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MICROWAVE EFFECTIVE ELECTROMAGNETIC RESPONSE OF SANDWICH LIKE MAGNETIC COMPOSITE

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In this study, the long wave approximations for the effective electromagnetic response of 2-*D* sandwich metamaterial structure, as infinite two-component flat composite with cylindrical metallic inclusions contained by the same infinite two-component flat composites with spherical metallic inclusions are obtained. The expressions for the response are obtained by generalizing the expressions of the electromagnetic response of the infinite chain of infinitely long metallic cylinders periodically immersed in the flat magneto-dielectric matrix. The generalization has been done by following the approaches of *S*- and *T*-matrices. The case of ferrite like metallic saturated inclusions is considered in the study. The analytically obtained results are compared with the numerically calculated ones.

Key words: metamaterials, electromagnetic response, effective parameters, Effective Medium Theory, microwave.

During the last decade, flat metamaterial structures gained significant interest [1–4]. One reason for this is the availability of existing methods for measuring the complex permittivity and permeability of bulk materials [5–8]. The second reason is related to the pursuit for making the characterization of metamaterials at «the effective inter-atomic» level.

This study is dedicated to the characterization of 2-*D* sandwich metamaterial structure as infinite two-component flat composite with cylindrical metallic inclusions contained by same infinite two-component flat composites with spherical metallic inclusions. The characterization of the structure is based on obtaining its effective electromagnetic response by deriving its long wave approximations of expressions of the complex effective dielectric and magnetic constants. The prerequisite for the problem being considered is the effective electromagnetic response of the infinite chain of infinite circular metallic cylinders periodically immersed in a magneto-dielectric matrix with the thickness equals to the diameter of the cylinders, as in [4]. Using the *S*- and *T*-matrices approaches [9], we extend the results of [4] for the case of the above chain structure containing a pair of similar, two-component composite slabs as infinite magneto-dielectric slabs periodically embedded with spherical metallic inclusions. It is supposed that the cylindrical inclusions and spherical ones are ferrite like metallic inclusions magnetized up to the saturation. Correctness of the analytically obtained expressions is assessed with the numerically obtained one by using Finite-Difference Time-Domain method (FDTD).

1. Main Relations. Let us consider the scatterer as 2-*D* infinite sandwich structure as shown in Fig. 1 where h is the thickness of lateral slabs, d is the spacing of chain of infinitely long metallic cylinders of the radius a. It is supposed that ε' and μ' are the dielectric and magnetic constants, respectively, of the cylinders immersed in a magneto-dielectric matrix with the dielectric and magnetic constants ε and μ, respectively while ε_{r2} and μ_{r2} are the dielectric and magnetic constants, respectively, of the spheres of radius r immersed in a magneto-dielectric matrix of the lateral slabs with the dielectric and magnetic constants $\tilde{\varepsilon}$ and $\tilde{\mu}$, respectively.

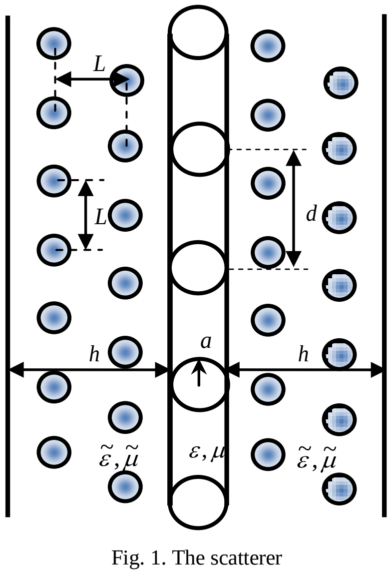

Fig. 1. The scatterer

Let us consider the normal incidence of an electromagnetic wave with frequency ω and wavenumber k on the above sandwich structure. Throughout our paper, we consider the initial plane electromagnetic wave that is normally incident to the flat boundaries of the structure. The wave has the magnetic induction vector parallel to the axes of cylinders while the electric intensity vector perpendicular to it.

As it has been shown in [4], the long-wave approximation ($ka, kd << 1$) of S-parameters for the above slab sandwich metamaterial structure for the case $\tilde{\varepsilon} = 1 = \varepsilon_{r2}$, $\tilde{\mu} = 1 = \mu_{r2}$ are defined by the equalities:

$$\tilde{S}_{11} = \frac{1}{kd}\left(2b_0^+ - 4b_1^-\right); \qquad (1)$$

$$\tilde{S}_{21} = 1 + \frac{1}{kd}\left(2b_0^+ + 4b_1^-\right), \qquad (2)$$

where $b_0^+ = \dfrac{-1}{I_0' + it_0}$; $I_0' = \dfrac{2}{kd}$; $t_0 = N_0 + \dfrac{i}{a_0'}$;

$$\xi = ka;\ N_0 = \frac{-2}{\pi}\log\frac{1.781kd}{4\pi} - 1.202\frac{(kd)^2}{4\pi^3};$$

$$a_0' = -\frac{i\pi\xi^2}{4}\,\frac{1-\eta K + \dfrac{\xi^2}{4}\left[\eta K\left(\dfrac{\eta^2}{2}+1\right) - \eta^2 + \dfrac{1}{2}\right]}{1-\dfrac{\xi^2}{4}\left[\eta^2 - 1 + 2\log\dfrac{2}{1.781\xi}(\eta K - 1)\right]};$$

$$K = \eta\frac{\varepsilon}{\varepsilon'};\ b_1^- = \frac{-kd}{4 + ikdt_1};\ \eta = \sqrt{\frac{\varepsilon'\mu'}{\varepsilon\mu}};$$

$$N_2 = \frac{-4\pi}{3(kd)^2} + \frac{1}{\pi} - 1.202\frac{(kd)^2}{8\pi^3};\ t_1 = N_0 + N_2 + \frac{i}{a_1'};$$

$$a_1' = -\frac{i\pi\xi^2}{4}\times$$

$$\times\frac{K - \eta + \dfrac{\xi^2}{8}\left[\eta\left(3+\eta^2\right) - K\left(1+3\eta^2\right)\right]}{K + \eta + \dfrac{\zeta^2}{8}\left[\eta + 2K - \eta^2(\eta + 3K) + 4\log\dfrac{2}{1.781\xi}(K-\eta)\right]}.$$

Here ε' is defined by the metal model as

$$\varepsilon'(\omega) = 1 + \frac{i\sigma}{\omega\varepsilon_0}, \qquad (3)$$

where σ is the conductivity of the inclusion metal, ε_0 is the permittivity of vacuum.

Let us consider the above slab metamaterial structure as a four-terminal network of sub-slabs with the field functions F_{I}, B_{I}, F_{II}, B_{II}, Fig. 2 where ε_{eff} and μ_{eff} are, respectively, the complex effective dielectric and magnetic constants of the considered slab for the case $\tilde{\varepsilon} = 1 = \varepsilon_{r2}$, $\tilde{\mu} = 1 = \mu_{r2}$, while $\tilde{\varepsilon}_{eff}$ and $\tilde{\mu}_{eff}$ are, respectively, the complex effective dielectric and magnetic constants of the lateral slabs.

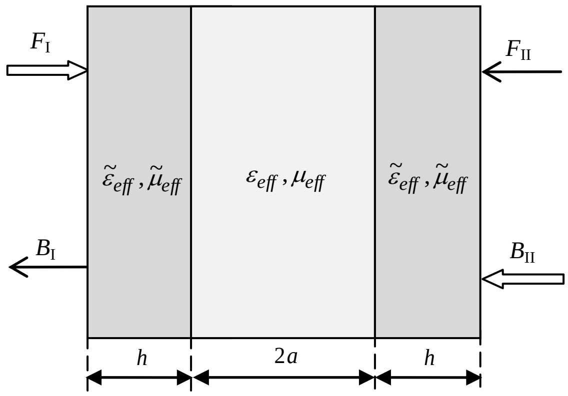

Fig. 2. Representation of the presented metamaterial slab as a four-terminal network of sub-slabs

The appropriate expressions of the complex effective constants ε_{eff} and μ_{eff} are obtained in [4] and are:

$$\varepsilon_{eff} = \frac{ic}{2a\omega}\left(\frac{1-\rho}{1+\rho}\right)\log\left(\frac{\tilde{S}_{11} + \tilde{S}_{21} - \rho}{1 - (\tilde{S}_{11} + \tilde{S}_{21})\rho}\right),$$
$$\mu_{eff} = \frac{ic}{2a\omega}\left(\frac{1+\rho}{1-\rho}\right)\log\left(\frac{\tilde{S}_{11} + \tilde{S}_{21} - \rho}{1 - (\tilde{S}_{11} + \tilde{S}_{21})\rho}\right), \qquad (4)$$

where $\tilde{S}_{11}$, $\tilde{S}_{21}$ are S-parameters of the considered metamaterial slab for the case $\tilde{\varepsilon} = 1 = \varepsilon'$, $\tilde{\mu} = 1 = \mu'$; $\rho = \dfrac{Z_{eff} - 1}{Z_{eff} + 1}$, $Z_{eff} = \sqrt{\dfrac{\mu_{eff}}{\varepsilon_{eff}}}$ is the normalized complex effective characteristic impedance of the metamaterial slab for the case $\tilde{\varepsilon} = 1 = \varepsilon_{r2}$, $\tilde{\mu} = 1 = \mu_{r2}$, c is the velocity of light in vacuum.

The expressions of the complex effective constants $\tilde{\varepsilon}_{eff}$ and $\tilde{\mu}_{eff}$ are given by [10]:

$$\tilde{\mu}_{eff}(\omega) = \mu_{r1}\left(1 + \frac{3F_s}{\dfrac{f(\theta) + 2b_m}{f(\theta) - b_m} - F_s}\right),$$
$$\tilde{\varepsilon}_{eff}(\omega) = \varepsilon_{r1}\left(1 + \frac{3F_s}{\dfrac{f(\theta) + 2b_e}{f(\theta) - b_e} - F_s}\right), \qquad (5a)$$

$$f(\theta) = \frac{2(\sin\theta - \theta\cos\theta)}{(\theta^2 - 1)\sin\theta + \theta\cos\theta}, \qquad (5b)$$

where $F_s = 4\pi r^3/3L^3$ is the metal volume fraction of the lateral slabs; L is the constant of unit cell of the lateral slabs; $b_m = \mu_{r1}/\mu_{r2}$; μ_{r1} is the magnetic constant of matrix of the lateral slabs; $b_e = \varepsilon_{r1}/\varepsilon_{r2}$,

ε_{r1} is the electric constant of matrix of the lateral slabs and ε_{r2} is exactly defined by the right side in Eq. (3); $\theta = (\omega/c)L\sqrt{\varepsilon'\mu_{r2}}$.

If the complex constants ε_{eff} and μ_{eff}, and *S*-parameters of the above four-terminal network are known for the case $\tilde{\varepsilon} = 1 = \varepsilon_{r2}$, $\tilde{\mu} = 1 = \mu_{r2}$, then its *S*-parameters for the case of arbitrary values of the constants $\tilde{\varepsilon}$, $\tilde{\mu}$ can be obtained by *T*-matrix of the four-terminal network defined via the matrix equality in [9]:

$$\begin{bmatrix} F_I \\ B_I \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} F_{II} \\ B_{II} \end{bmatrix}. \quad (6)$$

Let us obtain the elements of *T*-matrix in Eq. (6). The elements can be obtained by multiplying the field functions matrix for each sub-slab region of the four-terminal network as follows:

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} e^{i\tilde{k}_{eff}h} & 0 \\ 0 & e^{-i\tilde{k}_{eff}h} \end{bmatrix} \times$$

$$\times \begin{bmatrix} (1-R_{eff})^{-1} & R_{eff}(1-R_{eff})^{-1} \\ R_{eff}(1-R_{eff})^{-1} & (1-R_{eff})^{-1} \end{bmatrix} \begin{bmatrix} e^{2ik_{eff}a} & 0 \\ 0 & e^{-2ik_{eff}a} \end{bmatrix} \times \quad (7)$$

$$\times \begin{bmatrix} (1+R_{eff})^{-1} & -R_{eff}(1+R_{eff})^{-1} \\ -R_{eff}(1+R_{eff})^{-1} & -(1+R_{eff})^{-1} \end{bmatrix} \begin{bmatrix} e^{i\tilde{k}_{eff}h} & 0 \\ 0 & e^{-i\tilde{k}_{eff}h} \end{bmatrix},$$

where $\tilde{k}_{eff} = \sqrt{\tilde{\varepsilon}_{eff}\tilde{\mu}_{eff}}\,\omega/c$ is the wavenumber in the lateral slabs, $R_{eff} = \dfrac{\sqrt{\mu_{eff}/\varepsilon_{eff}} - 1}{\sqrt{\mu_{eff}/\varepsilon_{eff}} + 1}$ is the complex effective reflection coefficient at the plane boundaries between the first and second slabs (while $-R_{eff}$ is the complex effective reflection coefficient at the plane boundaries between the second and third slabs); $k_{eff} = \sqrt{\varepsilon_{eff}\mu_{eff}}\,\omega/c$ is the wavenumber in the second sub-slab. Multiplying matrices, gives:

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \frac{1}{1-R_{eff}^{\ 2}} \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \quad (8)$$

where $a_{11} = (e^{2ik_{eff}a} - R_{eff}^{\ 2} e^{-2ik_{eff}a})e^{2i\tilde{k}_{eff}h}$;

$a_{12} = -2iR_{eff}\sin 2k_{eff}a$; $a_{21} = -a_{12}$;

$a_{22} = (e^{-2ik_{eff}a} - R_{eff}^{\ 2} e^{2ik_{eff}a})e^{-2i\tilde{k}_{eff}h}$.

Taking in account the formula Eq. (8) and the fact that

$$\begin{bmatrix} \dfrac{1}{S_{12}} & \dfrac{-S_{22}}{S_{12}} \\ \dfrac{S_{11}}{S_{12}} & \dfrac{S_{12}^{\ 2} - S_{11}S_{22}}{S_{12}} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}, \quad (9)$$

gives:

$$S_{21} = \frac{(1-R_{eff}^{\ 2})e^{-2i\tilde{k}_{eff}h}}{e^{ik_{eff}a} - R_{eff}^{\ 2} e^{-ik_{eff}a}},$$
$$S_{11} = \frac{2iR_{eff}\, e^{-2i\tilde{k}_{eff}h} \sin 2k_{eff}a}{e^{ik_{eff}a} - R_{eff}^{\ 2} e^{-ik_{eff}a}}. \quad (10)$$

Having the expressions of *S*-parameters of the considered sandwich structure we can obtain its expressions of the effective dielectric and magnetic constants via the formulas obtained in [6]:

$$\varepsilon_{av} = n_{av}\frac{1-K-\sqrt{K^2-1}}{1+K+\sqrt{K^2-1}},$$
$$\mu_{av} = n_{av}\frac{1+K+\sqrt{K^2-1}}{1-K-\sqrt{K^2-1}}, \quad (11)$$

where

$$n_{av} = -\frac{\ln(|T|) + i(\varphi - 2\pi l)}{2(a+h)}, \quad l = 0, \pm 1, \pm 2, \ldots; \quad (12)$$

$$|T| = \frac{S_{11} + S_{21} - K - \sqrt{K^2-1}}{1 - (S_{11}+S_{21})\left(K + \sqrt{K^2-1}\right)}; \quad (13)$$

$$K = \frac{S_{11}^{\ 2} - S_{21}^{\ 2} + 1}{2S_{11}}; \quad (14)$$

and the phase φ is defined by:

$$T = |T|e^{i\varphi}. \quad (15)$$

In our study, we consider the case $l = 0$ in Eq. (12). In this case, the sandwich slab's thickness ($2h + 2a$) is less than the wavelength of initial electromagnetic wave in the slab [6].

2. The Effective Parameters: The Results of Modeling and Simulation. In this section we evaluate the accuracy and applicability range of mathematical model presented by the expressions Eqs. (10)–(15) for the case when $d = 1$mm, $a = 0.25$ mm, $L = 0.5$ mm. In our case, the matrix media are air to prevent losses due to the magneto-dielectric ($\varepsilon = 1 = \mu = \tilde{\mu} = \tilde{\varepsilon}$). Cobalt was used as material of the inclusions. In the case of saturation magnetization for such Cobalt: $\mu_{r2} = 250$. All of the calculations are done at the frequency equals to 1 GHz.

Let us compare the modeling results obtained through the model (10)–(15) with the numerically obtained results. The numerical results are obtained by FDTD simulations for evaluating the complex *S*-parameters that are being used for calculating the complex effective parameters via the formulas are analogous to that of Eqs. (11)–(15). The numerical experiments are done by using the free Meep FDTD software package. The comparisons are shown in Fig. 3–4 where the real parts of the effective constants are a function of metal volume fraction of the lateral slabs ($F = \pi r^2 / L^2$) for different values of the lateral slabs thickness h. As, it can be seen from the graphs; good agreement between the analytical and numerical results is observed on the low values of volume fraction of the spherical inclusions ($F < 0.3$) while it is clear that the analytical results are not in good agreement with the numerical ones as the volume fraction increases. Moreover, it can be observed from the graphs, better accuracy of the proposed mathematical model is obtained for the case of long lateral slabs ($h = lL, l \geq 5$) that is in good agreement with the main idea of Effective Medium Theory (EMT) according to which, the wave length of incident electromagnetic wave must be sufficiently longer than the thickness of scatterer [11–13]. At the same time, the numerical calculations have shown that the proposed analytical model Eqs. (10)–(15) is ineffective in the case when $r = a$.

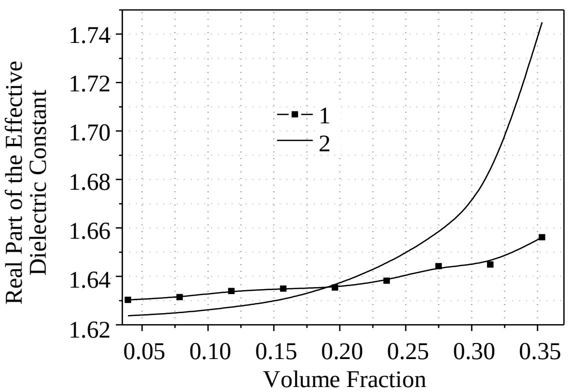

Fig. 3 Change of real part of the effective dielectric constant of the metamaterial slab versus the metal volume fraction F of spherical inclusions at 1 GHz: the line 1 is for the numerical simulations, the line 2 is for the analytical modeling

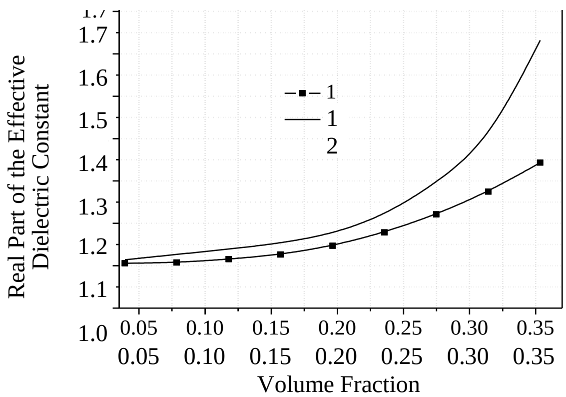

Fig. 4. Change of real part of the effective magnetic constant of the metamaterial slab versus the metal volume fraction F of spherical inclusions at 1 GHz: the line 1 is for the numerical simulations, the line 2 is for the analytical modelling

As we can observe from the graphs in Fig. 3–4, the enhancement of the real part of the complex effective dielectric constant takes place with respect to the value of the dielectric constant of the matrix while the enhancement of the real part of the complex effective magnetic constant is negligible. Furthermore, the real part of the effective constants increases with the volume fraction of the inclusions this is the well known result in [4, 14]. Anyway, comparing these results with the results in [4], we conclude that the main contribution in the enhancement of the constants is because of the cylindrical inclusions. It is also interesting to mention that the magnetization of the inclusions of the considered structure does not lead to the phenomena such as ultra-low index and negative magnetic constant while the same was found in [15, 16]. This means that the last two phenomena are normally observed in the case of the inclusions of the same geometry. Anyway the considered metamaterial structure can be used can for designing high directive patch antennas because of the enhancement of effective dielectric constant [17].

In our paper, we are not going to present the graphs for imaginary parts of the effective constants. This is because both the analytical modeling and numerical simulations have shown that the values of the above mentioned parameters are not increasing in the order of 10^{-3} which indicates low losses of the considered metamaterial structure, that, in turn, indicates a low level of damping of electromagnetic waves in the presented metamaterial slab.

Conclusion. In this paper, the electromagnetic response problem for 2-*D* sandwich metamaterial structure as infinite two-component slab composite with cylindrical metallic inclusions contained by same infinite two-component slab composites with spherical metallic inclusions is analytically solved in the microwave frequency range. The above response is found by means of applying *S*- and *T*-parameters approaches to the solution of electromagnetic response problem for the infinite chain of infinitely long metallic cylinders periodically immersed in the slab magneto-dielectric matrix. The case of Cobalt inclusions magnetized to saturation is considered. The enhancement of real part of the complex effective dielectric constant with respect to the value of dielectric constant of the matrix was found as a function of the volume fraction of cylinder inclusions while the enhancement of real part of the complex effective magnetic constant is neglected.

A good agreement between the analytical calculations and the numerical ones was found on the low values of the metal volume fraction of spherical inclusions.

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ЭФФЕКТИВНЫЙ СВЧ-ОТКЛИК СЭНДВИЧ-ПОДОБНОГО МАГНИТНОГО КОМПОЗИТА

Изучено длинноволновое приближение для эффективного электромагнитного отклика двухмерной метаматериальной сэндвич-структуры, представленной как бесконечный двухкомпонентный плоский композит с цилиндрическими металлическими включениями, заключенный между Одинаковыми бесконечными двухкомпонентными композитами со сферическими металлическими включениями. Выражения для отклика получены путем обобщения выражений для электромагнитного отклика бесконечной цепочки бесконечно длинных металлических цилиндров, периодически вставленных в плоскую магнитодиэлектрическую матрицу. Обобщение сделано с помощью теории *S*- и *T*-матриц. Рассмотрен случай ферритоподобных металлических включений, намагниченных до насыщения. Проведена оценка точности полученных аналитических выражений путем сравнения результатов аналитического моделирования с результатами численного эксперимента.

Ключевые слова: метаматериалы, электромагнитный отклик, эффективные параметры, метод эффективной среды, СВЧ-диапазон.

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ЕФЕКТИВНИЙ НВЧ-ВІДГУК САНДВІЧ-ПОДІБНОГО МАГНІТНОГО КОМПОЗИТУ

Вивчено довгохвильове наближення для ефективного електромагнітного відгуку двовимірної метаматеріальної сендвіч-структури, поданої як нескінчений двохкомпонентний композит з циліндричними металічними включеннями, що замкнений між однаковими нескінченними двохкомпонентними композитами, зі сферичними металічними включеннями. Вирази для відгуку отримано шляхом узагальнення виразів для електромагнітного відгуку нескінченного ланцюга нескінченно довгих металічних циліндрів, які періодично вставлені в плоску магнітодіелектричну матрицю. Узагальнення здійснено за допомогою *S*- і Т-матриць. Розглянуто випадок феритоподібних включень, що намагнічені до насичення. Проведено оцінку точності отриманих аналітичних виразів, порівнюючи результати аналітичного моделювання з результатами чисельного експерименту.

Ключові слова: метаматеріали, електромагнітний відгук, ефективні параметри, метод ефективного середовища, НВЧ-діапазон.

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