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Constitutive Parameter Extraction of Isotropic Inhomogeneous Metamaterials Involving Coupling

Etkileşim İçeren İzotropik Homojen Olmayan Metamalzemelerin Bünye Parametrelerinin Çıkarımı

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Abstract

An algorithm is proposed for accurate retrieval of electromagnetic parameters of isotropic inhomogeneous metamaterial(MM-a type of engineering materials) structures. It uses two sets of recursive scattering parameter relation (forward and backward directions) for obtaining average impedance. The effectiveness of the proposed method has been examined for the considered a three-layer inhomogeneous structure consisting of MMs with split-ring-resonators, and its accuracy has been compared with the other method which uses electromagnetic property extraction from scattering parameters only in forward direction.

Keywords: Metamaterials, extraction, isotropic, inhomogeneous

Geniş Özet

Metamalzeme(MM) karekterizasyonu, mükemmel lens ve görünmezlik pelerini gibi uygulamalarda kullanılan MM' lerin farklı özelliklerini anlamada önemlidir. Literatürde ölçülen/benzetimi gerçekleştirilen saçılma(S-) parametrelerine dayanan çeşitli çıkarım teknikleri bulunmaktadır. Tüm bu yöntemlerin ortak noktası, MM yapısının homojen olduğunu varsaymalarıdır. Bununla birlikte, farklı özelliklerdeki MM'lerin ardışıl eklenmesi ile çeşitli uygulamalarda kullanılabilecek yapılar oluşturulabilir. Fakat, bu durum homojen olmayan bir MM yapısının oluşmasına sebep olur. Homojen olmayan MM yapıları için önerilen yöntem, sadece bir tabakayı dikkate alır ve bundan dolayı çevresinde bulunan MM levhaları arasındaki birleştirme etkisini dikkate almaz.

Son zamanlarda, MM katmanları arasındaki etkileşimi hesaba katarak homojen olmayan izotropik ve bianizotropik MM yapılarının elektromanyetik özelliklerinin belirlenmesi için gerekli çıkarım prosedürleri geliştirilmiştir. Bu çalışmalarda, empedansı bulmak için sadece bir yönlü (ileri veya geri) tekrarlamalı S-parametre ifadeleri kümesi dikkate alınmıştır. Bununla birlikte, dalga empedansı için bir yönlü bir tekrarlamalı ifadeler kümesi, MM katmanları arasındaki etkileşimin çıkarılmasında çok etkili olmayabilir. Bu çalışmada, daha doğru elektromanyetik parametreler elde etmek ve her bir homojen olmayan izotropik MM katmanının dalga empedansını bulmak için, çift yönlü (ileri ve geri) tekrarlamalı saçılma parametre ifadelerini (S_{11} ve S_{21} ile S_{22} ve S_{21}) kullanan yeni bir algoritma önerilmektedir. Bu algoritma ile izotropik homojen olmayan metamalzeme yapılarının elektromanyetik parametrelerinin sonuçlarının daha doğru bir şekilde elde edilmesi amaçlanmıştır. Önerilen yöntemin literatürde çalışılan bir yönlü tekrarlamalı ifadeler kümesine dayalı yönteme göre avantajı, önerilen algoritma ile iki taraflı elektromanyetik çıkarım işlemi uygulanmasıdır. Önerilen yöntem ilk olarak ayrık halka rezonatör metamalzemelerden oluşan üç katmanlı homojen olmayan bir yapının benzetimi yapılarak saçılma parametreleri kullanılarak doğruluğu incelenmiş, daha sonra da literatürdeki mevcut olan aynı yöntemlerin sonuçları ile doğrulukları karşılaştırılmıştır. Amaçlanan yöntem ile literatürdeki yöntemlerin doğruluk derecelerini değerlendirmek için çıkarımı yapılan elektromanyetik özelliklerin kullanımı ile homojen olmayan MM yapısının tüm S-parametreleri incelenmiştir. S-parametrelerinin analizi için CST mikrodalga programı kullanılmıştır. Elde edilen incelemeler sonucunda, makalede önerilen çift yönlü tekrarlamalı saçılma parametre ifadeleri ile elde edilen sonuçların (özellikle empedans), literatürde önerilen tek yönlü tekrarlamalı saçılma parametre ifadeleri ile elde edilen sonuçlara göre daha yumuşak bir şekilde frekans ile değiştiği gözlemlenmiştir.

Anahtar kelimeler: Metamalzemeler, çıkarım, izotropik, homojen olmayan

1. Introduction

Characterization of metamaterials (MMs) is an important step in understanding their exotic applications such as perfect lens and invisibility cloaks. There are various retrieval techniques available in the literature based on measured/simulated scattering (S-) parameters [1-5]. The common point of all these methods is that they all assume that the MM structure is homogeneous. However, more intriguing properties of various MMs can be achieved by cascading them in the propagation direction, resulting in an inhomogeneous MM structure. The method [6] proposed for inhomogeneous MM slabs considers only-one layer and thus does not take into account the coupling effect between neighboring MM slabs. In recent studies [7],[8], retrieval procedures for extraction of electromagnetic properties of inhomogeneous isotropic and bianisotropic MM structures are proposed taking into account the coupling between nearby resonating MM slabs. In those studies, only one set of recursive S-parameter expressions (S_{11} and S_{21} for [7] and S_{11}, S_{22}, and S_{21} for [8]) was considered for finding the impedance. However, as to be demonstrated shortly, one set of recursive expressions for the wave impedance may not be so effective in extracting coupling between MM slabs because the coupling depends on the order of neighboring layers in the whole inhomogeneous MM structure. In this letter, we propose a new algorithm using two-directional recursive scattering parameter expressions (S_{11}&S_{21} set for the forward direction and S_{22}&S_{21} set for the backward direction) for obtaining more accurate wave impedance and refractive index of each layer of inhomogeneous isotropic MM structures.

2. Proposed Algorithm

Fig. 1 shows an inhomogeneous MM structure with m homogeneous isotropic reciprocal MM slabs. Wave impedance, refractive index, and the thickness of the kth layer ($1 \leq k \leq m$) are denoted by $\mathrm{Z_k}$, $\mathrm{n_k}$, and $\mathrm{d_k}$, respectively. $\mathrm{S_{11}^{(k)}}$ ($\mathrm{S_{21}^{(k)}}$) is the forward reflection (transmission) partial S-parameter from (through) the partial inhomogeneous structure specified from the interface between layers k and $k+1$ toward layer $m+1$. In a similar fashion, $\mathrm{S_{22}^{(k)}}$ ($\mathrm{S_{12}^{(k)}}$) is the backward reflection (transmission) partial *S*-parameter from (through) the partial inhomogeneous structure specified from the interface between layers $m - k$ and $m- k+1$ toward layer 1.

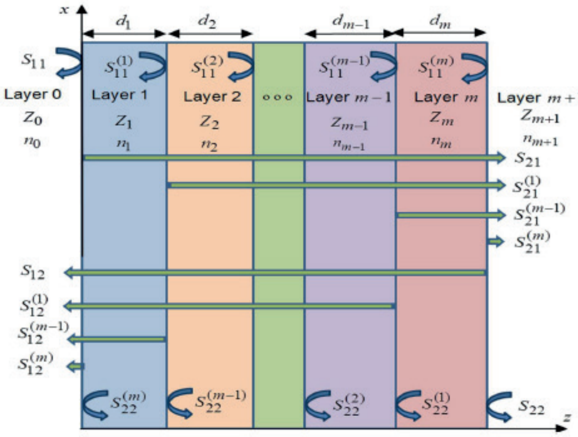


Figure 1: Demonstration of two-directional (forward and backward) recursive S-parameters of an m - layer inhomogeous MM structure.

Assuming that plane wave in $\mp z$ direction with linear polarization in x direction is incident to the inhomogeneous isotropic structure in Fig. 1, forward and backward recursive S- parameters can be written for e^{-iwt} time-reference as [7]

$$\mathrm{S_{11}^{(l)}} = \frac{(\mathrm{Z_l} + \mathrm{Z_{l-1}})\,\mathrm{S_{11}^{l-1}} - (\mathrm{Z_l} - \mathrm{Z_{l-1}})}{(\mathrm{Z_l} + \mathrm{Z_{l-1}}) - \mathrm{S_{11}^{l-1}}(\mathrm{Z_l} - \mathrm{Z_{l-1}})}\frac{1}{\mathrm{T_l^2}}, \qquad (1a)$$

$$\mathrm{S_{21}^{(l)}} = \frac{2\mathrm{Z_{l-1}}\,\mathrm{S_{21}^{(l-1)}}}{(\mathrm{Z_l} + \mathrm{Z_{l-1}}) - \mathrm{S_{11}^{(l-1)}}(\mathrm{Z_l} - \mathrm{Z_{l-1}})}\frac{1}{\mathrm{T_l}}, \qquad (1b)$$

$$\mathrm{S_{22}^{(l)}} = \frac{(\mathrm{Z_r} + \mathrm{Z_{r+1}})\,\mathrm{S_{22}^{(l-1)}} - (\mathrm{Z_r} - \mathrm{Z_{r+1}})}{(\mathrm{Z_r} + \mathrm{Z_{r+1}}) - \mathrm{S_{22}^{(l-1)}}(\mathrm{Z_r} - \mathrm{Z_{r+1}})}\frac{1}{\mathrm{T_r^2}}, \qquad (1c)$$

$$\mathrm{S_{12}^{(l)}} = \frac{2\mathrm{Z_{r+1}}\,\mathrm{S_{12}^{(l-1)}}}{(\mathrm{Z_r} + \mathrm{Z_{r+1}}) - \mathrm{S_{22}^{(l-1)}}(\mathrm{Z_r} - \mathrm{Z_{r+1}})}\frac{1}{\mathrm{T_r}}, \qquad (1d)$$

where $r = m - \mathrm{l} + 1$, $\mathrm{l} = 1, 2, \ldots\ldots\ldots, m$, and

$$\mathrm{Z_k} = \sqrt{\mu_k / \varepsilon_k}\ , \quad \mathrm{n}_k = \sqrt{\mu_k\, \varepsilon_k}\ , \qquad (2)$$
$$\mathrm{T_k} = e^{+ik_0 n_k d_k}$$

$$\mathrm{S_{11}^{(0)}} = \mathrm{S_{11}}\ , \quad \mathrm{S_{21}^{(0)}} = \mathrm{S_{21}}\ , \qquad (3)$$
$$\mathrm{S_{12}^{(0)}} = \mathrm{S_{12}}\ , \qquad \mathrm{S_{22}^{(0)}} = \mathrm{S_{22}}$$

$$S_{11}^{(m)} = \frac{Z_{m+1} - Z_m}{Z_{m+1} + Z_m}, \quad S_{21}^{(m)} = \frac{2Z_{m+1}}{Z_{m+1} + Z_m}, \qquad (4)$$

$$S_{22}^{(m)} = \frac{Z_0 - Z_1}{Z_0 + Z_1}, \qquad S_{12}^{(m)} = \frac{2Z_0}{Z_0 + Z_1}, \qquad (5)$$

Here, ε_k and μ_k are the complex permittivity and permittivity of the layer k, and k_0 is the free-space wave number.

It is seen from (1)-(5) that Z_k and $\mathrm{n_k}$ of any layer k [for $\mathrm{k} \neq 1$ and $k \neq$ m] is a function of $\mathrm{S_{11}^{(\mathit{k}-1)}}$, $\mathrm{S_{11}^{(\mathit{k}+1)}}$, $\mathrm{S_{21}^{(\mathit{k}-1)}}$, $\mathrm{S_{21}^{(\mathit{k}+1)}}$, $\mathrm{S_{22}^{(m-\mathit{k})}}$, and $\mathrm{S_{22}^{(m-\mathit{k}+2)}}$. For reciprocal MM slabs, we do not need to use $\mathrm{S_{12}^{(l)}}$ recursive relations. In order to determine Z_k and n_k, we use the following steps:

1) Apply a suitable technique [1], [2] to determine separately initial values for wave impedances and refractive indices of first k -1 layers and the last k+1 to m layers.

2) (Forward: +z direction) If $k \neq 1$, a) iterate $S_{11}^{(l)}$ and $S_{21}^{(l)}$ in (1a) and (1b) for $l < k$, b) express $S_{22}^{(l-1)}$ in terms of $\mathrm{S_{22}^{(l)}}$ in (1c), and c) iterate $S_{22}^{(l-1)}$ for $m - k + 2 < l \leq m$.

3) (Backward: - z direction) If $k \neq$ m, a) iterate $S_{22}^{(l)}$ in (1c) for $1 \leq l \leq$ m - k, b) express $S_{11}^{(l-1)}$ and $S_{21}^{(l-1)}$ in terms of $S_{11}^{(l)}$ and $S_{21}^{(l)}$ in (1a) and (1b), and c) iterate $S_{11}^{(l-1)}$ and $S_{21}^{(m-1)}$ for $k < l < m$.

4) Calculate $\mathrm{Z}_k^{(1)}$ by eliminating $\mathrm{T_l^2}$ from (1a) and (1c)

$$\mathrm{Z_k^{(1)^2}} = \mathrm{Z_{k-1}\, Z_{k+1}} \left(\frac{\mathrm{Z_{k+1}}\, \Lambda_1 - \mathrm{Z_{k-1}}\, \Lambda_2}{\mathrm{Z_{k+1}}\, \Lambda_3 - \mathrm{Z_{k-1}}\, \Lambda_4}\right), \qquad (6a)$$

$$\Lambda_1 = (1 + \mathrm{S_{22}^{(m-k)}})(1 + \mathrm{T_{k+1}^2}\, \mathrm{S_{11}^{(k+1)}})\Omega_1\,, \qquad (6b)$$

$$\Lambda_2 = \left(1 + S_{11}^{(k-1)}\right)\left(1 + T_{k-1}^2\, S_{22}^{(m-k+2)}\right)\Omega_2, \qquad (6c)$$

$$\Lambda_3 = \left(1 - \mathrm{S_{11}^{(k-1)}}\right)\left(1 - \mathrm{T_{k-1}^2}\, \mathrm{S_{22}^{(m-k+2)}}\right)\Omega_2\,, \qquad (6d)$$

$$\Lambda_4 = \left(1 - \mathrm{S_{22}^{(m-k)}}\right)\left(1 - \mathrm{T_{k+1}^2}\, \mathrm{S_{11}^{(k+1)}}\right)\Omega_1, \qquad (6e)$$

$$\Omega_1 = \left(1 - \mathrm{T}_{k-1}^2\, \mathrm{S}_{11}^{(k-1)}\, \mathrm{S}_{22}^{(\mathrm{m}-k+2)}\right), \tag{6f}$$

$$\Omega_2 = \left(1 - \mathrm{T}_{k+1}^2\, \mathrm{S}_{11}^{(k+1)}\, \mathrm{S}_{22}^{(\mathrm{m}-k)}\right), \tag{6g}$$

5) Calculate $\mathrm{Z}_k^{(2)}$ by eliminating T_l^2 from (1a) and (1b)

$$\mathrm{Z}_\mathrm{k}^{(2)^2} = \frac{(1+\mathrm{S}_{11}^{(k+1)}\,\mathrm{T}_{k+1}^2)^2 - \Omega_3^2\,(1+\mathrm{S}_{11}^{(k-1)})^2}{(\frac{1-\mathrm{S}_{11}^{(\mathrm{k}+1)}\ \mathrm{T}_{\mathrm{k}+1}^2}{\mathrm{Z}_{k+1}})^2 - \Omega_3^2(\frac{1-\ \mathrm{S}_{11}^{(\mathrm{k}-1)}}{\mathrm{Z}_{k-1}})^2}, \tag{7a}$$

$$\Omega_3 = \mathrm{S}_{21}^{(k+1)}\,\frac{\mathrm{T}_{k+1}}{\mathrm{S}_{21}^{(k-1)}}, \tag{7b}$$

6) In evaluation of $Z_k^{(1)}$ and $Z_k^{(2)}$ from (6) and (7), $T_{k-1}^2\, S_{22}^{(m-k+2)} \rightarrow 0$ if $\mathrm{k} = 1$, and $T_{k+1}^2\, S_{11}^{(k+1)} \rightarrow 0$ and $T_{k+1}^2\, S_{21}^{(k+1)} \rightarrow 1$ if $k = m$. Then, $Z_k = (Z_k^{(1)} + Z_k^{(2)})/2$.
7) Obtain T_k^2 from (1a) [or (1c)] using the value of Z_k

$$\mathrm{T}_\mathrm{k}^2 = \Omega_4\,\frac{(\mathrm{Z}_\mathrm{k}-\mathrm{Z}_{\mathrm{k}-1}) - \mathrm{S}_{11}^{(\mathrm{k}-1)}(\mathrm{Z}_\mathrm{k}+\mathrm{Z}_{\mathrm{k}+1})}{(\mathrm{Z}_\mathrm{k}-\mathrm{Z}_{\mathrm{k}-1})\mathrm{S}_{11}^{(\mathrm{k}-1)} - (\mathrm{Z}_\mathrm{k}+\mathrm{Z}_{\mathrm{k}+1})}, \tag{8a}$$

$$\Omega_4 = \frac{(Z_{k+1}-Z_k)\,S_{11}^{(k+1)}\,T_{k+1}^2 + (Z_{k+1}+Z_k)}{(Z_{k+1}-Z_k) + S_{11}^{(k+1)}\,T_{k+1}^2(Z_{k+1}+Z_k)}, \tag{8b}$$

Then, extract n_k from (8a)

$$n_k = \frac{-iln\left(T_k^2\right) + 2\pi m_b}{2k_0 d_k}, m_b = 0, \mp1, \mp2, .., \tag{9}$$

where m_b denotes the branch index whose correct value can be determined from [3].
8) Reiterate the steps 2 through 6 for any other layer in the inhomogeneous MM structure using newly found Z_k and n_k values of the layer k.
9) Repeat the steps 1 through 8 for the layers whose electromagnetic parameters are computed till the end of the maximum iteration number (N_{max}).
Because the mean value of $Z_k^{(1)}$ and $Z_k^{(2)}$ is used for Z_k in steps 4 - 6, it can be considered that our proposed algorithm is combination of the method [6] and the method [7].

3. Simulations and Validation

For validation of our extraction algorithm, we extracted electromagnetic properties of an inhomogeneous MM structure in Fig. 2(a) consisting of a MM slab with split-ring-resonator (SRR), FR4 material, and a MM slab with SRR and Wire. The dimensions of the SRR and SRR-Wire structures were set similar to those of the study [7] in order to compare the results. The SRR structure in cubical form with side d_1 = 2.5 mm is constructed over the front face of the FR4 substrate with thickness 0.25 mm, and relative electrical permittivity $\varepsilon_{rs} = 4.4(1 + j0.02)$ ($\mu_{rs} = 1$). It has an outer ring 2.2 mm, a separation distance between rings 0.15 mm, a linewidth of each ring 0.2 mm, and a gap of both rings 0.15 mm. Besides, for the SRR-Wire structure, in addition to the SRR configuration it has a wire with 0.2 mm linewidth extending in the *x* direction at the back of the FR4 substrate. FR4 material has thickness of d_2 = 2.0 mm. It is known that the SRR and SRR - Wire structures show isotropic MM slab property [2] for the assumed plane wave propagation in the *z* direction with polarization vector in the *x* direction.

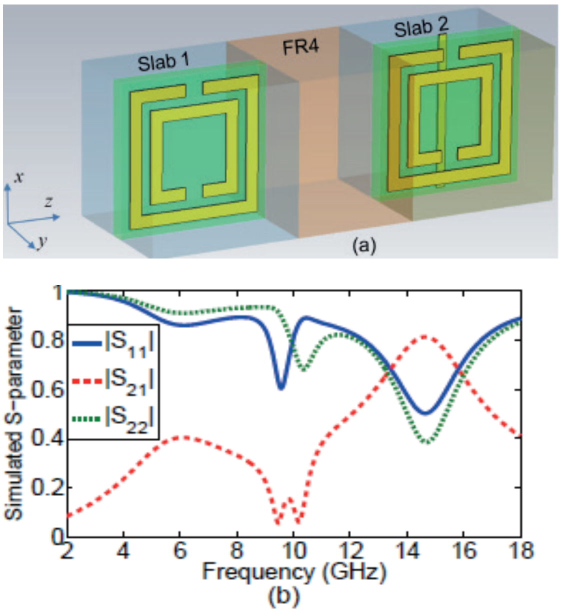


Figure 2: (a) Geometry of the analyzed three-layer [SRR, FR4, and SRR-Wire] inhomogeneous structure and (b) its simulated magnitudes of S-parameters.

We used the CST Microwave Studio for obtaining simulated S-parameters. Two waveguide ports were located over *xy* planes at $z = 0$ and $z = d_1 + d_2 + \ldots + d_m$ for extraction of electromagnetic properties of inhomogeneous isotropic MM structures. Perfect electric (magnetic) conductors were assumed to be located at *yz (xz)* planes to simulate uniform plane wave propagation in +*z* direction with polarization in + *x* direction. Adaptive meshing feature of the CST program was set active, and 114, 362 hexahedral cells for f= 2:18 GHz were used to discretize the computational domain. Magnitudes of simulated S-parameters of the whole inhomogeneous MM structure are shown in Fig. 2(b). It is seen from Fig. 2(b) that magnitudes of S_{11} and S_{22} are different due to reflection asymmetry of the inhomogeneous MM structure.

We applied our retrieval algorithm (in conjunction with the transfer-matrix method [2]) and the retrieval algorithm in [7](or another similar retrieval algorithm [8]) to extract electromagnetic properties of the SRR - Wire structure using the S- parameters of the three - layer inhomogeneous isotropic MM structure in Fig. 2(a). We set $\mathrm{N}_{\max} = 3$ for both algorithms. In addition, we applied the method in [1] using simulated S-parameters of the SRR-Wire only. Figs. 3(a) and 3(b) illustrate the extracted real parts of z_3 and n_3 of the SRR-Wire structure obtained by all methods. For conciseness, imaginary parts of extracted parameters the SRR-wire structure are not shown. It is seen from Fig. 3 that retrieved real parts of z_3 and n_3 by the extraction algorithm [7] and our extraction algorithm are in good agreement with each other and with the retrieved real parts of z_3 and n_3 by the extraction algorithm [1] except around resonance region between 9 and 11 GHz (see $|S_{21}|$ in Fig.2(b)) due to coupling between resonating MM slabs.

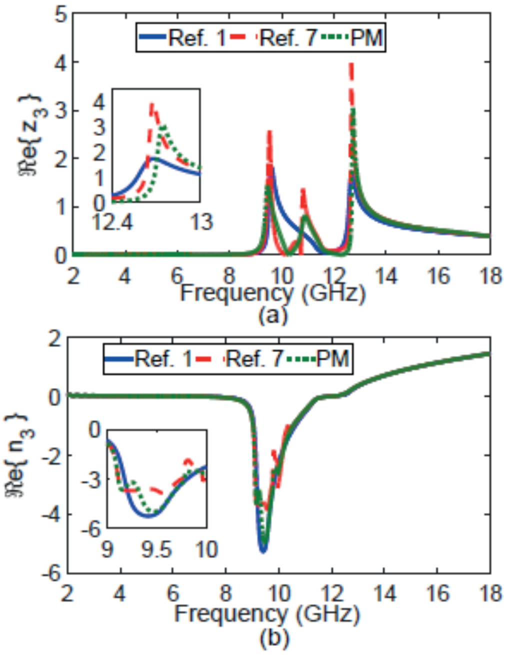
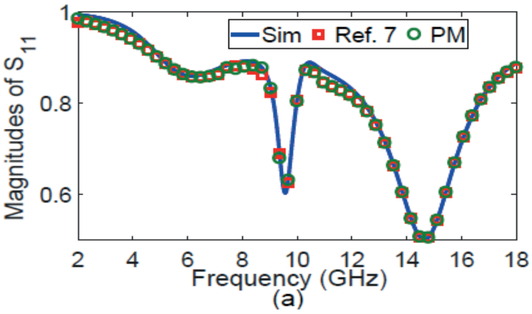


Figure 3: Real parts of retrieved (a) z_3 and (b) n_3 of the SRR-Wire MM slab by the extraction techniques in [1]and [7], and the proposed method (PM).

Nonetheless, our extraction algorithm retrieves more smother electromagnetic parameters (see the insets in Figs. 3(a) and 3(b)) around the resonance region compared with the parameters retrieved by the extraction algorithm [7], since our algorithm considers two-directional recursive S-parameters (S_{11}&S_{21} and S_{22}&S_{21}) in evaluation of electromagnetic parameters of each isotropic MM slab. Besides, Figs. 4(a) and 4(b) illustrate the magnitudes of reconstructed (and simulated) S_{11} and S_{21} of the whole structure using electromagnetic properties of each slab extracted by our algorithm and the method [7] using the transfer matrix method [2]. It is seen from Figs. 4(a) and 4(b) that simulated and reconstructed S - parameters are in good agreement with one another except for some small differences especially around the resonance region. Therefore, although retrieved parameters of MM slabs by our algorithm and the algorithm [7] could produce similar reconstructed S-parameters of the whole three - layer inhomogeneous structure, our algorithm produces more smoother extracted electromagnetic parameters of individual MM slabs by applying two-directional recursive S-parameters.



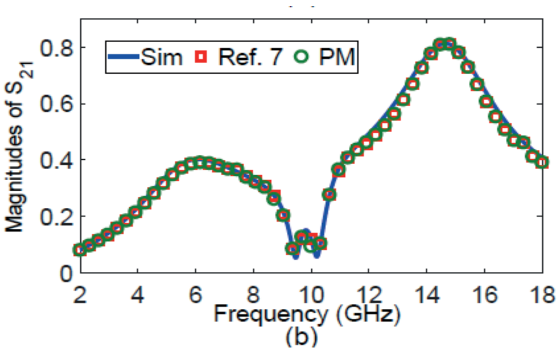


Figure 4: Simulated (Sim) and retrieved (a) $|S_{11}|$ and (b) $|S_{21}|$ of the whole structure by the algorithm [7] and the proposed method (PM).

4. Conclusion

A retrieval method is proposed for smoother and accurate extraction of electromagnetic parameters of isotropic inhomogeneous metamaterial structures. The advantage of the proposed method over the examined method in the literature is while our proposed algorithm uses two-directional recursive electromagnetic extraction process, the method in the literature just uses one-directional recursive electromagnetic property extraction process. Our proposed method was firstly validated by simulated scattering parameters of a three-layer inhomogeneous structure composed of split-ring-resonator MM slabs, and then its accuracy was compared with the accuracy of the examined method available in the literature.

5. Acknowledgment

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6. References

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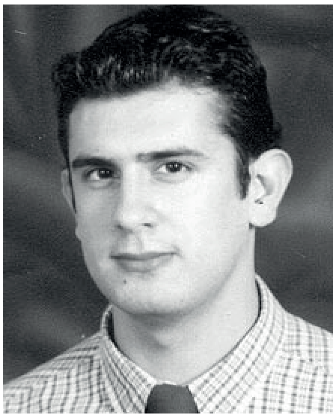

Uğur Cem HASAR, lisans ve yüksek Lisans derecelerini sırasıyla 2000 ve 2002 yıllarında Adana, Çukurova Üniversitesi, Elektrik-Elektronik Mühendisliği bölümünden almıştır. Doktora eğitimini 2008 yılında, Binghamton, New York Eyalet Üniversitesi, Elektrik ve Bilgisayar Mühendisliği bölümünde tamamlamıştır. 2000-2005 yılları arasında Çukurova Üniversitesi Elektrik-Elektronik Mühendisliği Bölümünde, 2005-2008 yılları arasında ise Erzurum, Atatürk Üniversitesi Elektrik ve Elektronik Mühendisliği Bölümünde Araştırma Görevlisi olarak görev yapmıştır. 2009-2011 yılları arasında Erzurum, Atatürk Üniversitesi Elektrik-Elektronik Mühendisliği Bölümünde yardımcı doçent, 2011-2013 yılları arasında ise Doçent olarak görev yapmıştır. Daha sonra Gaziantep Üniversitesi, Elektrik-Elektronik Bölümünde Doçent olarak görev yapmaya başlamıştır. Şu an aynı üniversitede Profesör olarak görevine devam etmektedir.
Başlıca araştırma alanları arasında mikrodalga frekanslarında malzemelerin tahribatsız muayenesi ve değerlendirilmesi, yeni kalibrasyon bağlı ve bağımsız mikrodalga yöntemleri ile geleneksel malzemelerin elektriksel ve fiziksel karakterizasyonun yapılması, milimetre dalgaları ve THz frekansları, yüksek güç yoğunluğu uygulamaları için yüksek sıcaklıkta paketleme, gözenekli silikon temelli cihazlar ve uygulamaları ve metamalzemeler bulunmaktadır.

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