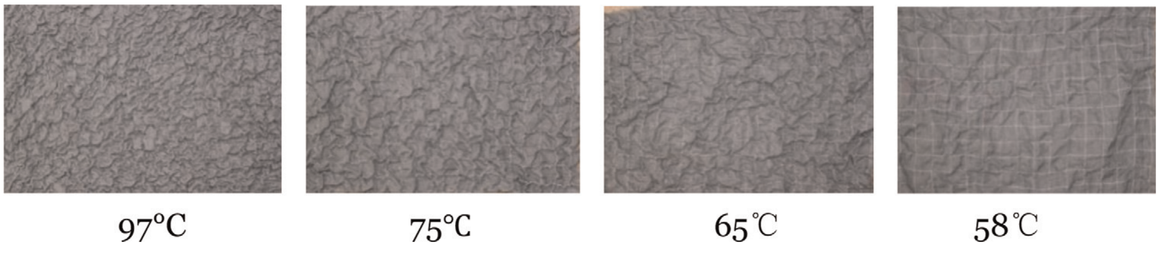

Figure 27.
Stainless steel fabrics with concave structure embedded with high heat shrinkage wires.

woven into a plain fabric with a square weight of 127 g/m^2 (as shown in **Figure 26**). The fabrics are treated at different temperatures to obtain fabrics with different concave and convex structures, as shown in **Figure 27**.

It can be seen from **Figure 27** that the fabrics have different degrees of unevenness at different heat processing temperatures. The higher the treatment temperature, the more obvious the uneven structure; the lower the treatment temperature, the smaller the uneven structure. At 58°C, the fabric has a smaller degree of shrinkage.

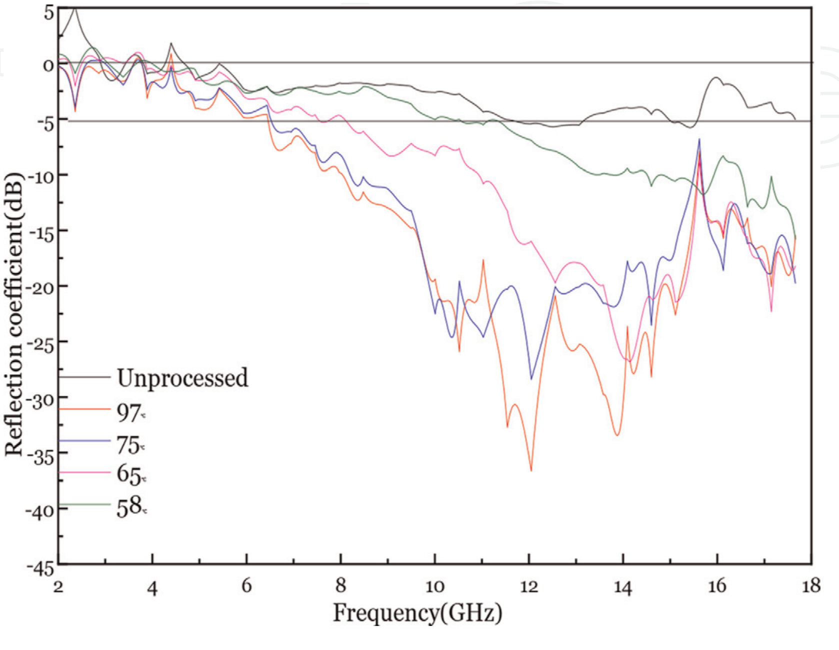

Figure 28.
Comparison of reflection coefficients under different conditions.

As **Figure 28** shows, in the range of 2–18 GHz, for the fabrics containing the heat shrinkage yarns in both directions, as the processing temperature is lowered, the degree of the uneven structure of the fabrics is reduced, the unit size of the concave and convex structure becomes larger, which make the fabrics have poor scattering performance for radar waves. Besides, the reflection coefficients are becoming more and more higher and the difference is obvious. At a frequency of 14 GHz, the reflection coefficients of fabrics having heat treatment temperatures of 97, 75, 65, and 58°C and untreated fabrics, respectively, are −39, −27, −24, −10, and −4 dB. It can be seen from the shrinkage structure at different temperatures that the degree of wrinkles of the fabrics after treatment at 97°C is significantly higher than that of the wrinkles treated at other temperatures. The unevenness of the fabric structure causes the electromagnetic waves to form the diffuse reflection in the structure; meanwhile, the electromagnetic wave scattering forms multiple absorptions on the adjacent two intersecting slopes.

3.4 Frequency selective surface textile materials

3.4.1 The structure and properties of frequency selective surface textile materials

Frequency selective surface (FSS) is an infinitely large periodic array structure that is one-dimensional, two-dimensional, etc. It is mainly divided into two types: patch type and aperture type, which have frequency selective characteristic for the propagation of electromagnetic wave in space. The patch type can totally reflect electromagnetic waves of a specific frequency, and the aperture type can transmit all electromagnetic waves of a specific frequency.

The textiles are light, soft, and flexible in processing. Relying on the media of textile materials, textile processing technology will qualify the textile products to attain the filtering characteristics and light, soft, and other characteristics, which can be applied in more fields [13]. Flexible periodic array structure prepared by textile processing technology is called frequency selective fabric (FSF). According to the filtering characteristics, the frequency selective fabric can be divided into four frequency response characteristics: high pass, low pass, band pass, and band stop, as shown in **Figure 29**.

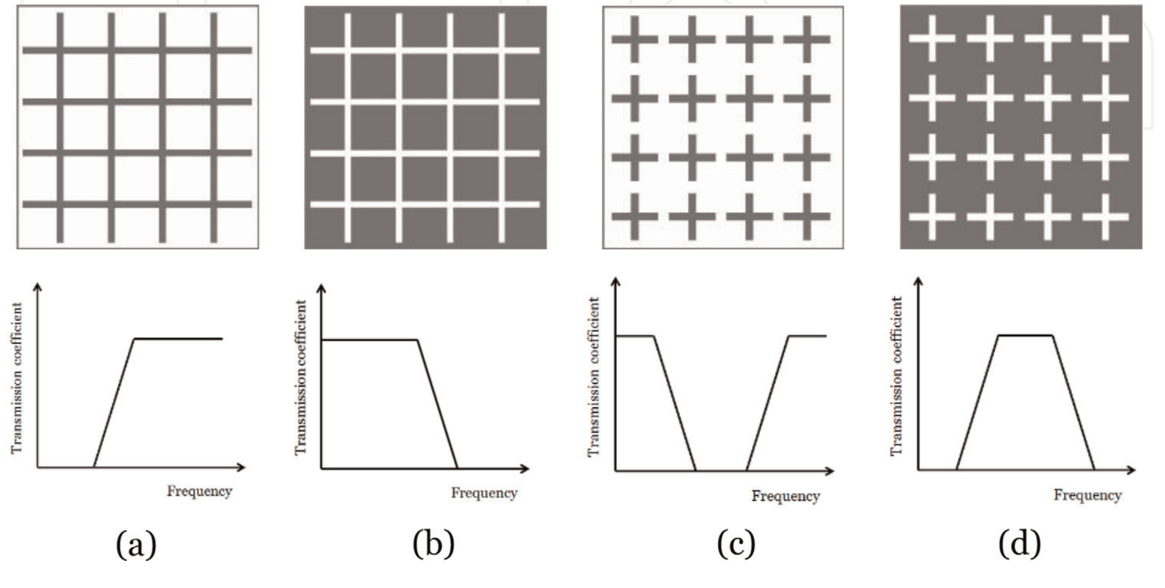

Figure 29.
The four frequency response characteristics of the frequency selective surface. (a) High pass; (b) low pass; (c) band stop; and (d) band pass.

3.4.2 The processing of frequency selective surface textiles

3.4.2.1 The method for preparing frequency selective surface textiles

The researches mainly focus on the preparation of frequency selective fabrics with high-precision two-dimensional periodic structure produced by different textile processing techniques, which can be roughly divided into four categories [14].

1. Continuous conductive yarns form a periodic structure in the fabric. The continuous carbon fibers are directly woven into a square or rectangular periodic structure, as shown in **Figure 30**. Since the conductive carbon fibers are continuously present in the fabric, the structure is actually a conductive grid formed by the conductive yarns in the woven fabric. This structure is more suitable for the preparation of isotropic electromagnetic shielding fabrics, not a true frequency selective periodic structure, which is confirmed by the absence of resonance peaks in the test curves reported in the article.

2. The cut commercialized conductive material unit is directly bonded to the nonconductive fabric substrate, as shown in **Figure 31**.

3. Depositing conductive materials on the surface of fabrics by screen printing, inkjet printing, and other textile finishing techniques can form the conductive structural unit, as shown in **Figure 32**.

4. The high conductive yarns are formed into a periodic structural unit by textile weaving processing techniques such as weaving, weft knitting, embroidery, and so on, as shown in **Figure 33**.

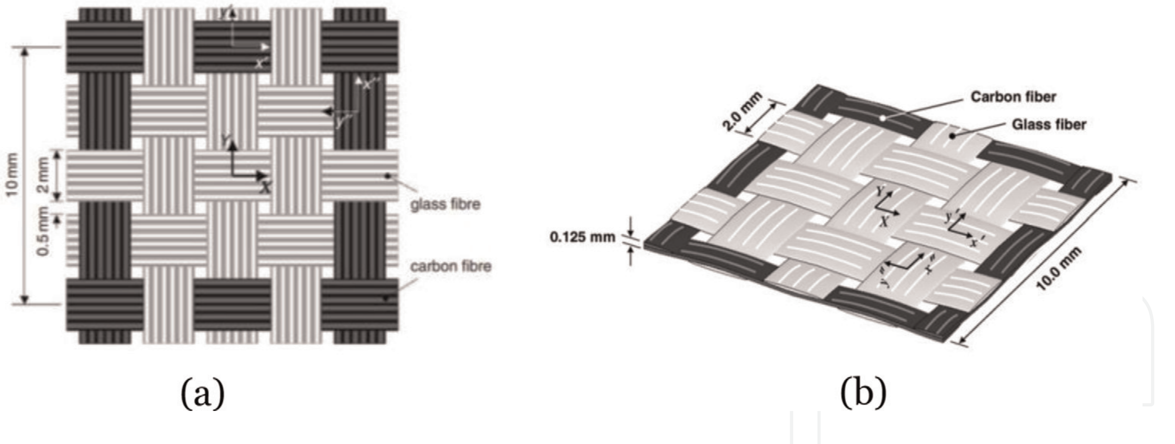

Figure 30.
Continuous conductive yarns form a periodic structure in the fabric. (a) Woven in a square structure and (b) Woven in a square structure rectangle.

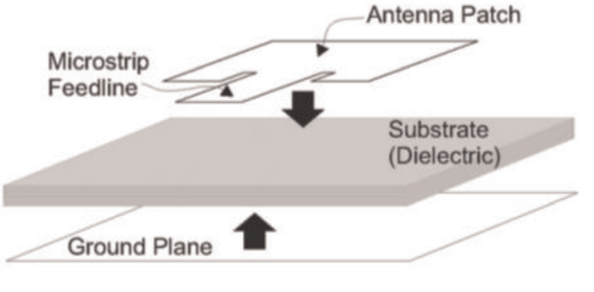

Figure 31.
The conductive material is adhered to the substrate to form a periodic structure.

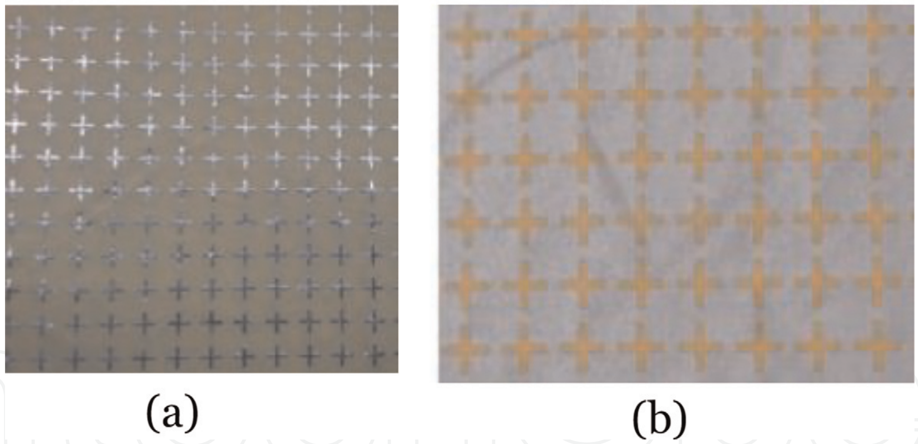

Figure 32.
Screen printing and inkjet printing form a periodic structure. (a) The screen printing and (b) The inkjet printing.

Figure 33.
The periodic structures produced by knitting and embroidery processes. (a) The samples of woven fabrics and (b) The samples of knitted fabrics.

In China, the team that studies the periodic structure of textile materials is mainly a joint research group composed of Professor Meiwu Shi in textile materials and Professor Qun Wang in electromagnetic materials. Based on preliminary sample preparation, theoretical simulation analysis, and the preliminary experimental results and research ideas of special electromagnetic functional textile materials, in the aspect of 2D FSF, various types of bandpass, band-stop filter fabrics, etc. have been prepared by weaving, electroless plating, embroidery, transfer printing, and so on. Through experiments, the effects of cell shape and dimensional changes, periodic spacing, and dielectric materials on transmission and reflection coefficients have been studied.

3.4.2.2 The comparison for frequency selective surface textile materials produced by different processing methods

The preparation of frequency selective surface for flexible materials mainly includes screen printing, laser processing, and computer embroidery [15].

The screen printing is to stretch and fix synthetic fibers, silk fabrics, or mental wire meshes on the frame, using the method of making the hand-painted film or photochemical plate to make the screen printing plate, and the metal ink is squeezed from the mesh of the pattern portion, which is a process for extruding onto a fabric to form a sample. **Figure 34** shows a ring-shaped frequency selective surface of a complementary structure prepared by the screen printing method.

The complementary cross-type frequency selective surface prepared by the laser processing method is directly produced by laser processing on the flexible medium

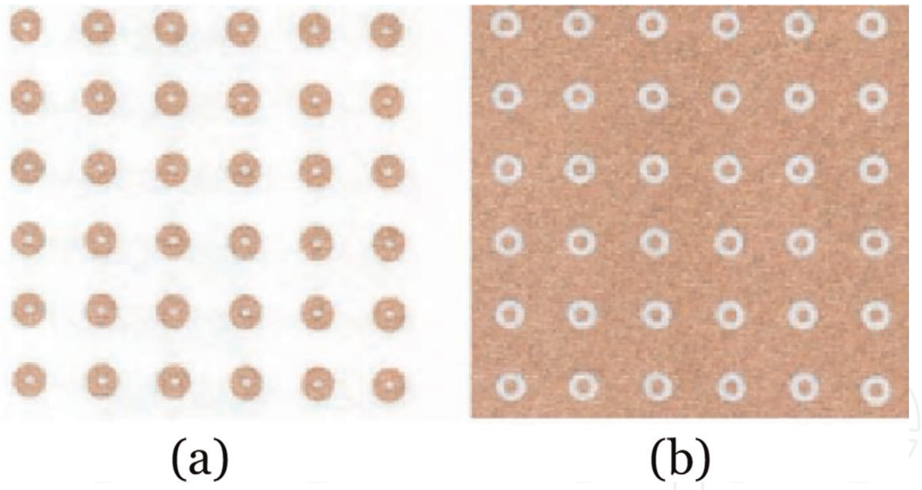

Figure 34.
The ways of screen printing processing. (a) The patch type and (b) The aperture type.

to which metal materials are pasted. The patch type (slit type) sample torn off the excess metal (patch metal) at the gap to obtain the final sample, thus ensuring the process precision of the patch type frequency selective surface (**Figure 35**).

The frequency selective surface with ring patch type is prepared by computer embroidery technology. According to the unit pattern and size of frequency selective surface period designed, the processing personnel uses the sample programming system to make the programming sample, and the needle position data of the design pattern is designed. Using these needle position data to control the computer embroidery machine, the silver-plated yarns are embroidered onto the fabric to produce the fabric material frequency selective surface (**Figure 36**).

The screen printing technology is more adaptable and can be applied to the flexible medium surface in printing; besides, the process is simple, the cost is low, and the quality is relatively stable. However, the screen printing processing has low production efficiency and is only suitable for small batch production, and the image accuracy produced is not high, which has a certain influence on the frequency response characteristics of the product.

The laser processing technology is characterized by high quality, high efficiency, and low cost. The laser processing is a kind of non-contact processing, and the frequency selection surface patterns at the sharp corners such as precise polygons can be obtained, and the products have high precision. Because the excess metal needs to be removed during the sample preparation processing to obtain the desired sample, the production efficiency of the product is affected.

The precision of computer embroidery technology when preparing flexible frequency selective surface is affected by the fineness of the needle, but the process

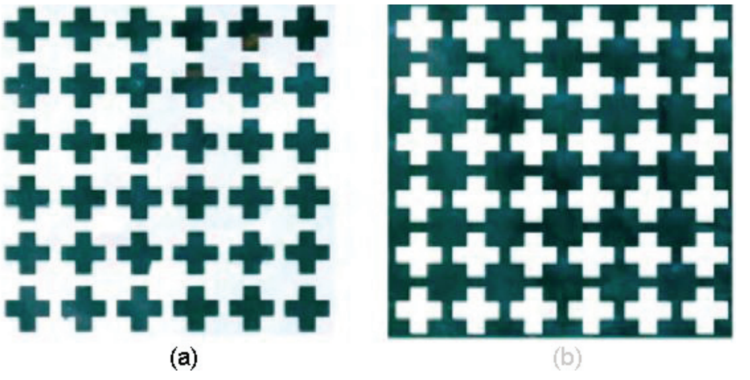

Figure 35.
The laser engraving. (a) The patch type and (b) The aperture type.

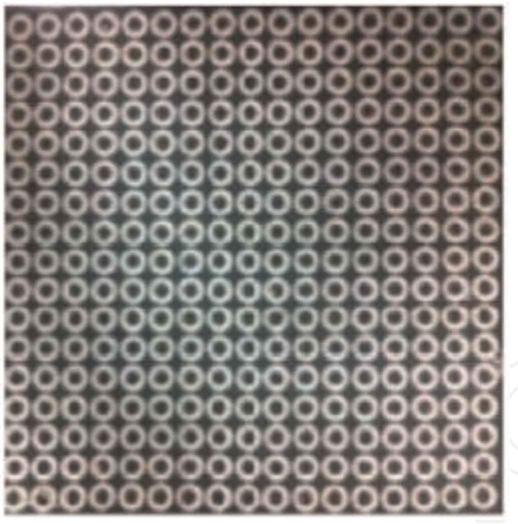

Figure 36.
The computer embroidery processing.

is simple and the production efficiency is the highest. It is suitable for mass production and exhibits better band resistance characteristics at the resonance frequency. The fabric-based frequency selective surface structure can be directly integrated into various textiles such as tents, clothing, and decorative products, and has the advantages of portability, maintenance-free, and low cost.

3.4.3 The frequency selective textile materials with three-dimensional periodic structure

The single-performance frequency selective surface can no longer meet complex electromagnetic wave environments. Incident angle stability, multi-band, wide passband, miniaturization, flexibility, and active frequency selective surfaces are the research hotspots of frequency selective surface in recent years. The use of various processing techniques to convert a two-dimensional FSF into a three-dimensional structure can bring more performance to the frequency selective surface [16].

The 3D FSF consists of the structural unit (white part in **Figure 37**), the dielectric unit (black part in **Figure 37**), and the base medium (gray part in **Figure 37**). In the z-axis direction, the conical stereoscopic periodic structure composed of the structural unit and the dielectric unit and a composite structure of the dipole plane periodically loaded with a base medium structure. At the same time, the 3D FSF has

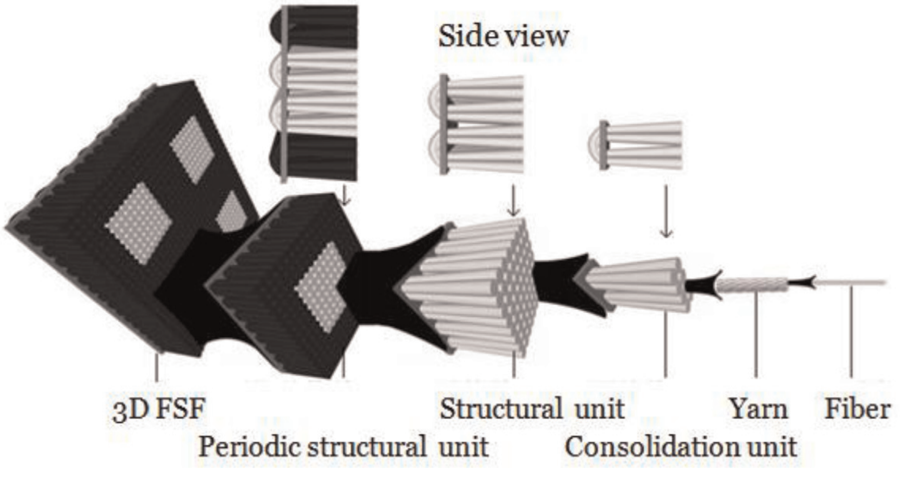

Figure 37.
The multi-scale structure of 3D FSF.

a multi-scale structure and easily deformable feature, and the electromagnetic parameters can be adjusted at multiple scales or by deformation.

Compared with metal periodic structural materials, 3D FSF is characterized by flexibility and can achieve deformation control. During use, the base medium will be the main bearer for external force, especially the elastic base medium with large deformation. The deformation of the substrate medium will cause changes in the size and other dimensions of the various scale structures fixed thereon, further leading to changes in electromagnetic response characteristics [17]. It can be seen that the electromagnetic response of the 3D FSF can be regulated by deformation.

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