Theoretical analysis and numerical simulation of electromagnetic parameters of Fe-C coaxial single fiber

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\section*{Article info}

\textbf{Abstract}

Based on the Maxwell equation, the electromagnetic model in the coaxial fiber was described. The interaction with electromagnetic wave was analysed and the theoretical formula of axial permeability ($\mu_a$), axial permittivity ($\varepsilon_a$), radial permeability ($\mu_r$), and radial permittivity ($\varepsilon_r$) of Fe-C coaxial fiber were derived, and the demagnetization factor ($N$) of fibrous material was revised. Calculation results indicate that the composite fiber has stronger anisotropy and better EM dissipation performance than the hollow carbon fiber and solid iron fiber with the same volume content. These properties can be enhanced through increasing aspect ratio and carbon content. The $\mu_a$ is 5.18–4.46i, $\mu_r$ is 2.58–0.50i, $\varepsilon_a$ is 7.63–6.97i, and $\varepsilon_r$ is 1.98–0.15i when the electromagnetic wave frequency is 5 GHz with the outer diameter of 0.866 $\mu$m, inner diameter of 0.500 $\mu$m, and length of 20 $\mu$m. The maximum of the imaginary part of $\mu_a$ and $\varepsilon_a$ are much larger than that of $\mu_r$ and $\varepsilon_r$ when the structural parameters change, and the maximum of $\mu_a$ and $\varepsilon_a$ can reach 6.429 and 23.59. Simulation results show that greater conductivity, larger aspect ratio, thin iron shell play important roles to improve the electromagnetic matching ability and microwave attenuation for the Fe-C coaxial fibers.

\section*{1. Introduction}

In recent years, the demand for electromagnetic wave absorbers and electromagnetic wave absorbing materials is ever growing in military (reduction of radar signature of aircraft, ships, tanks, and targets) as well as in civilian applications (reduction of electromagnetic interference among components and circuits, reduction of the back-radiation of microstrip radiators). Electromagnetic wave absorbing material is a kind of functional material that can absorb electromagnetic wave effectively and convert electromagnetic energy into thermal energy or make electromagnetic wave disappear by interference \cite{1–4}. The basic requirements for the design of electromagnetic wave absorbing materials are as follows: (1) it should minimize the front-face reflection and improve the impedance matching at the air to materials interface (impedance matching characteristic), (2) it should increase the absorption of electromagnetic waves through high values of dielectric and magnetic losses (attenuation characteristic), and (3) it is expected to be applied in a wide frequency range \cite{5,6}. Therefore, electromagnetic wave absorbing materials with “low density, wide band, thin thickness, and high absorptivity” are currently gaining much attention in the field of electromagnetic compatibility (EMC) and electromagnetic interference (EMI) \cite{7,8}.

To a large extent, the theoretical and experimental efforts designed to provide electromagnetic wave absorbing materials are associated with two important features of their electromagnetic properties. The first is based on enhanced magnetic losses due to resonance phenomenon. Additionally, it has been argued that the second feature is related to enhanced dielectric losses. Many studies were carried out to investigate the electromagnetic absorption properties of electromagnetic wave absorbers employing ferrite \cite{9–12}, carbonyl iron powders \cite{13}, polycrystalline iron fibers \cite{14}, metallic magnetic nanosized powders \cite{15}, graphite \cite{16}, carbon black \cite{17,18}, carbon fibers \cite{19–21}, carbon nanotubes \cite{22–24}, graphene \cite{25}, and so on. However, the key point is that the dielectric absorbers have narrow absorbing frequency bandwidth. At the mean time, the utility of magnetic absorbers is also constrained due to the fact that high weight penalty particularly for applications is on airborne systems and that absorption performance is governed by Snoek’s limit, i.e., the product of the
resonance frequency and the initial permeability is approximately constant. Thus, if the resonance frequency increases, the initial permeability decreases in inverse proportion [26]. Fortunately, recent considerable researches [27, 28] indicate that the magnetic absorbers in combination with dielectric absorbers for electromagnetic wave absorbing materials can offer multiple absorbing mechanisms and tune the real and imaginary parts of the effective permittivity and permeability, which provide a large flexibility for design and properties control.

Generally, the electromagnetic absorbing performance of any electromagnetic wave absorbing materials is linked to their intrinsic electromagnetic properties (i.e., conductivity, complex permittivity and permeability), which can be tailored through changing geometry, composition, morphology, and volume fraction of the filler particles, as well as to extrinsic properties such as the thickness and working frequencies. It is clear that the electromagnetic wave absorption properties can be improved by adjusting the above parameters. A primary question with these materials is how the electromagnetic parameters of a composite medium can be evaluated as a function of the intrinsic parameters of the phases, volume fraction, shape and size, and geometrical arrangement associated with the material mixture. Note that the present-day numerical techniques allow us to deal directly with the experimentally relevant range of the model parameters, e.g., density functional theory (DFT) [29], finite element method (FEM) [30], boundary integral equation (BIE) [31], first-principles molecular dynamics (FPMD) [32], finite integration algorithm (FIA) [33], Monte Carlo (MC) [34], multipole moments [35], differential evolution (DE) [36], genetic algorithm (GA) [37], or finite-difference-time-domain (FDTD) [38]. However, most of researches are based on the absorber-fillers loaded polymer composites and the absorber-fillers have fallen short of this goal for a variety of reasons, such as the efficiency of computational methods and computing power. The main problem of the validated theoretical methods used for the electromagnetic response of absorbers-filler is that real calculations are not easy, and the challenge is to find a reasonable balance between the choice of method, desired accuracy, and computational expense, because the shape size, geometry, and composition of the absorber-fillers is different. Current research is pushing available approximations toward the description of fluctuations on the hierarchy of structure scales that are relevant to the problem.

As both computing power and the efficiency of computational methods are steadily increasing, it is becoming possible to investigate new absorber-fillers through computer simulations, before they have even been synthesized. For example, based on Maxwell–Garrett mixing law, the real permeability of spherical, flaky and acicular particles is determined by shapes of the particles and related to the ratio of demagnetizing field and magnetization in the uniform magnetization material, i.e., demagnetizing factor [39]. The physical parameters characterizing these systems are numerically tunable so that it is viable for one to do the theoretical design and optimization of novel optimized multifunctional materials. Different geometry particles including solid sphere [40], core-shell particles [41], solid fiber [42], hollow fiber [43], profiled fiber [44] and single or multiply layers structures [45] have also made great progress currently. Fibrous materials have attracted much attention in recent years because of their shape anisotropy. The aspect ratio of fiber is a crucial parameter in determining the charge and wave transport mechanisms in such composite materials, a larger aspect ratio can increase the anisotropy field, and consequently influence the absorption features induced by natural ferromagnetic resonance.

Due to their potential applications in electromagnetic wave absorbing materials, this research attempts to apply Fe-C coaxial fibers as an absorber to electromagnetic wave absorbing materials [46]. Knowledge of the electromagnetic wave properties of Fe-C coaxial fibers is essential for applying them to producing electromagnetic wave absorbing materials. In this paper, the theoretical formula of electromagnetic parameters of Fe-C coaxial single fiber will be derived based on the macroscopic electromagnetic theory and Maxwell theory and the numerical calculations of electromagnetic anisotropy of these fibers will be described in great detail according to their aspect ratio, inner and outer diameter, and electrical conductivity.

2. Model and theoretical analysis

2.1. Electromagnetic model construction

Consider the Fe-C coaxial fiber structure placed in microwave field, and the external magnetic field component is \( \vec{H}_0 \); the external electric field component is \( \vec{E}_0 \). Suppose that linearly polarized plane harmonic electromagnetic wave with time dependence of \( \exp (- i \omega t) \) (\( \omega = 2 \pi f \) is an angular frequency, \( f \) is a linear frequency in Hz; we will use \( f \) in figures) is normally incident in the surface of the structure, shown in Fig. 1 (Electromagnetic model). It is sufficient to consider an electromagnetic wave polarized along the parallel and perpendicular plane due to the anisotropy of the problem [47]. With the axis of the fiber as the z-axis, the length, radius of iron shell and carbon core are denoted respectively \( l, a \) and \( b \).

In high frequency electromagnetic field, the permeability and permittivity of a short Fe-C coaxial fiber are second-order tensors due to shape anisotropy [48]. The relative permeability and permittivity components parallel to the fiber are denoted \( \mu_{||} \) and \( \varepsilon_{||} \), respectively, and the relative permeability and permittivity components perpendicular to the fiber are denoted \( \mu_{\perp} \) and \( \varepsilon_{\perp} \), respectively. In this section, the theoretical formula of permeability \( \mu_{\perp} \) and \( \mu_{||} \) and permittivity \( \varepsilon_{\perp} \) and \( \varepsilon_{||} \) will be derived in turn. In electromagnetic field, the permeability and permittivity of the Fe-C coaxial fiber can be described as following

\[
\begin{pmatrix}
\mu_{||} & 0 & 0 \\
0 & \mu_{\perp} & 0 \\
0 & 0 & \mu_{||}
\end{pmatrix}
\quad \begin{pmatrix}
\varepsilon_{||} & 0 & 0 \\
0 & \varepsilon_{\perp} & 0 \\
0 & 0 & \varepsilon_{||}
\end{pmatrix}
\]

Fig. 1. The schematic for composites loaded Fe-C coaxial fiber in electromagnetic field and single fiber geometric model.
The excellent functional properties of the composites are obtained through the function of the composition effect of composites, which involve two aspects: the material design and the process operation. Generally according to the composite phenomenon in composites, the composition effect of composites can be divided into two categories: the linear effect and the nonlinear effect. Due to the Fe–C coaxial fiber is usually composed of two types of materials, the two estimation methods to solve the relative intrinsic electromagnetic parameters of materials depend on the volume fraction are used [49, 50]. The first method is given by,

\[ e_i = \frac{1}{e_1 + \frac{1}{e_2}}, \quad \mu_i = \frac{1}{\mu_1 + \frac{1}{\mu_2}}, \quad \sigma = \frac{1}{\sigma_1 + \sigma_2} \]

the second method is given by,

\[ e_i = \frac{1}{e_1 + \frac{1}{e_2}}, \quad \mu_i = \frac{1}{\mu_1 + \frac{1}{\mu_2}} \quad \text{and} \quad \sigma = \frac{1}{\sigma_1 + \frac{1}{\sigma_2}} \]

where \( e_1 \) and \( \mu_1 \) are the relative permittivity and relative permeability of iron shell, \( e_2 \) and \( \mu_2 \) are the relative permittivity and relative permeability of carbon core, \( \sigma_1 \) and \( \sigma_2 \) are the electrical conductivity of shell and core, \( e_1 \) and \( e_2 \) are the volume fraction of shell and core.

### 2.2. Axial permeability

There is a magnetic moment \( m \) generated from the fiber under the high-frequency magnetic field. Due to the movement and interaction of electrons, magnetic moment should be constituted by: (1) intrinsic magnetic moment \( m_i \) generated by magnetization of rotation of magnetic domain and displacement of magnetic domain wall; (2) induced magnetic moment \( m_e \) generated by eddy current, according to the superposition principle known as [51, 52],

\[ m = m_i + m_e \]  

in addition,

\[ m_i = \mu_0 \int J_1(\mu_i-1)H dV \]  

\[ m_e = \frac{1}{2} \int \nabla \times J(r) dV \]  

where \( \mu_i \) is the intrinsic permeability, \( r \) is the position vector, \( J(r) \) is the eddy current density that is given by \( \nabla \times H \) in the light of the Maxwell Garnett law, \( V \) is the volume of the Fe–C coaxial fiber. Time-harmonic electromagnetic field in the Fe–C coaxial fiber is applied to Maxwell Equation form in the passive and borderless space [51, 52].

\[ \nabla \times E = -j\omega \mu H \]  

and the wave equation is obtained,

\[ \nabla \times E = -j\omega \mu_0 \sigma H \]  

where \( \sigma \) is the electrical conductivity of the composite fiber, \( \mu_0 \) and \( \mu_0 \) are the vacuum permeability and relative permeability of the composite fiber, respectively. When the polarization direction of the electromagnetic wave magnetic field is parallel to the z-axis \((H^0 = H_0e^{j\omega t}e_z)\), taking into account the boundary conditions and rotational symmetry of fibers, magnetic field component within the fibers can be expressed as, \( H_x = H_y = 0, H_z = H_0, \) and \( H_{z,rad} = H_0 \cos \theta \) in the cylindrical polar coordinates. Then, formula (5) can be rewritten as,

\[ \frac{d^2 H_z}{dr^2} + \frac{1}{r} \frac{dH_z}{dr} - j\omega \mu_0 \sigma \mu H_z = 0 \]  

Formula (6) is the Bessel function of order 0, its general solution

\[ H_z = A_1 J_0(\mu_0 r) + A_2 N_0(\mu_0 r) \]  

where, \( k \) is defined as \( k^2 = -j\omega \mu_0 \sigma \mu \) (\( \mu_0 \) is the vacuum permeability), according to the second method \( k \) can be simplified as,

\[ k = \left\{ \frac{-j\omega \mu_0 \mu_1 \mu_2 (a^2 - b^2) \sigma_1 + b^2 \sigma_2}{(a^2 - b^2) \mu_2 + b^2 \mu_1} \right\}^{\frac{1}{2}} \]  

\( J_0 \) is the Bessel function of order 0, \( N_0 \) is the Neumann function of order 0, \( A_1 \) and \( A_2 \) are the undetermined constants. Considering \( J_0(0) = 1 \) and \( N_0(0) = \infty \), and justification of formula (7), \( A_2 \) must equal 0, and \( A_1 \) should be \( H_0\cos \theta \) from the boundary conditions. Therefore, magnetic field inside the Fe–C coaxial fiber is,

\[ H = J_0(\mu_0 r) H_0 e^{j\omega t} e_z \]  

Taking into account the demagnetizing inside the fiber and uniform magnetization of magnetic materials, the time factor should be omitted and the axial demagnetization factor can be defined as \( N_1 \). The real magnetic field inside the fiber is,

\[ H = J_0(\mu_0 r) H_0 - N_1 M \]

and the eddy current density \( j(r) = \nabla \times H = k J_0(\mu_0 r) H_0 e_z \) can be obtained from Maxwell equation \( J_1 \) is the Bessel function of order 1, substitute this equation and formula (7) with formula (2) and formula (3). The solutions of intrinsic magnetic moment \( m_i \) and induced magnetic moment \( m_e \) are,

\[ m_i = \mu_0 \int J_1(\mu_i-1)H_0 dV \]

and

\[ m_e = \frac{1}{2} \int \nabla \times J(r) dV = \mu_0 \int \left[ \frac{J_1(\mu_i-1)H_0}{\mu_0 \mu_1} \right] dV \]

Furthermore, the total magnetic moment \( m = \mu_0 2 m_i \) and the average magnetization can be learned through simplifying simultaneous equations (9) and Eq. (10).

\[ M = \mu_0 \frac{2 J_1(\mu_0 r)}{J_0(\mu_0 r)} \]  

Axial magnetic permeability of Fe–C coaxial fiber is,

\[ \mu = 1 + \mu_0 \frac{2 J_1(\mu_0 r)}{J_0(\mu_0 r)} \]  

From the second method of linear effect and Eq. (8),

\[ \mu_i = 1 + \frac{\alpha^2 \mu_0 \mu_1 \mu_2}{(a^2 - b^2) \mu_2 + b^2 \mu_1} \left[ \frac{J_1(\mu_0 \mu_1 \mu_2 (a^2 - b^2) \sigma_1 + b^2 \sigma_2)}{(a^2 - b^2) \mu_2 + b^2 \mu_1} \right]^{\frac{1}{2}} \]

\[ \mu_i = 1 + \frac{\alpha^2 \mu_0 \mu_1 \mu_2}{(a^2 - b^2) \mu_2 + b^2 \mu_1} \left[ \frac{J_1(\mu_0 \mu_1 \mu_2 (a^2 - b^2) \sigma_1 + b^2 \sigma_2)}{(a^2 - b^2) \mu_2 + b^2 \mu_1} \right]^{\frac{1}{2}} - 1 \]

\[ \mu_i = 1 + \frac{\alpha^2 \mu_0 \mu_1 \mu_2}{(a^2 - b^2) \mu_2 + b^2 \mu_1} \left[ \frac{J_1(\mu_0 \mu_1 \mu_2 (a^2 - b^2) \sigma_1 + b^2 \sigma_2)}{(a^2 - b^2) \mu_2 + b^2 \mu_1} \right]^{\frac{1}{2}} - 1 \]

\[ \mu_i = 1 + \frac{\alpha^2 \mu_0 \mu_1 \mu_2}{(a^2 - b^2) \mu_2 + b^2 \mu_1} \left[ \frac{J_1(\mu_0 \mu_1 \mu_2 (a^2 - b^2) \sigma_1 + b^2 \sigma_2)}{(a^2 - b^2) \mu_2 + b^2 \mu_1} \right]^{\frac{1}{2}} - 1 \]
2.3. Radial permeability

When the incident direction of electromagnetic wave is along the x-axis, which perpendicular to the Fe-C coaxial fiber direction, outside the magnetic field is \( H^{(0)} = H_{\text{out}}(r, t)e^{\text{j}\omega t} \) and formula (5) can be written as [53],
\[
H = \beta kH_0 e^{\text{j}kr} \left\{ \frac{J_1(\lambda r)}{r} \cos \theta \mathbf{e}_r + \left\{ \frac{J_1(\lambda r)}{r} - k f_0(\lambda r) \right\} \sin \theta \mathbf{e}_\theta \right\}
\]
(16)

It can be obtained from the symmetry of fiber and the direction of magnetic field that the direction of the average magnetization is along the x-axis. Also let \( M = M_0 \mathbf{e}_r \), the time factor is omitted and the demagnetization factor is substituted, the actual magnetic field in the composite fiber is,
\[
H = \beta kH_0 \left\{ \frac{J_1(\lambda r)}{r} \cos \theta \mathbf{e}_r + \left\{ \frac{J_1(\lambda r)}{r} - k f_0(\lambda r) \right\} \sin \theta \mathbf{e}_\theta \right\}
\]
\[- N_\text{a}M \cos \theta \mathbf{e}_r - \sin \theta \mathbf{e}_\theta \]
(17)

where \( N_\text{a} \) is the radial demagnetization factor.

In order to solve the undetermined coefficients \( \beta \), the boundary condition equations should be solved first. Since the magnetization of the composite fiber have great influence on the outside magnetic field, \( H^{(0)} \) is converted into \( H^{(0)} \neq H_0 e^{\text{j}\omega t} \mathbf{e}_r \), but the outside magnetic field still satisfies the Maxwell equation, \( \nabla \times H = 0 \) and \( \nabla \cdot H = 0 \). Besides, \( H^{(0)} = -\nabla \Phi_0 \), where \( \Phi_0 \) is the magnetic scalar potential and it should meet the following equation,
\[
\nabla^2 \Phi_0 = 0
\]
(18)

When \( r \to \infty \), \( \Phi_0 = -H_0 r \cos \theta \). At the same time, considering \( \Phi_0(r, \theta) = \Phi_0(r, \theta - \pi) \) from the symmetry, it follows the answer of formula (18), \( \Phi_0 = (-H_0 r + \pi \cos \theta) \), where \( B \) is the undetermined constant. Through the above results, the modified outside magnetic field can be obtained,
\[
H^{(0)} = \left( \frac{H_0 + B}{r^2} \right) \cos \theta \mathbf{e}_r + \left( -H_0 + B \right) \frac{r}{\pi} \sin \theta \mathbf{e}_\theta
\]
(19)

From the boundary conditions which (1) \( r = a \) and \( \theta = \frac{\pi}{2} \), \( H^{(0)} = H_1 \); (2) \( r = a \) and \( \theta = 0 \), \( H^{(0)} = \mu_i H^{(0)} \); and the formula (17), formula (19), \( \beta \) can be obtained,
\[
\beta = \frac{a}{\kappa H_0} \frac{2H_0 + N_\text{a}(\mu_i + 1)M}{(\mu_i - 1) J_1(\kappa a) + k a f_0(\kappa a)}
\]
(20)

Formula (20) is substituted into formula (17), and the intrinsic magnetic moment should be,
\[
m = \int \int \{ (\mu_i - 1) H_0 \} dV
\]
\[= \pi a^2 \mu_i (\mu_i - 1) \left\{ \frac{J_1(\kappa a)}{2J_0(\kappa a)} \left[ \frac{2H_0 + N_\text{a}(\mu_i + 1)M}{(\mu_i - 1) J_1(\kappa a) + k a f_0(\kappa a)} \right] - N_\text{a}M \right\} \mathbf{e}_r
\]
(21)

and the induce magnetic moment
\[
m_e = \frac{1}{2} \int \int r \times j \mathbf{e}_r dV = \pi a^2 \mu_i \frac{\beta k H_0}{\kappa a} \left[ 2f_0(\kappa a) - k a f_0(\kappa a) \right] \mathbf{e}_x
\]
(22)

The total magnetic moment is,
\[
m = m_0 + m_e = \pi a^2 \mu_i \left\{ \frac{2J_1(\kappa a) - k a f_0(\kappa a)}{(\mu_i - 1) J_1(\kappa a) + k a f_0(\kappa a)} \left[ H_0 + \frac{1}{2} N_\text{a}(\mu_i + 1)M \right] - N_\text{a}M (\mu_i - 1) \right\} \mathbf{e}_r
\]
(23)

with the simultaneous formula (23) and \( m = \pi a^2 M \), the average magnetization is,
\[
M = \frac{\mu_i}{\mu_i - 1} \left\{ \frac{2J_1(\kappa a)}{J_0(\kappa a)} - 1 \right\} \left\{ \frac{1}{\kappa a} \frac{h_0}{a h_0} + 1 + N_\text{a} \right\} \frac{H_0 \mathbf{e}_x}{(\mu_i - 1)\frac{h_0}{a h_0} + 1 + N_\text{a} (3\mu_i - 1) \frac{1}{\kappa a} \frac{h_0}{a h_0} - 1}
\]
(24)

The radial magnetic permeability of Fe-C coaxial fiber is as follows,
\[
\mu_r = 1 + \frac{\frac{\mu_i}{\mu_i - 1} \left\{ \frac{2J_1(\kappa a)}{J_0(\kappa a)} - 1 \right\} \left\{ \frac{1}{\kappa a} \frac{h_0}{a h_0} + 1 + N_\text{a} \right\}}{\left\{ \frac{1}{\kappa a} \frac{h_0}{a h_0} - 1 \right\} \left\{ \frac{1}{\kappa a} \frac{h_0}{a h_0} + 1 + N_\text{a} \right\} \left\{ \frac{1}{\kappa a} \frac{h_0}{a h_0} - 1 \right\}}^{\frac{1}{2} - \frac{1}{\kappa a} \frac{h_0}{a h_0}}
\]
(25)

where \( k = \left\{ \frac{2J_1(\kappa a) - k a f_0(\kappa a)}{(\mu_i - 1) J_1(\kappa a) + k a f_0(\kappa a)} \right\}^{\frac{1}{2}} \).

2.4. Axial permittivity

The electric field direction is parallel to the axial direction of the composite fiber, that is to say,
\[
E^{(0)} = E_0 e^{\text{j}\omega t} \mathbf{e}_z
\]
(26)

And make the average electric field inside the fiber meet the condition that,
\[
E = E(r) e^{\text{j}\omega t} \mathbf{e}_z
\]
(27)

Wu [53] solved the voltage of the conductive fiber in the high frequency electromagnetic field by describing a conductive single fiber as an equivalent circuit (RC circuit). In this study, since the wavelength of the applied microwave electric field is also much greater than the size of single fiber and the inductance in the fiber is not significant, single polarized fiber can also be equivalent to the RC circuit [54]. The voltage inside the fiber can be expressed as,
\[
V = R \frac{dE}{dt} + \frac{q}{C}
\]
(28)

where \( R \) is the equivalent resistance of the Fe-C coaxial fiber, \( C \) is the equivalent capacitance of the Fe-C coaxial fiber, \( q \) is the electric charge on the Fe-C coaxial fiber, which can be calculated through that,
\[
V = E e^{\text{j}\omega t} R \frac{1}{\pi a^2} \frac{C}{\kappa a \sigma}
\]
(29)

The axial depolarization factor and radial depolarization factor are still represented by \( N_i \) and \( N_s \), since the demagnetization factor and depolarization factor of the Fe-C coaxial fiber are provided by the same form. If polarization meets the condition that \( P = Pe^{\text{j}\omega t} \mathbf{e}_r \), the electric charge should be,
\[
q = \frac{P}{\pi a^2}
\]
(30)

When substituting formula (29) and the calculated \( V, R, C, q \) into formula (28), the dipole moment can be expressed,
\[
p = \pi a^2 \frac{\mu_i \sigma}{\kappa a \sigma + j \omega \varepsilon_0} e^{\text{j}\omega t} \mathbf{e}_z
\]
(31)

This formula coincide completely with the expression of dipole moment solved by Swinford [55] using different approach, and according to Helmholtz equation \( \nabla \times H + \mu_0 H = 0 \) and \( \nabla \times E + \varepsilon_0 E = 0 \), electric field inside the Fe-C coaxial fiber can be derived from formula (9),
\[
E = \frac{J_0(\kappa a)}{\kappa a f_0(\kappa a)} E_0 - \frac{N_\text{a}}{\varepsilon_0} p \mathbf{e}_z
\]
(32)

The average electric field inside the Fe-C coaxial fiber is,
\[
E = \frac{1}{\pi a^2} \int_0^{\pi a} \int_0^\infty \left[ \frac{J_0(\kappa a)}{\kappa a f_0(\kappa a)} E_0 - \frac{N_\text{a}}{\varepsilon_0} p \right] r dr \mathbf{e}_z
\]
(33)

Substituting the average electric dipole moment that is obtained from formula (32), the polarization equation, \( P = \pi a^2 \mu_0 p e^{\text{j}\omega t} \) into formula (30), then the polarization of the Fe-C coaxial fiber should be,
\[ p = \frac{\varepsilon_0 \sigma}{2N_\varepsilon + j\omega \varepsilon_0} \frac{2}{ka} J_1(ka) E_0 e^{j\omega t} e_z \]  

(33)

And the axial permittivity of Fe-C coaxial fiber can be easily obtained:

\[ \varepsilon_1 = 1 + \frac{a^2 \varepsilon_0}{2N_\varepsilon (a^2 - b^2 - r^2 - l^2) + j\omega \varepsilon_0} \left[ \frac{2}{ka} J_1(ka) \right]^2 \frac{1}{a} \left( \frac{\varepsilon_0}{\varepsilon_1} \right)^2 \]  

(34)

2.5. Radial permittivity

When the electric field direction is perpendicular to the z-axis, the initial outside electric field can be expressed as:

\[ E^0 = E_0 e^{j\omega t} e_z \]  

(35)

the electric dipole moment is

\[ P = Pe^{j\omega t} e_z \]  

(36)

The same procedure from the axial permittivity may be easily adapted to obtain the electric dipole moment,

\[ P = 2a \left( \frac{\varepsilon_0 \sigma}{2N_\varepsilon + j\omega \varepsilon_0} \right) V E_x \]  

(37)

For the purpose of solving the voltage in formula (37), the electric field must be solved first. When the average polarization is set as \( P = Pe^{j\omega t} e_z \), the electric field can be obtained according to formula (17) and duality principle between the electric and magnetic fields:

\[ E = \frac{b \varepsilon_0}{N_\varepsilon} \left( \frac{J_1(ka)}{ka} \right) \cos \varphi_e + \frac{J_1(kr)}{kr} \sin \varphi_e \right) \]  

\[ - \frac{\varepsilon_0}{N_\varepsilon} P \cos \varphi_e - \sin \varphi_e \]  

(38)

where the constant \( b \) is defined under these boundary conditions.

For the electric potential, generated from the outer space of the Fe-C coaxial fiber, it is referred as the electric dipole moment with unit length. It is

\[ \varphi_e = \left( -E_0 \frac{N_\varepsilon P}{\varepsilon_0} \frac{a^2}{r^2} \right) \cos \varphi_{e0} \]  

(39)

thus,

\[ E^0 = -\nabla \varphi_e = \left( -E_0 + \frac{N_\varepsilon P}{\varepsilon_0} \frac{a^2}{r^2} \right) \cos \varphi_{e0} e_z \]  

\[ + \left( -E_0 + \frac{N_\varepsilon P}{\varepsilon_0} \frac{a^2}{r^2} \right) \sin \varphi_{e0} e_y \]  

(40)

When \( r = a \) and \( \theta = \frac{\pi}{2} \), \( E^0 = E_z \), simultaneous formula (40), \( \beta \) can be defined as:

\[ \beta = \frac{a}{k} \frac{1}{ja k a (ka) - J_1(ka)} \]  

(41)

And through the symmetry of electric field, the average electric field is,

\[ \bar{E} = \frac{4}{2\pi a^2} \int_0^{\frac{\pi}{2}} \int_0^a E \cdot dr \cdot d\theta = \frac{b \varepsilon_0}{Na \varepsilon_0} \frac{J_1(ka)}{a} - \frac{N_\varepsilon P}{\varepsilon_0} \]  

(42)

The voltage can be obtained from formula (42) and formula (41),

\[ V = \frac{1}{2a} \int_0^{\frac{\pi}{2}} d\theta \int_0^a 2\sqrt{\alpha^2 - y^2} E \cdot e^{j\omega t} dy = \frac{a}{2} \left[ \frac{1}{ka J_1(ka) - J_1(ka)} \right] E \cdot - \frac{N_\varepsilon P}{\varepsilon_0} \]  

(43)

and the polarization is also obtained from formula (43), formula (17) and \( P = Pe^{j\omega t} e_z \).

\[ p = \frac{\varepsilon_0 \sigma}{2N_\varepsilon + j\omega \varepsilon_0} \frac{2}{ka} J_1(ka) E_0 e^{j\omega t} e_z \]  

(44)

Thus, the radial permittivity of Fe-C coaxial fiber is realized as

\[ \varepsilon_r = 1 + \frac{a^2 \varepsilon_0}{2N_\varepsilon (a^2 - b^2 - r^2 - l^2) + j\omega \varepsilon_0} \left[ \frac{2}{ka} J_1(ka) \right]^2 \]  

(45)

where \( k = \left\{ \frac{2}{ka} J_1(ka) \right\} ^2 \).

2.6. Demagnetization factor and depolarization factor

Considering the internal demagnetizing and depolarizing process of composite fiber material, the demagnetization factor and the depolarization factor were used during the calculation process. There are two viewpoints about the theory of magnetic medium in physics. One is the magnetic charge theory and it is considered that the magnetic field is generated by the positive and negative magnetic charges. The other is the molecular current theory (Ampere hypothesis) and the minimum unit (magnetism molecule) used to compose the magnet is circle electric current. The meanings of magnetic flux density and magnetic field strength of these two views are different, but the calculation results can be equivalent [56]. Also based on magnetic charge theory, the magnetic field \( \mathbf{H} \) generated by the magnetic charge which are uniformly distributed on the end face of the cylinder can be calculated. The point \( P \) which is in the yz plane is taken as the calculated filed point (as shown in the Fig. 2, \( P(r, z) \)). The surface element \( dS \) is taken from the circular disk whose magnetic charge surface density is \( \varphi \).

\[ dS = \rho d\theta d\phi \]  

(46)

and the surface element \( dS \) carry magnetic charge,

\[ dq_{m} = \sigma dS = \sigma \rho d\theta d\phi \]  

(47)

And the magnetic field intensity from the surface element \( dS \) to the point \( P \) should be [57],

\[ dH = \frac{1}{4\pi} \frac{dq_{m}}{s^2} \]  

(48)

where \( s \) is the distance from the surface element to the point \( P \),

\[ s = \sqrt{(r - \rho \cos \theta)^2 + (r - \rho \sin \theta)^2 + z^2} \]  

(49)

Fig. 2. The calculated filed point \( P \) and magnetic field of circular disk with magnetic charge.
The z component of the magnetic field intensity should be,

$$dH_z = \frac{1}{4\pi} \frac{zdq_m}{r^3} = \frac{\varphi}{4\pi r^3} \frac{z\rho d\rho d\theta}{(\rho \cos \theta)^2 + (r - \rho \sin \theta)^2 + z^2}$$ (50)

The z component of the magnetic field intensity generated by magnetic charges of the disk should be,

$$H_z(r, z) = \frac{\varphi}{4\pi} \int_0^\infty \rho d\rho \int_0^{2\pi} \frac{z d\theta}{(\rho \cos \theta)^2 + (r - \rho \sin \theta)^2 + z^2} = \sigma A(r, z)$$

(51)

where, the function $A(r, z)$ is defined as,

$$A(r, z) = \frac{1}{4\pi} \int_0^\infty \rho d\rho \int_0^{2\pi} \frac{z d\theta}{(\rho \cos \theta)^2 + (r - \rho \sin \theta)^2 + z^2}$$ (52)

According to superposition principle of magnetic field, the total magnetic intensity $H$ of the point $P$ is the magnetic intensity vector sum generated by the magnetic charges of the two end face, and the z component is,

$$H_z(r, z) = \varphi |A(r, z) + A(r, l - z)|$$ (53)

Finally, the axial demagnetizing factor of the point $P(r, \theta, z)$ can be obtained,

$$N_z(r, z) = \frac{\varphi}{\epsilon} |A(r, z) + A(r, l - z)|$$ (54)

In order to analyse conveniently, set $l = l/a, m = m/a, n = n/a$, and the function $A(r, z)$ can also be expressed as,

$$A(r, z) = \frac{C(m, n)}{r^3}$$ (55)

where

$$C(m, n) = \frac{1}{4\pi} \int_0^{2\pi} \xi d\xi \int_0^\pi \frac{nd\theta}{(\xi \cos \theta + m \cos \theta)^2 + n^2}$$

and $\xi = r/a$.

Thus the axial demagnetizing factor of the point $P(r, \theta, z)$ is expressed as,

$$N_z(r, z) = C(m, n) + C(m, l - n)$$ (56)

and the axial demagnetizing factor is obviously related to not only the shape of cylinder, but also the point position. For the point of axis of the cylinder, the demagnetizing factor should be,

$$N_z(0, z) = C(0, n) + C(0, l - n)$$

$$= 1 - \frac{1}{2} \left( \frac{n}{\sqrt{1 + n^2}} + \frac{l - n}{\sqrt{1 + (l - n)^2}} \right)$$ (0 < n < l) (57)

Because of

$$C(0, n) = \frac{1}{4\pi} \int_0^{2\pi} \xi d\xi \int_0^\pi \frac{nd\theta}{(\xi \cos \theta + m \cos \theta)^2 + n^2} = \frac{1}{2} \int_0^{2\pi} \frac{n \xi d\xi}{(\xi \cos \theta + m \cos \theta)^2 + n^2}$$

$$= \frac{1}{2} \left( 1 - \frac{n}{\sqrt{1 + n^2}} \right)$$ (58)

For a single fiber, the mean value of the factor $N_z$ is used to represent axial demagnetizing factor of the fiber,

$$N_z = \frac{\int_0^l N_z dn}{l} = \int_0^l N_z dn = \frac{1}{2} \left[ \frac{1}{\sqrt{1 + x^2}} + \frac{r - n}{\sqrt{1 + (r - n)^2}} \right] dn$$

$$= 1 + \frac{1}{2} \sqrt{1 + \frac{1}{l^2}}$$ (59)

According to the literature [58], the radial demagnetization factor of the fiber should be,

$$N_r = \frac{l}{2(l^2 - 4a^2)} - \frac{a^2 l}{(l^2 - 4a^2) \sqrt{l^2 - 4a^2}} \ln \frac{1 + \sqrt{l^2 - 4a^2}}{1 - \sqrt{l^2 - 4a^2}}$$ (60)

In addition, due to the similar fiber model is referred as an ellipsoid in the process of solving the depolarization factor [53], the depolarization factor should keep the same with the demagnetization factor.

3. Results and discussions

In order to further study the influence of geometric parameters on the effective electromagnetic parameters, and optimize the structural parameters of Fe-C coaxial fiber, we proceed the coupling calculation for multiple sets of data with the real and imaginary part of permeability and permittivity ($\mu', \mu'', \varepsilon', \varepsilon''$) as the fibrous characteristic varies. If: (1) the composite fiber geometric parameters include the radius of core and shell, the length of fiber; (2) electromagnetic environmental parameters, mainly refer to external electromagnetic field harmonic frequency; (3) intrinsic parameters of the component material of composite fiber are clear. Suppose: (1) $a = 0.866 \mu m, b = 0.5 \mu m, l = 20 \mu m$; (2) $f = 5$ GHz; (3) $\mu_1 = 7.5-i9$, $\mu_2 = 0.9-0.1i$. (Carbon is used as core material in this fiber because carbonaceous materials are generally used as dielectric absorber, and $\mu' = 1, \mu'' = 0$); (4) $\sigma_1 = 1 \times 10^7$ S/M, $\sigma_2 = 0.65 \times 10^7$ S/M [61]. According to the formula (15), (25), (34) and (45), the effective permittivity and effective permeability of Fe-C coaxial fibers in different directions rate were calculated. The electromagnetic parameters of different types of fiber at 5 GHz are shown in Table 1.

The results show that the effective permittivity and permeability of Fe-C coaxial fibers have significant anisotropy, and the axial electromagnetic parameters is much greater than that of radial electromagnetic parameters, which is due to the much greater axial demagnetization factor and depolarization factor of fibrous material than its axial value. The demagnetization effect has a significant influence on the effective electromagnetic parameters of fiber-based material. It can also be seen from Table 1 that the imaginary part of the four electromagnetic parameters of Fe-C coaxial fiber are much greater than single solid iron fiber and hollow carbon fiber, and the values of tan$\sigma$ are significantly larger than those of the other two materials, which indicates that (1) the Fe-C coaxial fibers can inhale more waves than the other two fibers, (2) the more inhaled waves will be converted into thermal energy instead of reflection, which makes great significance to improve the electromagnetic wave absorbing performance.

3.1. The influence of inner and outer diameter on the electromagnetic parameters

The composition ratio of these two materials will directly affect the changes of the electromagnetic parameters because the Fe-C coaxial fiber is made of the iron shell and the carbon core. According to the EM model, the material composition is determined by the respective volume fraction. Based on the second method of linear effect, the influence of the volume fraction on the electromagnetic parameters can be simplified to study the trends of axial and radial electromagnetic parameters when the shell and core diameters change and determine the value of inner and outer dimensions when extreme point of electromagnetic parameters occur. In this study, the variation of the real and the imaginary part of permeability and permittivity are simulated when the inner and outer dimension are defined from the range of 0.5–0.7 $\mu m$ as the boundary conditions change. Fig. 3 shows the influence of the combination of shell diameter and core diameter combination on the axial permeability.

When $b$ (inner radius) is smaller, with the increase of $a$ (outer radius) of the Fe-C coaxial fiber, both the $\mu'$ and the $\mu''$ are declining; when $b$ is larger, with the increase of $a$, above parameters
increase significantly. The critical value of these two different variation is 0.2 \( \mu_m \) (\( b = 0.2 \mu_m \)). The maximum of \( \mu' \) is 6.674 when \( a = 0.7 \mu_m \), \( b = 0.12 \mu_m \). Minimum of both the real part and the imaginary part appear as \( b = 0.5 \mu_m \). It can also be indicated from Fig. 3 that the trend of the imaginary part is significantly greater than the real part, which will cause a rapid change of the tan\( \theta \). Since the good conductor skin effect, the impact on the permeability of the inner diameter is significantly greater than the outer diameter while the real part of the axial permeability of the Fe-C coaxial fiber significantly decreases, the imaginary part steeply increases with inner radius increasing continuously.

Fig. 4 shows a relationship between the inner and outer diameters and radial permeability. The relationship between \( \mu_r \) and \( a \) is similar to \( \mu_m \). When \( b \) is small, due to the skin effect, the real and imaginary parts of permeability will increase as the outer diameter decreases. However, both the real parts and the imaginary parts firstly increase then decrease with the increase of the inner diameter. The maximum of the \( \mu_r \) respectively present at \( a = 0.5 \mu_m \), \( b = 0.21 \mu_m \); \( a = 0.53 \mu_m \), \( b = 0.49 \mu_m \), and the values are 2.6770 and 0.5685. The minimum values of the \( \mu' \) and the \( \mu'' \) are 0.8990 and 0.1169 when \( a = b = 0.5 \mu_m \). Obviously, the more the carbon is, the smaller the value of magnetic parameters of the Fe-C coaxial fiber is, which is caused by poor performance of magnetic conductivity of carbon.

Fig. 5 shows the influence of shell diameter and core diameter combination on the \( e_r \) vs. \( e_k \). The trend of the \( e_r \) is similar to the \( e_k \). Both increase with continuously increasing the outer diameters and decreases with declining the inner diameters. That is to say, to make the value of the \( e_r \) larger, the outer diameters should be larger and the inner diameters smaller. The maximum of the real parts is 14.43 when \( a = 0.7 \mu_m \), \( b = 0.04 \mu_m \), and the maximum of the imaginary parts is 46.76 when \( a = 0.7 \mu_m \), \( b = 0.0 \mu_m \). The minimum of the real parts and the imaginary parts are 4.284 and 3.617 respectively when \( a = 0.5 \mu_m \), \( b = 0.5 \mu_m \). At this time, Fe-C coaxial fibers are completely filled with carbon. It can be observed from Figs. 3 and 5 that the effect of outer diameter on the \( e_r \) is much larger than the \( e_k \).

The relationship between the radial permittivity and inner and outer diameter is shown in Fig. 6. Different from effect on the permeability, the trend of the \( e_r \) is complex under different conditions. The \( e_r \) increases with increasing outer diameters and

### Table 1: Electromagnetic parameters of different types of fiber.

<table>
<thead>
<tr>
<th>Type of fiber</th>
<th>( \mu'^a )</th>
<th>( \tan\beta^b )</th>
<th>( \mu''^c )</th>
<th>( \tan\theta^d )</th>
<th>( e_r^e )</th>
<th>( \tan\phi^f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon solid fiber</td>
<td>0.90–0.12i</td>
<td>0.134</td>
<td>0.90–0.13i</td>
<td>0.145</td>
<td>4.39–3.61i</td>
<td>1.076</td>
</tr>
<tr>
<td>Iron hollow fiber [43]</td>
<td>6.94–6.77i</td>
<td>1.477</td>
<td>2.55–0.42i</td>
<td>0.166</td>
<td>23.87–1.28i</td>
<td>0.054</td>
</tr>
<tr>
<td>Fe-C coaxial fiber</td>
<td>5.18–4.46i</td>
<td>1.164</td>
<td>2.58–0.50i</td>
<td>0.196</td>
<td>7.63–6.97i</td>
<td>1.296</td>
</tr>
</tbody>
</table>

\( \mu' \) is axial permeability.
\( \tan\beta \) is loss tangent.
\( \mu'' \) is radial permeability.
\( e_r \) is axial permittivity.
\( e_k \) is radial permittivity.
decreasing internal diameters. When $a = 0.7 \, \mu m$, $b = 0.5 \, \mu m$, the maximum of $\varepsilon_r$ is 2.023 and when $a = 0.7 \, \mu m$, $b = 0$ the minimum is 1.694, in this case, the Fe-C coaxial fiber is composed entirely of iron. The imaginary part enlarges with increasing the outer diameter. Under the influence of decreasing internal diameter, it enlarges firstly and reduces later. The maximum is 0.1962, minimum is 0.01474, respectively appearing at $a = 0.7 \, \mu m$, $b = 0.17 \, \mu m$ and $a = 0.5 \, \mu m$, $b = 0.5 \, \mu m$. From these datas, the key to control the equivalent permittivity depends on content of carbon become clear.

3.2. The influence of aspect ratio on the electromagnetic parameters

Considering the demagnetization factor ($N$), which is greatly affected by the aspect ratio ($l$) according to formula (59), has a significant influence on the electromagnetic parameters of absorbers, the numerical simulation of relative relationship in electromagnetic parameters is carried out with the fiber length. Since the axial electromagnetic parameter is much larger than the radial electromagnetic parameters, and the fiber length has a significant effect on the axial electromagnetic parameters, the relationship between the length and the axial electromagnetic parameters can be shown without the radial electromagnetic parameters. Other parameter conditions are identical in the last section, specifically, $a = 0.6 \, \mu m$; $b = 0.4 \, \mu m$. The relationship between axial permeability and fiber length is shown in Fig. 7(a), axial permittivity in Fig. 7(b).

Fig. 7(a) indicate that the $\mu_r$ increases first, then decrease while the length of Fe-C coaxial fiber continues growing, and the maximum is 4.242. During the initial stage, the $\mu_r$ shows rapid growth, and the growth trend gradually decline. When the length is 25 $\mu m$, both the $\mu_r$ and the $\mu_r'$ are 4.196 which is the only equal point, and the magnetic loss tangent is 1. When the length increases to 40$\mu m$, the imaginary part reaches 4.46, by this time, the growth trend is not obvious. The above objectives indicate that with the increase of the fiber length, its magnetic loss tangent will continue to
increase so that the capability in magnetic energy dissipation of the electromagnetic wave are gradually improved. 

Fig. 7(b) indicates that while the length of the Fe-C coaxial continues to grow, both the \( e'_l \) and the \( e''_l \) are almost linear increase. Moreover, the growth trend in the imaginary parts is faster than the real parts. \( e'_l = e''_l = 8.863 \). When the length is 30 \( \mu \)m (dielectric \( \tan \sigma \) is 1), this trend also reflects dielectric loss angle increase, which will cause the improvement on capability in electric energy dissipation of the electromagnetic wave. Evidently, the increase in the aspect ratio results in the decrease in axial demagnetization factor, which further contributes to the rapid increase of the imaginary parts of axial permittivity. Importantly, controlling length of the fiber has a great impact on improving tans.

3.3. The influence of electrical conductivity on the permittivity of coaxial fiber

Generally speaking, it is meaningful to research the relationship between the electrical conductivity and the permittivity, especially for dielectric absorber. Based on previous researches, the shell and core are made of good conductor which has great electrical conductivity such as iron fiber and carbon. Fig. 8. shows the axial permittivity of Fe-C coaxial fiber changing with the electrical conductivity at 5 GHz. In Fig. 7, the geometric parameters are identified as: \( a = 0.6 \mu \)m, \( b = 0.4 \mu \)m, \( f = 20 \mu \)m, and the transparent grid-like surfaces represent the \( e'_l \) and the shaded surfaces represent the \( e''_l \). In addition, when the electrical conductivity of a single material becomes greater, the electrical conductivity of other material will have a greater impact on the permittivity, and the maximum of the real parts can reach 6.914. But the real parts and the imaginary parts have roughly the same growth rate, so the dielectric loss tans have little change. Therefore, it is an effective way to consider the dissipation of absorbed electromagnetic wave so as to enhance electrical conductivity.

4. Conclusions

Through combining electrodynamics theory with composite materials theory based on Maxwell theory, the original calculation formula of EM parameters of the electromagnetic model of Fe-C coaxial fiber is modified. Theoretical formula of effective permeability and effective permittivity of the Fe-C coaxial fiber are obtained. In 5 GHz EM field, \( \mu _l \) and \( e'_l \) are 5.18-4.46i and 7.63-6.97i, \( \mu _l \) and \( e''_l \) are 2.58-0.50i and 1.98-0.15i, respectively. The imaginary parts and \( \tan \sigma \) of permeability and permittivity of the Fe-C coaxial fiber are larger than that of two other fibers with the same volume. In addition, axial and radial dielectric tans reach 1.296 and 0.076 that are much greater than two other fibers.

Dissipation capability of inhaled electromagnetic wave of the Fe-C coaxial fiber is significantly superior. Optimized parameters of Fe-C coaxial fiber are obtained as follow: when radius is 0.5\( \mu \)m and carbon content is 3.2%, \( \mu _l \) reach maximum, 6.429; when radius is 0.53\( \mu \)m and carbon content is 85.5%, \( \mu _l \) reach maximum, 0.569; when aspect ratio are 4.16 and 5, both magnetic and dielectric tans are 1; when \( \sigma \) is greater, \( e''_l \) is increased. Due to significant anisotropy, the variation of axial and radial parameters is different, and the axial value is more representative than the radial value. Therefore, for the purpose of increasing the axial electromagnetic parameters and improving the ability of electromagnetic loss, the composite fiber with greater conductivity, larger aspect ratio, thin iron shell materials, should be employed as the idea absorber.

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Fig. 8. The axial permittivity vs electrical conductivity at 5 GHz.