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The use of carbon/dielectric fiber woven fabrics as filters for electromagnetic radiation

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ABSTRACT

Fabrics that allow selected microwave frequencies to pass through, called frequency selective fabric composites (FSFCs), were fabricated by weaving carbon fibers and dielectric fibers in periodic patterns. Design parameters affecting the electromagnetic characteristics (EM) of the FSFCs were widely discussed with respect to electrical conductivity of carbon fibers, the type of dielectric fiber and matrix, and weaving patterns. Transmission coefficients of square FSFCs with the aperture sizes of 10 mm and 20 mm were investigated considering electrical conductivity of carbon rovings, fiber undulation, and aperture-to-cell ratio. Compared with metallic frequency selective surfaces (FSSs), lower electrical conductivity of the carbon rovings caused a partial transmission near resonance frequency. The fiber undulation made little effect on the electromagnetic property of FSFCs. In addition, as the aperture-to-cell ratio decreased, the transmission of microwaves through FSFCs substantially decreased around resonance frequencies. The distinct difference in the microwave property of FSFC and FSS near resonance frequency shows that FSFCs can be new candidates as impedance modifier for microwave devices, such as microwave absorbers.

1. Introduction

Two-dimensional planar periodic structures may exhibit low-pass or high-pass spectral behavior depending on the array element type, the aperture or the patch. The periodic structures are known as frequency selective surfaces (FSSs). FSSs have been extensively studied due to their frequency resonating property [1–5]. A common example of FSS is the metallic mesh screen embedded in the door of a microwave oven. This metallic screen blocks electromagnetic radiation from transmitting out of the microwave oven, while allowing visible-light frequencies to pass through the mesh screen so that the operator can safely see inside the oven [6]. In addition, attempts to modify the effective resistance of the Salisbury screen led to the introduction of FSS technology [7], and also FSSs have been combined with continuous fiber-reinforced structural composites and particulate polymer composites to develop aircraft radomes as a band-pass filter and radar-absorbing materials (RAMs) as a band-stop filter for military purposes, so-called stealth technology [7–10].

In general, FSSs are composed of metal, such as copper or aluminum. They are fabricated by chemical etching of a metal-coated thin film on a dielectric film, such as Kapton, using standard circuit board processes. The process requires a second bonding and an adhesive film to attach the FSS film to other structures. It is also possible to employ the same chemical etching techniques directly with a metallized dielectric substrate that is fabricated by curing the dielectric composite sheet with a metal coating. Therefore, the metal-coated composite includes a surplus amount of matrix that

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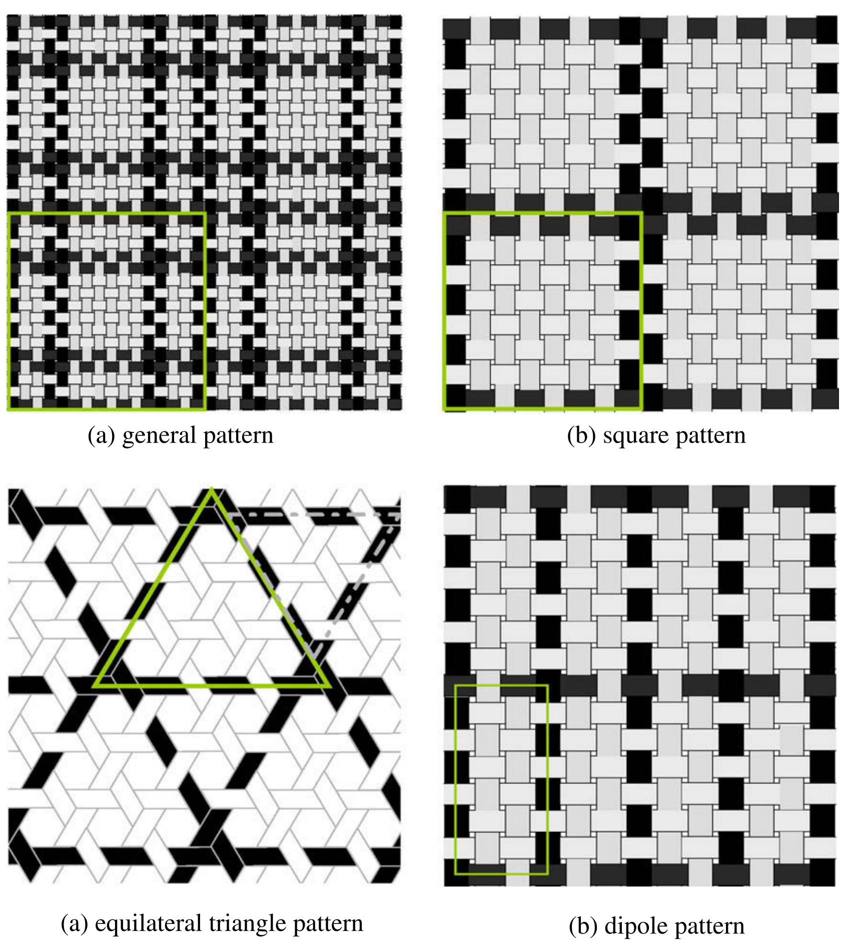
cannot be absorbed into curing accessories such as peel ply and bleeders as the metal exists between the dielectrics and the curing accessories, which results in a decrease of mechanical properties. However, the embedment of the metallic FSS into multilayered structural fiber composites has been studied for years in case of mainly focusing on microwave absorbing functions of the composites [9].

Composite materials which have been used in aerospace engineering can also be employed to realize FSSs. As result of these endeavors, a type of capacitive FSS was made of cross-shaped carbon film by a spraying technique [11], although the layer including the composite patches by itself cannot be considered as reinforcement because of the patches disconnected with each other. On the other hand, a type of inductive FSS was developed by a grid composite structure with glass or carbon fibers filled with spongy materials. The grid can be treated as both reinforcement and impedance modifier, but it needs a thickness to possess sufficient mechanical stiffness and strength [12].

An inductive FSS can be composed of carbon fibers and low-loss dielectric fibers, each with high specific stiffness and strength. These fibers are placed and woven together at regular intervals in order to build a pattern. Carbon fibers reflect incident waves due to the high electrical conductivity, corresponding to metal parts in an established FSS. Dielectric fibers with low permittivity, such as glass, boron, and quartz, transmit most of the incident waves and correspond to aperture parts. Fig. 1 shows the realizable frequency selective fabric composite (FSFCs) with weave patterns or unit cells, such as a square, an equilateral triangle or a dipole. The term, *aperture*, means the middle region of FSFCs where only dielectric fibers are placed.

Due to the high electrical conductivity, carbon fiber composites in unidirectional composite and fabric forms have been used as electromagnetic interference (EMI) shielding material [13–16], and have been investigated regarding the microwave material properties, the fiber orientation and anisotropy of laminates, and the angle and polarization of the incident wave [17,18]. The dominant shielding effectiveness of continuous carbon fiber-reinforced composites mainly results from the reflection, rather than absorption and internal/multiple reflection [13,14]. Microwave properties of glass fiber composites in unidirectional and fabric forms have also been studied experimentally and theoretically [17,18], regarding the parameters mentioned for the carbon composites. However, microwave properties of both fiber composites about weaving patterns were limitedly available and were not studied systematically. Therefore, in our knowledge, this work is the first study on electromagnetic characteristics of hybrid fabric composites with both carbon and dielectric fibers.



(a) general pattern (b) square pattern

(a) equilateral triangle pattern (b) dipole pattern

Fig. 1 – FSFCs with realizable weave patterns.

Compared to a metallic FSS, the FSFC has a less precise size as it is difficult to realize a perfect fiber alignment as well as the exact width of fiber rovings. Nevertheless, the FSFC has advantages over a metallic FSS. Besides the co-curing with dielectric substrates and the reduction in a surplus amount of matrix as mentioned before, the FSFC does not require a backup structure to support it, as the woven structure and matrix keep the element shape of the FSFC intact. In addition, existing fabric fabrication processes make mass production of FSFCs possible, which is very important to apply the FSFC to huge industrial facilities or infrastructures, as well as aircrafts and warships.

This work launched to substitute metallic FSSs with FSFCs which can be used both as impedance modifier to improve absorbing bandwidth of microwave absorbers [8,19,20] and load-bearing layer. In this study, the design parameters of a general FSFC were widely discussed for electromagnetic (EM) application. And then, EM characteristics of the newly proposed FSFC [21] were investigated with regard to fiber volume fraction, anisotropy and frequency dependence of constituent materials. After this endeavor, the FSFC will be used as an impedance modifier embedded into multilayered microwave absorbers [22–24] whose each layer can be composed of a MWCNT (multi-walled carbon nanotube) loaded glass/epoxy fabric composite with different particle loading [24].

2. Design parameters

Properties of fiber-reinforced composites can be designed or tailored by changing the type of fibers and matrices, directions of reinforcement, and stacking sequences. This tailorability of material properties makes it possible to meet design requirements under various environments, such as high temperature, high mechanical loading. Thus, design parameters mainly affecting the electromagnetic characteristics of the proposed FSFCs were investigated.

2.1. *Electrical conductivity of carbon fibers*

The electrical conductivity of carbon fibers depends on the type of precursor, either the polyacrylonitrile (PAN) precursor or the pitch precursor. The PAN-based carbon fibers tend to have an intermediate stiffness and a relatively high strength, whereas the pitch-based carbon fibers tend to exhibit high stiffness and high electrical and thermal conductivities [27,28]. The electrical conductivity of carbon fibers also has a dependency on the heat treatment temperature (HTT). Controlling the HTT can cause the conductivity to be in a range of 10^4–10^5 S/m [25,26].

If the hybrid yarns of carbon and low-loss dielectric fibers, shown in Fig. 2, are used instead of carbon fibers, they can lead to the variation of transmission near a resonance frequency. This is due to the hybrid yarns having a lower conductivity than typical carbon fibers and due to the fact that the skin depth $(1/\sqrt{\pi f \mu \sigma})$ is proportional to the electrical conductivity σ. The skin depth is defined as a depth below the surface of the conductor at which the electric field is reduced by a factor of $1/e$ ($\approx$0.368). In other words, the control of the carbon fraction of the hybrid yarns can result in a variation of electromagnetic characteristics of the FSFCs.

2.2. *Form of fibers and weave patterns*

Fibers usually assume the form of yarns or rovings. Yarns can be defined as an assembly of twisted monofilaments or strands, and rovings can be thought of as parallel continuous monofilaments or strands. After curing, rovings have more uniform cross sections than yarns do, as the twists play a role in maintaining the original ellipse-like cross sections. In addition, there is a tendency that the higher the tow size (i.e., the number of filaments) is, the higher the width and thickness of the yarns or rovings are. Therefore, the width and thickness of fibers can be controlled by the form of fibers or tow sizes. In general, commercial carbon fibers have tow sizes of 3 K, 6 K, 12 K, and 24 K. Sometimes, carbon fibers with 1 K or 48 K tow sizes have been produced at customer's requests. The fiber of tow size 3 K has a width of about 2 mm, while the fiber of tow size 12 K has a width of 3.5–4.5 mm. As shown in Fig. 3, the gap between the carbon fiber rovings can be also a factor to make an affect on the EM property of the FSFC, because it has a function like a dipole with a unit cell of the FSFC.

The application of fibers with higher tow sizes or special cross section shapes offers the possibility of positive uses of the fiber crimping or undulation. In this case, the FSFC can be classified to a 'thick' FSS. Although microwaves are normal to the entire FSFC, the waves are obliquely incident to the crimping regions that result in multiple reflections or cancellations.

Weave patterns of FSFCs can be determined in the consideration of their mechanical and thermal properties, as well as through their EM characteristics or array element types. The mechanical and thermal properties of textile composites have been widely studied [29,30]. If a FSFC is attached onto or embedded into other dielectric materials, the mechanical and thermal properties may be regarded as key factors due to several problems, such as a residual stress and a mismatching in the coefficient of thermal expansion. It is possible to reduce such problems by selecting a weave pattern that

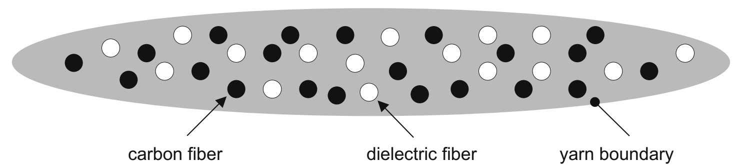
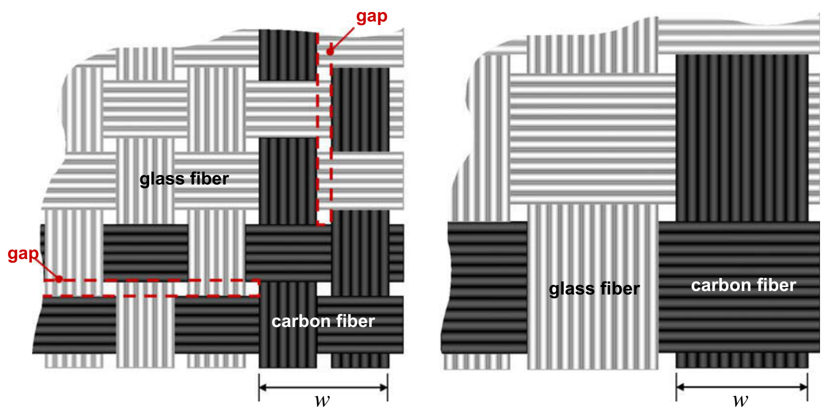
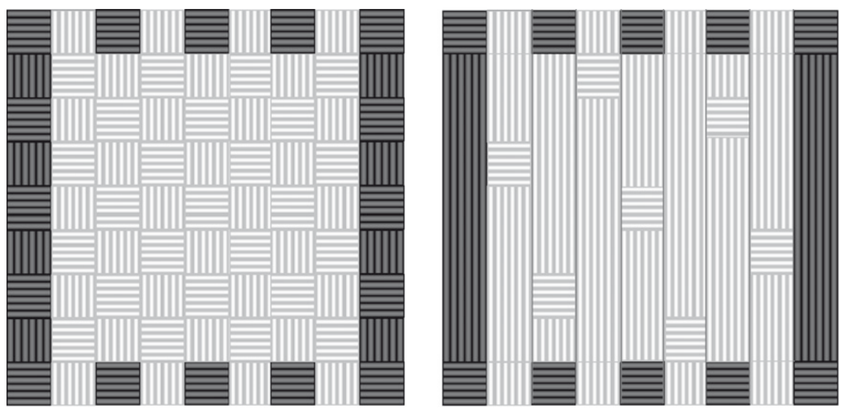


Fig. 2 – Schematic of a hybrid yarn with carbon and low-loss dielectric fibers.



a) for low tow size (b) for high tow size

Fig. 3 – Two weave patterns with and without a gap between carbon rovings.



(a) plain weave (b) 8-harness satin weave

Fig. 4 – Schematic of two FSFCs with the same array elements and the different weave patterns.

has similar properties to the other dielectrics. Fig. 4 shows the same square array element shapes with the different weave patterns of a plain weave and an eight-harness satin weave.

2.3. *Type of dielectric fibers and matrices*

Dielectric fibers, such as glass, quartz, aramid, or polyethylene, have dielectric constants in the range of 2.0–6.0 [2,27,28]. The selection of the dielectric fibers should be made according to the environment in which FSFCs will be used. As an example of this, Spectra polyethylene fibers are suitable for structures requiring a low dielectric constant, while they are not suitable for structures used at temperatures above 130 °C [2,27].

There is a variety of matrix materials, epoxy, phenol, polyimide, bismaleimide, and others, whose dielectric constants range from 3.0 to 4.0. The transverse electrical conductivity of fiber-reinforced composites depends on the composition of the matrix material [25]. In addition, as thermal stability is a primary concern about a polymer matrix, the use environment is also important. Thus, the matrix composition and the use environment should be taken into account to select the matrix materials.

3. Experiment

The two measurement systems were used for the transmission coefficient of a fabricated FSFC. In X-band (8.2–12.4 GHz), the free space technique system (HVS Technologies, Pennsylvania, USA) was used for measuring the transmission coefficient of transverse electromagnetic (TEM) waves [17,24]. The system consists of a pair of spot-focusing horn lens antennas (transmit and receive antennas), a sample holder, an HP 8510C network analyzer and a computer for data acquisition. The specimen size for this equipment was 120 mm × 120 mm × 0.125 mm. This system used the spot-focusing horn lens antennas for minimizing diffraction effects, the TRL (through-reflect-line) calibration technique and the time-domain gating of the HP 8510C network analyzer for minimizing multiple reflection [17,24]. The error bound of S_{11} (-0.00524 dB < S_{11} < 0.00652 dB) was obtained, which designated the maximum and minimum uncertainties in S_{11} measurement in free space. For the 18–30 GHz range, two BBHA9170 broadband horn antennas from Schwarzbeck Co. and an 8530A receiver were utilized. The distance between the two antennas was 1.8 m, which satisfies the far field condition ($=2d^2/\lambda$) at 30 GHz. In order to measure the transmission coefficient, a scattering parameter, S_{21}, was measured when a FSFC, 800 mm × 800 mm × 0.125 mm, was placed and not placed between the two antennas [2]. Fig. 5 shows the experimental setup to measure transmission coefficient in 18–30 GHz. Two samples were used in the two frequency ranges.

4. Modeling and simulation

In this study, the investigation of EM characteristics of FSFCs was carried out regarding the uncertainty of fiber conductivity (about fiber volume fraction and frequency dispersion), fiber undulation, and aperture-to-cell ratio. The FSFC on simulation was fabricated as a plain-weave type with square elements in a cell size of 10 mm and an aperture size of 8 mm. T300 and E-glass were used as carbon and dielectric fibers, and an epoxy was selected as matrix. The electrical conductivity of T300, a PAN-based fiber, is 5.9×10^4 S/m [31]. Each roving had a width of 2.0 mm, and the distance between rovings was 0.5 mm. As shown in Figs. 6 and 7, the transverse cross section was assumed to be elliptical and the major and minor axes of the elliptical cross section were taken as the width of a fiber roving (2.0 mm), and the half of the specimen thickness (0.625 mm), respectively.

The numerical analyses in this study were conducted through the use of CST Microwave Studio 5.1, a commercial three-dimensional analysis tool for electromagnetic fields, because fiber rovings have anisotropic material properties and nonlinear geometry.

4.1. *Anisotropy and electrical conductivity of carbon fibers*

A fiber roving can be considered as a unidirectional fiber-reinforced composite. Therefore, it is necessary to consider the anisotropic electrical conductivity of the roving, although the electrical conductivity of the T300 carbon fiber itself can be assumed to be isotropic. The longitudinal and transverse conductivity of the unidirectional composite or the fiber roving can be predicted by using the rule of mixtures [25]. In Fig. 7, the x′-axis and the x″-axis are taken parallel to the fiber direction while the y′-axis and the y″-axis are taken to the transverse direction. It is known that the longitudinal electrical conductivity, $\sigma_{r,1}$, is well predicted by Eq. (1) for more than a fiber volume fraction (V_f) of 0.6 whereas the transverse one, $\sigma_{r,2}$, is difficult to predict. This is because Eq. (2) was formulated with the assumption that there is no contact between fibers, and because the higher V_f is, the more contacts exist.

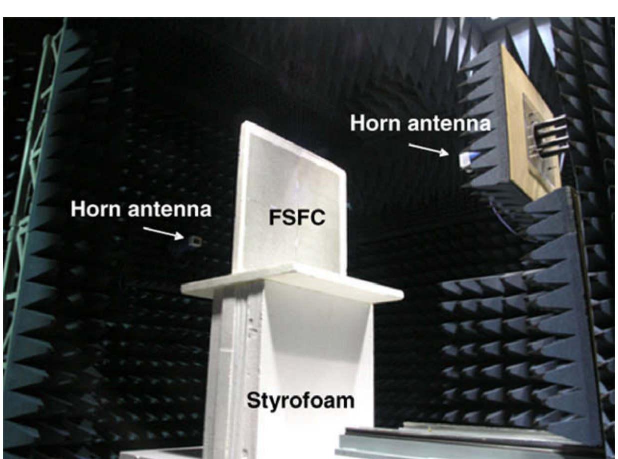


Fig. 5 – Measurement setup for transmission coefficient in 18–30 GHz.

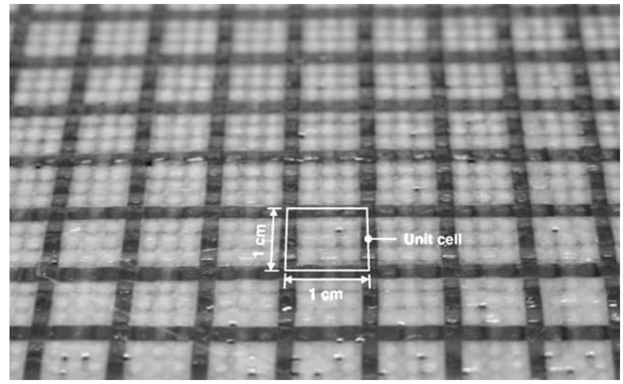


Fig. 6 – A photograph of a fabricated FSFC.

$$\sigma_{r,1} \leqslant V_f\sigma_f + (1 - V_f)\sigma_m \quad (1)$$

$$\frac{1}{\sigma_{r,2}} \leqslant \frac{V_f}{\sigma_f} + \frac{(1 - V_f)}{\sigma_m} \quad (2)$$

Carbon fibers have the conductivity, σ_{fc}, of 10^4–10^5 S/m and epoxy matrices have the conductivity, σ_m, of 10^{-10}–10^{-17} S/m [28]. Therefore, since $\sigma_{fc} \gg \sigma_m$, $\sigma_{r,2} \approx \sigma_m$ from Eq. (2). In reality, $\sigma_{r,2}$ is much higher than ranges of σ_m. As V_f increases from 0.6 to 0.7, the ratio ($\alpha = \sigma_{r,1}/\sigma_{r,2}$) decreases from a value less than 10^3 to a few decades due to the direct contact between fibers [25]. Therefore, $\sigma_{r,2}$ was taken as $\sigma_{r,1}/\alpha$ and α was selected to consider the real phase of the transverse electrical conductivity according to fiber volume fraction.

It is difficult to measure V_{fc} in a cured state as carbon and glass fibers are woven together. The typical volume fractions of a unidirectional composite usually range from 0.6 to 0.7. Thus, the two carbon fiber volume fraction of a roving, V_{fc}, was considered in this study. The coefficients of anisotropy, α, were taken as 400 and 50 for the two volume fractions, respectively [25].

The AC (alternating current) conductivity of carbon fibers might have frequency dependence, and the AC conductivity is different from the DC (direct current) one. In addition, the AC and DC conductivities are highly dependent on the heat treatment temperature (HTT). Bilikov [26] measured the electrical conductivity of PAN-based carbon fibers according to HTT and frequency. He found out that $\beta(\sigma_{AC}/\sigma_{DC})$ bounds from 0.75 to 1.75 in the HTT ranges from 1400 °C to 2600 °C and in the frequency range from 9.6 GHz to 16.4 GHz. Because the HTT of T300 has not been released to the public and β shows only a little variation for a specific HTT, β was taken to be in the same range from 0.75 to 1.75 in our simulation.

Table 1 shows the electrical conductivity of a carbon roving, σ_{rc}, according to V_{fc}. $\sigma_{rc,1}$ and $\sigma_{rc,2}$ denote the longitudinal and transverse conductivities of a carbon roving.

Glass fiber rovings have anisotropic permittivity. It can also be predicted by the rule of mixture concerning a unidi-

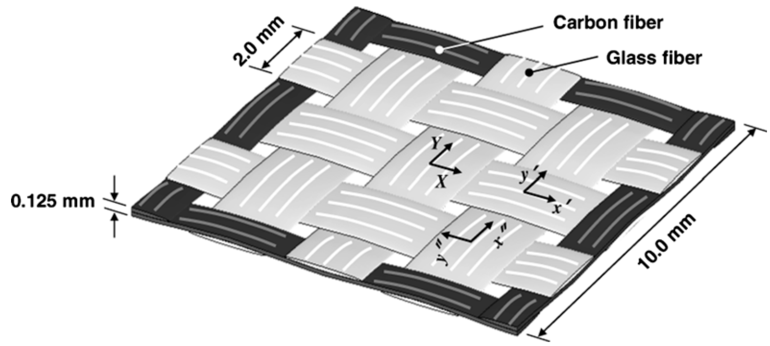


Fig. 7 – Schematic of a unit element of a FSFC with the aperture size of 8 mm and the cell size of 10 mm.

Table 1 – The electrical conductivities of carbon rovings with fiber volume fraction.

V_{fc}		0.6	0.7
α		400	50
β	0.75	$\sigma_{fc,1}$, 2.7×10^4 S/m	$\sigma_{fc,1}$, 3.1×10^4 S/m
		$\sigma_{fc,2}$, 6.6×10^1 S/m	$\sigma_{fc,2}$, 6.2×10^2 S/m
	1.0	$\sigma_{fc,1}$, 3.5×10^4 S/m	$\sigma_{fc,1}$, 4.1×10^4 S/m
		$\sigma_{fc,2}$, 8.9×10^1 S/m	$\sigma_{fc,2}$, 8.3×10^2 S/m
	1.75	$\sigma_{fc,1}$, 6.2×10^4 S/m	$\sigma_{fc,1}$, 7.2×10^4 S/m
		$\sigma_{fc,2}$, 1.5×10^2 S/m	$\sigma_{fc,2}$, 1.4×10^3 S/m

rectional composite in the same form of Eqs. (1) and (2). The permittivities of the E-glass fibers and the epoxy are 6.1-*j*0.03 and 3.0-*j*0.03 at 10 GHz, respectively [2]. Thus, the glass rovings have a permittivity of 4.9-*j*0.03 and 5.2-*j*0.03 at the fiber volume fraction of a glass roving, V_{fg}, 0.6 and 0.7, respectively, at 10 GHz. The permittivity of the glass roving in the other frequencies was determined by applying the first-order Debye model.

The simulation and measurement results in Fig. 8 show that the fabricated FSFC is a high pass filter that reflects most low frequency microwaves and that transmits high frequency waves near a resonance frequency. Although the uncertainty of fiber volume fraction and material property was taken into account, the simulation was found to be in good agreement with the measurement. This is an indication that V_{fc} may be assumed a reasonable value between 0.6 and 0.7 for a prediction of the electromagnetic characteristics of FSFCs.

The difference between the simulation and the measurement is due to several reasons. Among these are the difference between the real fiber volume fraction and the assumed one, the finite specimen size and the edge scattering derived from this, the local misalignment of the carbon fiber rovings, and the perpendicularity of the specimen to the antennas [21].

4.2. *Fiber undulation*

Although it might be considered that the fiber undulation effect might be negligible in cases that the FSFC thickness is lower than the cell size of the FSFC and the wavelengths in the frequency band, the effect should be understood clearly. The material properties for $V_{fc} = 0.6$, $V_{fg} = 0.6$, and $\beta = 1.0$ were used here. The FSFC without fiber undulation was modeled as a plate FSS with identical properties and 0.0625 mm in thickness. Fig. 9 shows the transmitted power of the FSFC both considering fiber undulation and not considering it. It was found that the undulation had little effect on the property of the fabricated FSFC.

4.3. *Aperture-to-cell ratio*

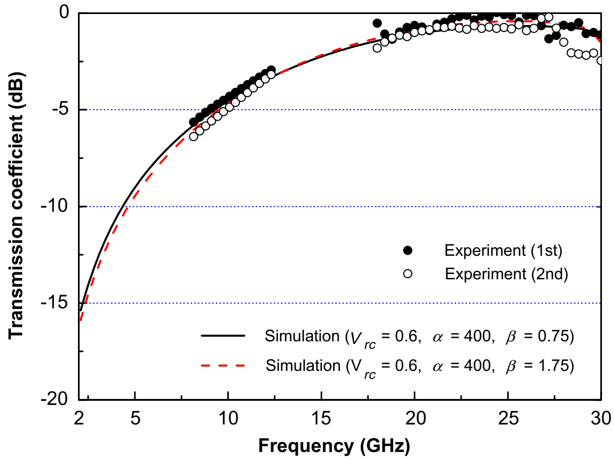
The ratio has a profound effect on the EM characteristics of the FSFC. In the case that a FSFC is composed of fiber rovings with the width of 2 mm and the gap of each roving of 0.5 mm, the FSFC with a cell size of 10 mm can have only two aperture sizes, 3 mm and 8 mm. Hence, the evaluation of the effect of the aperture-to-cell ratio (C/A) was made for another FSFC with a cell size of 20 mm, as shown in Fig. 10. The transmission of the FSFC was compared to that of the metallic FSS made of copper with the same geometry, as shown in Fig. 11.

The resonance frequency of a metallic FSS is predicted by several theoretical models [1,4,32] for normally incident microwaves. Lee's model [1] expressed the normalized inductance of a metallic FSS as

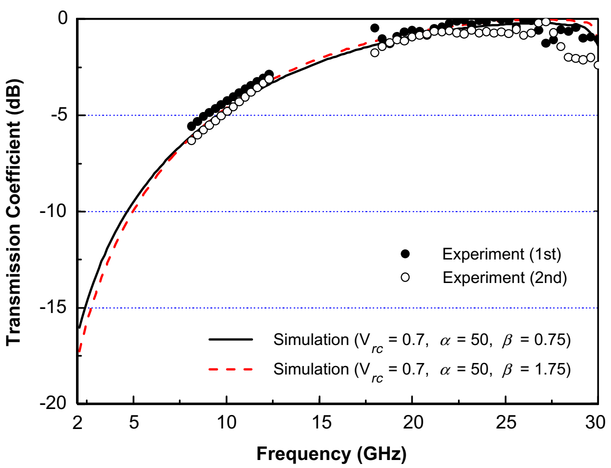
$$Y_{ind} = (-j)(\upsilon - \upsilon^{-1})\left[\frac{A}{C} + \frac{1}{2}\left(\frac{A}{\lambda}\right)^2\right]\left[\ln\csc\left(\frac{\pi}{2}\frac{\delta}{A}\right)\right]^{-1}$$
$$\upsilon = \left(1 - 0.41\frac{\delta}{A}\right)\left(\frac{\lambda}{A}\right) \quad (3)$$

where *A*, *C*, and λ are the cell and aperture sizes, and the wavelength. $\delta = (A-C)/2$. From Eq. (3), Y_{ind} depends only on two parameters; A/λ and C/A. It was confirmed that a total transmission ($Y_{ind} = 0$) occurs at

$$\frac{A}{\lambda} = 1 - 0.41\frac{\delta}{A} \quad (4)$$



(a) for V_{fc} = 0.6



(b) for V_{fc} = 0.7

Fig. 8 – Simulated (lines) and measured (circles) results of the transmission coefficient of a fabricated FSFC. (a) For $V_{fc} = 0.6$ (b) for $V_{fc} = 0.7$.

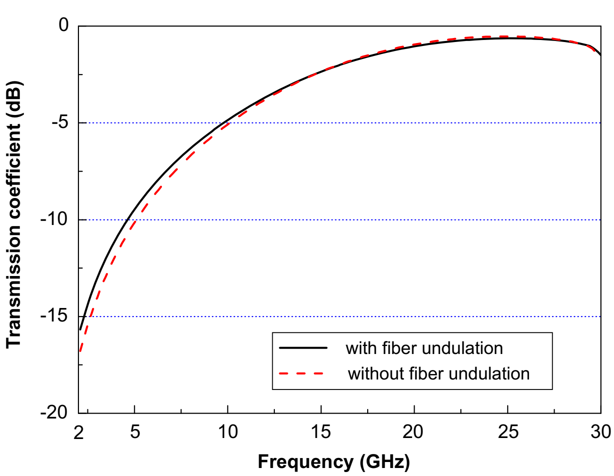


Fig. 9 – Simulated transmission coefficients of a FSFC with and without considering the fiber undulation.

For most practical screens with low aperture-to-cell ratio, (δ/A) ⩽ 0.3. Hence, the entire transmission takes place when A is slightly less than one wavelength.

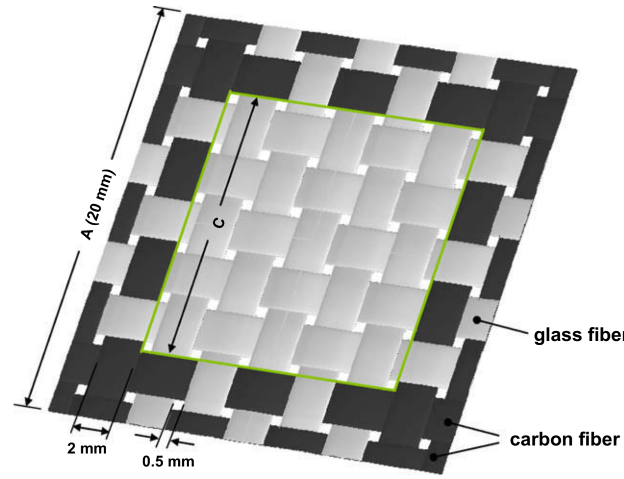


Fig. 10 – A FSFC using carbon and glass fiber rovings with the width of 2.0 mm and with the distance between the rovings of 0.5 mm.

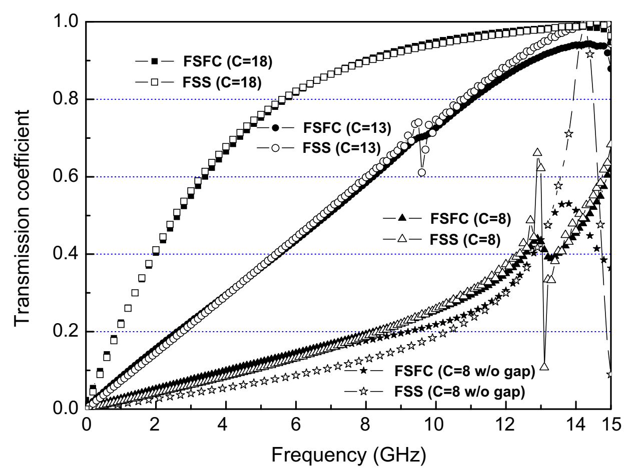


Fig. 11 – Simulated transmission coefficients of a square FSFC and a metallic FSS with the cell size of 20 mm with regard to the aperture size.

The FSS with the high C/A ratio of 18/20 has the resonance frequency at 14.7 GHz, which is equal to the value calculated by Eqs. (3) and (4). However, the FSFC with the same ratio has the frequency at 14.2 GHz. This may be mainly attributed to the dielectric loading effect, that is, dielectric materials onto a freestanding FSS shift the resonance frequency downward [5], because the apertures of FSFCs are filled with dielectric fibers and a polymer matrix, rather than free space.

Fig. 11 shows that the FSFC transmits an amount of microwave energy near its resonance frequency. It is more evident that FSFCs with low aperture-to-cell ratios lose high-pass property, as observed from the result of 8/20 and 13/20 ratios. The transmission coefficient of FSFC and FSS of 8/20 ratio without the gap was also calculated, as well as the result with gaps. For the FSFCs and FSSs without gaps, the span, (A−C)/2, is assumed to be fully composed of carbon fiber rovings or metals. The metallic FSS without the gap has a perfect transmission at around 14.2 GHz, while the transmission coefficient of FSFC without the gap is 0.53 at 13.7 GHz. The skin depths of carbon fiber rovings of $V_{fc} = 0.6$ are 0.022 mm and 0.436 mm in longitudinal and transverse directions at 15 GHz, respectively. However, the skin depth of copper is about 0.5 μm. Therefore, considering the thickness of carbon rovings (0.125/2 mm), it could be said that the low electrical conductivity of fiber rovings mainly contributes to the partial transmission near resonance frequency.

Peaks at 9.6 GHz for 13/20 ratio and 13.0 GHz for 8/20 ratio in transmission coefficient can be attributed to the gap between the rovings, in comparison with the cases with and without the gap. Dual-square-loop or multiple-square-loop FSSs can be treated as transmission lines with a combination of parallel and serial capacitances and inductances, which gives dual or multiple resonance frequencies [33]. The FSFC with air gaps in this study can also be treated in the similar way as an aperture FSS with an inside square loop within the aperture (the inside loop is connected with the aperture FSS at the junctions of carbon rovings). Due to the facts, the peak can occur in both FSFCs and FSSs with air gaps.

When taking into account manufacturing process, typical FSSs have (A–C) region flat and fully covered with metals, while FSFCs usually have the gap between fiber rovings. From the point of view, the distinct behaviors of FSFCs near resonance frequency could offer a possibility to improve the performance of microwave absorbers.

5. Conclusion

FSFCs, as inductive FSS, consisting of carbon and low-loss dielectric fibers, were proposed. The design parameters to tailor the properties of FSFCs were discussed with regard to electrical conductivity of carbon fibers, form of fibers and weave patterns, and type of dielectric fibers and matrices.

The EM characteristics of a FSFC were simulated and investigated with regard to the electrical properties of the constituents, the fiber undulation, and the aperture-to-cell ratio. In comparison with metallic FSSs, it could be believed that the low electrical conductivity of carbon fiber rovings causes partial transmission in resonance frequency ranges. The undulation had little effect on the EM properties. The aperture-to-cell ratio made a big difference in the EM characteristics of FSFCs, as the ratio did in those of metallic FSSs. For the high aperture-to-cell ratio, the FSFC and the metallic FSS had similar EM characteristics, that is, the FSFC was able to function as a high pass filter, although it has a partial reflection near a resonance frequency. However, for intermediate and low aperture-to-cell ratios, as the aperture size decreased, the reflection of FSFCs near the resonance frequency increased. In other words, FSFCs lost the high-pass property due to low electrical conductivity of carbon fibers and the gap between fiber rovings. The peculiar EM properties of the FSFC near resonance frequency make them useful as impedance modifiers. Among a variety of their applications, there are radar-absorbing materials and structures as an alternative to metallic FSS.

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