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ANOMALOUS PROPERTIES OF SCATTERING FROM CAVITIES PARTIALLY LOADED WITH DOUBLE-NEGATIVE OR SINGLE-NEGATIVE METAMATERIALS

F. Bilotti and A. Alù

University of Roma Tre
Department of Applied Electronics
via della Vasca Navale 84, 00146, Rome, Italy

N. Engheta

University of Pennsylvania
Department of Electrical and Systems Engineering
Philadelphia, PA, USA

L. Vegni

University of Roma Tre
Department of Applied Electronics
via della Vasca Navale 84, 00146, Rome, Italy

Abstract—In this paper, the theoretical justification and the numerical verification of the anomalous scattering from cavities partially filled with metamaterials are presented. A hybrid numerical formulation based on the Finite Element Method (FEM) and on the Boundary Integral (BI) for the analysis of cavity backed structures with complex loading metamaterials is first presented. The proposed approach allows the analysis of cavities filled with materials described by tensorial linear constitutive relations, which may well describe artificial metamaterials synthesized with proper inclusions in a host dielectric. It is found that cavities loaded with pairs of metamaterial layers with "resonant" features possess unusual scattering properties, and with judicious selection of constitutive parameters for these materials the transparency effect or significant enhancement in the backscattering from such cavities are obtained. This may be considered as a first step towards the analysis of the scattering and radiating features of cavity-backed patch antennas and reflect-arrays in presence of multilayered metamaterial loads.

1. INTRODUCTION

The interest in artificially engineered materials has sensibly grown in recent years. Technological advances make now possible the realization of complex composites exhibiting some desired features at microwave and optical frequencies. Ferrites, due to their easily obtainable non-reciprocal properties and tuning capabilities, have long been used for radio-frequency circuits, waveguides and components (see [1, 2] and references therein). For a long time such materials have been considered in the microwave community one of the rare examples of complex materials actually usable in real-life components. Some chiral and bi-anisotropic samples have been realized in the past and have been suggested for potential use in radomes, phase-shifters, polarizers, loadings for rectangular waveguides, etc [3–7]. It is also speculated that such materials, characterized by an inherent coupling between electric and magnetic field effects (magneto-electric effect), may potentially be exploited in a suitable way also for integrated circuit and microstrip antenna applications using thin film and micro-resonator technologies [6, 7].

Moreover, the advent of metamaterials, i.e., *engineered* materials synthesized by including suitable particles in a host medium that lead to exciting electromagnetic properties otherwise not easily available in nature, have opened new possibilities to researchers and designers working on the enhancement of component performances, usually limited by some physical constraints when standard materials are employed. When the size of each inclusion and the distance between them are electrically small, a homogenization process may be employed and the electromagnetic properties of the metamaterial are then consequently described by tensorial constitutive relations (see e.g., [8]). Furthermore, when the magneto-electric coupling effect in each particle is negligible and the possible anisotropic effects do not affect the excitation under consideration, these metamaterials may be treated as quasi-isotropic and described by scalar constitutive parameters.

In this latter family, special attention has been paid particularly to metamaterials exhibiting low or negative scalar constitutive parameters in limited frequency ranges. Such materials have been experimentally demonstrated [9–11] and their theoretical electromagnetic properties and applications have been extensively studied [12–22]. In particular, the use of double-negative (DNG) materials [13], in which both permittivity and permeability have negative real parts, or single negative (SNG) media, in which only one of the two parameters has a negative real part, (such as epsilon-negative — ENG — and mu-negative — MNG — material [19]) has been proposed in some recent works in order to overcome some intrinsic physical limitations in microwave and optical applications [17–22]. Moreover, it has been shown how a suitable pairing of *conjugate* materials with oppositely signed real parts of their constitutive parameters may strongly affect the scattering [19] and guiding [18] properties of the whole system, due to an inherent resonance at the common interface between the two materials.

The aim of the present paper is to show how a similar pairing may modify the usual scattering properties of metallic cavities when they are filled with *conjugate* metamaterial pairs. To this end, a general variational formulation for the analysis of cavities filled with stratified linear complex materials is exploited. A Finite Element — Boundary Integral (FE-BI) numerical code based on this formulation, already developed and validated in a recent publication [23] through other numerical results and measurements available in the literature, has been applied here to analyze the monostatic scattering properties of metamaterial filled cavities. The numerical simulations confirm how, similar to the other geometries already studied, a suitable pairing of conjugate materials may induce an anomalous transparency of the cavity or conversely enhance its scattering properties, when compared with similar cavities filled by regular materials.

2. FORMULATION OF THE PROBLEM

The geometry of the electromagnetic problem considered here is sketched in Fig. 1. A cavity with perfectly electric conducting (PEC) metallic walls is filled with a stratified (inhomogeneous in general) linear medium and each material layer is assumed to be described by tensorial constitutive relations, which take into account possible magneto-electric effects. An arbitrary number of PEC patches may also be added at any interface, although one may consider no patch at all. Notice that the possible anisotropy of the filling materials are consistent with the metamaterial loads, for which the possible non-

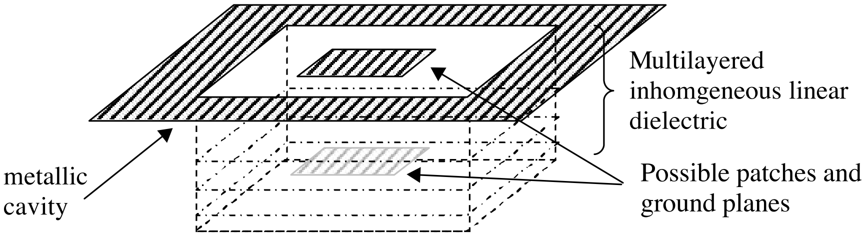

Figure 1. Geometry of a metallic cavity filled with a multilayered inhomogeneous linear materials.

random orientation of the small inclusions, once homogenized, may easily lead to anisotropic or bi-anisotropic constitutive relations [8].

Assuming the $\exp[j\omega t]$ excitation by a generic electric source $\boldsymbol{J}$ (which may model a plane wave, a probe feed or a microstrip feeding line) and applying the variational method [24–26], the electromagnetic problem reduces to the following functional [23]:

$$F(\boldsymbol{E},\boldsymbol{E}^a) = \left\langle \left(\underline{\boldsymbol{\mu}}^a\right)^{-1} \cdot \left(\nabla\times\boldsymbol{E}^a + j\omega\underline{\boldsymbol{\xi}}\cdot\boldsymbol{E}^a\right), \nabla\times\boldsymbol{E} + j\omega\underline{\boldsymbol{\zeta}}\cdot\boldsymbol{E}\right\rangle \\ +\omega^2\left\langle \boldsymbol{E}^a, \underline{\boldsymbol{\varepsilon}}\cdot\boldsymbol{E}\right\rangle - \left\langle \boldsymbol{E}^a, j\omega\boldsymbol{J}\right\rangle - \left\langle j\omega\boldsymbol{J}^a, \boldsymbol{E}\right\rangle \\ +2\omega^2\varepsilon_0 \int_{S_{ap}} (\hat{\boldsymbol{n}}\times\boldsymbol{E}^a)^* \cdot \left[\int_{S_{ap}} \underline{\boldsymbol{G}}(\boldsymbol{r},\boldsymbol{r}')\cdot\left[\hat{\boldsymbol{z}}\times\boldsymbol{E}(\boldsymbol{r}')\right] dS'\right] dS, \quad (1)$$

where the last term on the right side, called boundary-integral (BI) term, takes into account the radiation from the cavity, whereas the tensors $\underline{\boldsymbol{\xi}}$ and $\underline{\boldsymbol{\zeta}}$ take into account the magneto-electric effect. For the definition of the remaining symbols in the previous formula, you may refer to [23].

The solution of the electromagnetic field is obtained assuming that the functional (1) is stationary for arbitrarily small variations of the electric field around its stationary point. The resulting equation $\delta F(\boldsymbol{E},\boldsymbol{E}^a) = 0$ is solved numerically with a Finite Element Method formulation.

To this end, the cavity is discretized into N brick elements and the unknown fields $\boldsymbol{E}$ and $\boldsymbol{E}^a$ are expanded in terms of a set of vector basis functions $\boldsymbol{W}_i$ as:

$$\boldsymbol{E} \cong \sum_{i=1}^{N} E_i\boldsymbol{W}_i \qquad \boldsymbol{E}^a \cong \sum_{i=1}^{N} E_i^a\boldsymbol{W}_i$$

where E_i and E_i^a are unknown complex coefficients. Applying a standard Rayleigh-Ritz procedure [27], the analytic equation $\delta F(\boldsymbol{E}, \boldsymbol{E}^a) = 0$ is transformed into a usual linear system of equations of the form $\underline{\boldsymbol{A}} \cdot \boldsymbol{X} = \boldsymbol{B}$. The elements of the vectors $\boldsymbol{X}$ and $\boldsymbol{B}$ are given by:

$$\begin{aligned} X_i &= E_i & i &= 1, , \ldots, N \\ B_i &= \int_V \boldsymbol{W}_i \cdot \boldsymbol{J} dV & i &= 1, \ldots, N \end{aligned}$$

while the entries of the matrix $\underline{\boldsymbol{A}}$ are expressed as:

$$A_{ij} = A_{ij}^{(1)} + A_{ij}^{(2)} + A_{ij}^{(3)} + A_{ij}^{(4)} + A_{ij}^{(5)} + A_{ij}^{(B.I.)} \quad i, j = 1, \ldots, N$$

with

$$\begin{aligned} A_{ij}^{(1)} &= -\int_V (\nabla \times \boldsymbol{W}_i) \cdot \underline{\boldsymbol{\mu}}^{-1} \cdot (\nabla \times \boldsymbol{W}_j) dV \\ A_{ij}^{(2)} &= -j\omega \int_V (\nabla \times \boldsymbol{W}_i) \cdot \underline{\boldsymbol{\mu}}^{-1} \cdot (\underline{\boldsymbol{\zeta}} \cdot \boldsymbol{W}_j) dV \\ A_{ij}^{(3)} &= j\omega \int_V \boldsymbol{W}_i \cdot \underline{\boldsymbol{\xi}} \cdot \underline{\boldsymbol{\mu}}^{-1} \cdot (\nabla \times \boldsymbol{W}_j) dV \\ A_{ij}^{(4)} &= -\omega^2 \int_V \boldsymbol{W}_i \cdot \underline{\boldsymbol{\xi}} \cdot \underline{\boldsymbol{\mu}}^{-1} \cdot (\underline{\boldsymbol{\zeta}} \cdot \boldsymbol{W}_j) dV \\ A_{ij}^{(5)} &= \omega^2 \int_V \boldsymbol{W}_i \cdot (\underline{\boldsymbol{\varepsilon}} \cdot \boldsymbol{W}_j) dV \end{aligned}$$

$$\begin{aligned} A_{ij}^{(B.I.)} = 2\omega^2 \varepsilon_0 \lambda_i \lambda_j & \int_{S_{ap}} (\hat{\boldsymbol{z}} \times \boldsymbol{W}_i) \cdot \left[\int_{S_{ap}} G_0(\boldsymbol{r}, \boldsymbol{r}') \left[\hat{\boldsymbol{z}} \times \boldsymbol{W}_j \right] dS' \right] dS \\ & - \frac{2}{\mu_0} \lambda_i \lambda_j \int_{S_{ap}} \nabla \cdot (\hat{\boldsymbol{z}} \times \boldsymbol{W}_i) \cdot \left[\int_{S_{ap}} G_0(\boldsymbol{r}, \boldsymbol{r}') \left[\nabla' \cdot (\hat{\boldsymbol{z}} \times \boldsymbol{W}_j) \right] dS' \right] dS \end{aligned} \tag{2}$$

In the previous expressions, V is the volume of the cavity, S_{ap} is the aperture surface, $\lambda_{i,j}$ are coefficients vanishing on metallic traces placed at the aperture plane and having a unitary value elsewhere.

The term $A_{ij}^{(B.I.)}$ in particular is the boundary integral $(B.I.)$ contribution and involves the free space Green's function $G_0(\boldsymbol{r}, \boldsymbol{r}')$. It should be noted that in the evaluation of its surface integrals the derivatives have been transferred from the Green's function to the terms $\boldsymbol{W}_i \times \hat{\boldsymbol{z}}$ and $\boldsymbol{W}'_j \times \hat{\boldsymbol{z}}$, invoking the divergence theorem as proposed in [24, 25]. The vector basis functions $\boldsymbol{W}_i$, are chosen as in [24] for brick elements. In order to compute the overall electromagnetic fields produced by this structure, the resulting linear system is solved, and thus the electromagnetic fields both inside the cavity and on the aperture are found. The evaluation of the radiated field, then, is a straightforward matter.

It should be noted that the formulation presented here is also effective for dispersive constitutive parameters, which is a typical (and necessary) property of the metamaterials with negative constitutive parameters considered in the next section [13].

3. ANOMALOUS PROPERTIES OF SCATTERING FROM METALLIC CAVITIES WITH METAMATERIAL LOADING: THEORETICAL BACKGROUND AND NUMERICAL RESULTS

In some recent works, it has been shown how pairing isotropic metamaterials with "*conjugate*" electromagnetic response functions might induce an anomalous resonance, which leads to several interesting effects with potential applications in the RF and optical domains. For instance, it has been shown how pairing materials with oppositely-signed constitutive parameters might induce an anomalous transparency in an infinite planar bilayer [19] or it might induce a strong resonance in the scattering from ultra-thin spherical and cylindrical particles [20, 21]. A similar metamaterial juxtaposition may also provide enhancement in the transmission through sub-wavelength holes in a PEC metallic flat screen as shown in [22], where the use of such bilayers as covers has been proposed.

In this work, we are interested to explore whether similar anomalies in the scattering response of these bilayers in metallic cavities of finite size may be found. This may be a first step towards the use of these *interface resonances* in more complicated antenna problems involving cavity-backed patches or reflect-arrays.

The cascade of a DNG planar layer with a DPS layer has been shown to be effective in *canceling* the phase delay induced by the DPS layer [17]. (Here, by "DPS", we mean a conventional, "double-positive" medium in which real parts of permittivity and permeability are positive). This effect may be employed in making compact sub-

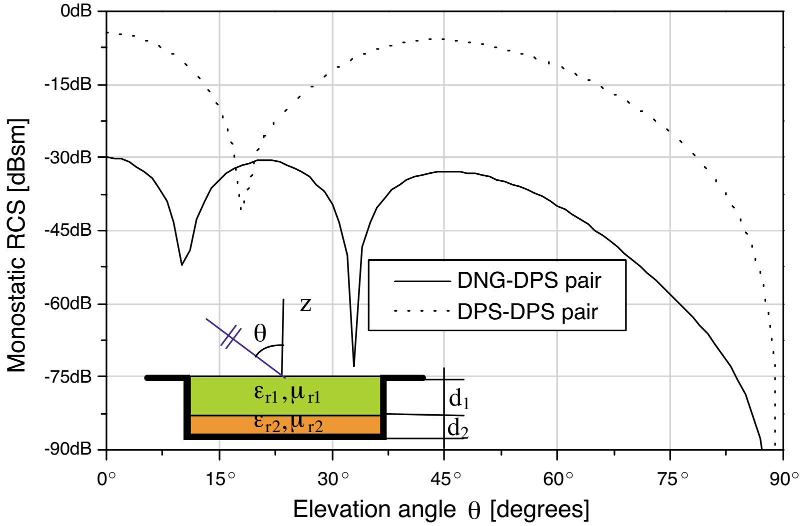

Figure 2. Monostatic RCS $\sigma_{\theta\theta}$ at $f = 5\,\text{GHz}$ for a θ-polarized incident plane wave. The cavity dimensions are: $10\,\text{cm} \times 10\,\text{cm} \times 1.5\,\text{cm}$; while the slab parameters are: $d_1 = 1\,\text{cm}$, $d_2 = 0.5\,\text{cm}$, $\varepsilon_{r1} = \pm 2$, $\mu_{r1} = \pm 1$, $\varepsilon_{r2} = 4$, $\mu_{r2} = 2$.

wavelength parallel-plate waveguides [18] or in drastically reducing the reflection from an infinite planar dielectric layer [19]. In a similar way, we intuitively expect that filling the cavity of Fig. 1 with such a pair, can lead to a sensible reduction of the scattering from the structure, as compared with a cavity of the same size filled with only DPS materials. This intuition is confirmed numerically by the results reported in Fig. 2. A metallic cavity with dimensions $10\,\text{cm} \times 10\,\text{cm} \times 1.5\,\text{cm}$ has been filled with two planar layers as shown in the inset of Fig. 2. The bilayer has been designed to have:

$$|k_{DPS}| d_{DPS} = |k_{DNG}| d_{DNG}, \tag{3}$$

which ensures total transparency when the bilayer is infinitely extended, as found in [19]. In the figure, the monostatic radar cross section (RCS) of the cavity is reported for a θ-polarized incident plane wave impinging on the cavity filled with a DPS-DPS pair and with a DPS-DNG pair. We note how the overall RCS of the DPS-DNG cavity is significantly lower than the one for the DPS-DPS filling. This effect is intuitively explained by the phase compensation caused by the DNG layer cascaded with the DPS one. Therefore, the proper choice of the thicknesses of the two layers, following formula (3), effectively

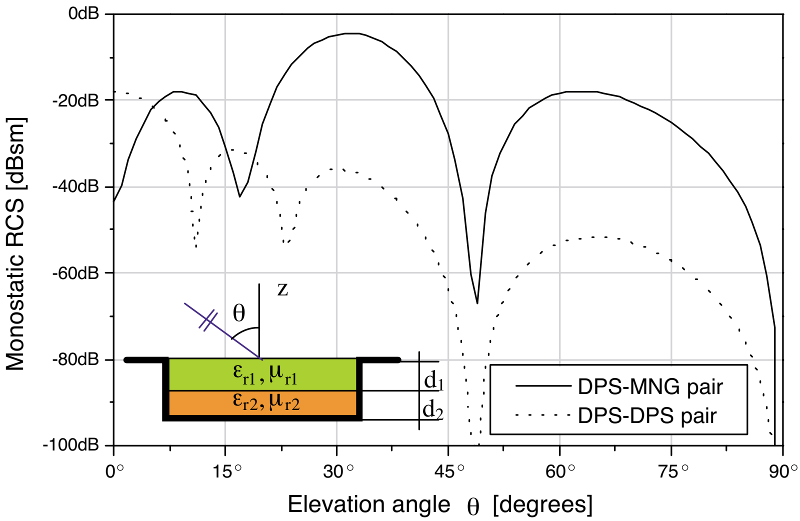

Figure 3. Monostatic RCS $\sigma_{\theta\theta}$ at $f = 10\,\text{GHz}$ for a θ-polarized incident plane wave. The cavity dimensions are: $10\,\text{cm}\times 10\,\text{cm}\times 1.5\,\text{cm}$; while the slab parameters are: $d_1 = 1.02\,\text{cm}$, $d_2 = 1.02\,\text{cm}$, $\varepsilon_{r1} = 9.957$, $\mu_{r1} = 0.037$, $\varepsilon_{r2} = 5.747$, $\mu_{r2} = \pm 0.283$.

reduces the depth of the cavity, resulting in a drastic reduction of its backscattering. We expect that this effect is more pronounced for a cavity with larger transverse dimensions, since formula (3) ensures complete transparency only for a transversely-infinite bilayer. This intuition is confirmed by our numerical results (not reported here for the sake of brevity).

In a recent work [22], the authors have been interested in enhancing the transmission through a subwavelength hole in an opaque flat screen and have suggested an optimized thin metamaterial bilayer that ensures a resonant behavior capable of enhancing the field amplitude on the screen, causing a significant increase in transmission. We have tried to fill the cavity of Fig. 1 with that optimized DPS-MNG bilayer, expecting an increase in the cavity RCS due to a similar resonance effect. Fig. 3 reports the results for this numerical simulation: the cavity has been filled with the optimized bilayer presented in [22], with $\varepsilon_{r1} = 9.957$, $\mu_{r1} = 0.037$, $\varepsilon_{r2} = 5.747$, $\mu_{r2} = -0.283$, for a layer thickness $d_1 = d_2 = 1.02\,\text{cm}$, to work at frequency $f = 10\,\text{GHz}$. We have compared the monostatic RCS of this cavity with the one of a DPS-DPS cavity filled with the same materials, but with a reversed sign in the permeability of the MNG medium. Notice

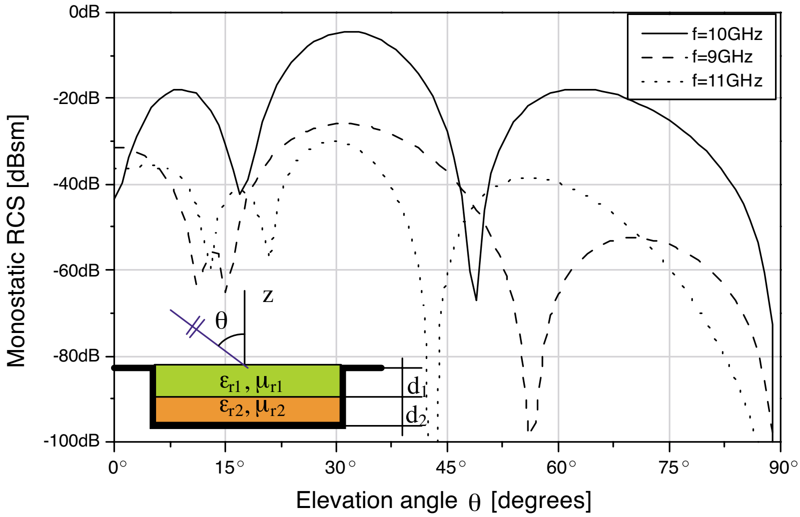

Figure 4. Monostatic RCS $\sigma_{\theta\theta}$ for a θ-polarized incident plane wave at three different frequencies. The cavity dimensions are: $10\,\mathrm{cm} \times 10\,\mathrm{cm} \times 1.5\,\mathrm{cm}$; while the slab parameters are: $d_1 = 1.02\,\mathrm{cm}$, $d_2 = 1.02\,\mathrm{cm}$, $\varepsilon_{r1} = 9.957$, $\mu_{r1} = 0.037$, $\varepsilon_{r2} = 5.747$, $\mu_{r2} = -0.283$. Here the dispersion of the material parameters is not taken into account, i.e., it is assumed that the material parameters stay unchanged for the three frequencies chosen here.

how the overall monostatic RCS is drastically increased in the DPS-MNG case, even if the scattering peaks have been shifted due to the change in the materials filling the cavity.

Fig. 4 shows the variation of the monostatic RCS for the same optimized DPS-MNG load, but with different operating frequencies. Since the bilayer thickness had been optimized to yield its resonance at $f = 10\,\mathrm{GHz}$, we note that a change in the frequency causes reduction of the overall monostatic RCS, bringing it to values comparable with the case of DPS-DPS filling shown in Fig. 3. Here, we did not take into account the dispersion of the material parameters, i.e., it is assumed that the material parameters are unchanged as we choose three frequencies $f = 9\,\mathrm{GHz}$, $10\,\mathrm{GHz}$, $11\,\mathrm{GHz}$.

Here again, we expect this resonant behavior to be more effective for a cavity with larger transverse dimensions, since the bilayer had been designed for the case of an infinite transverse section.

As a final simulation, we use our numerical code to analyze the effects of the possible anisotropics of the filling materials. We

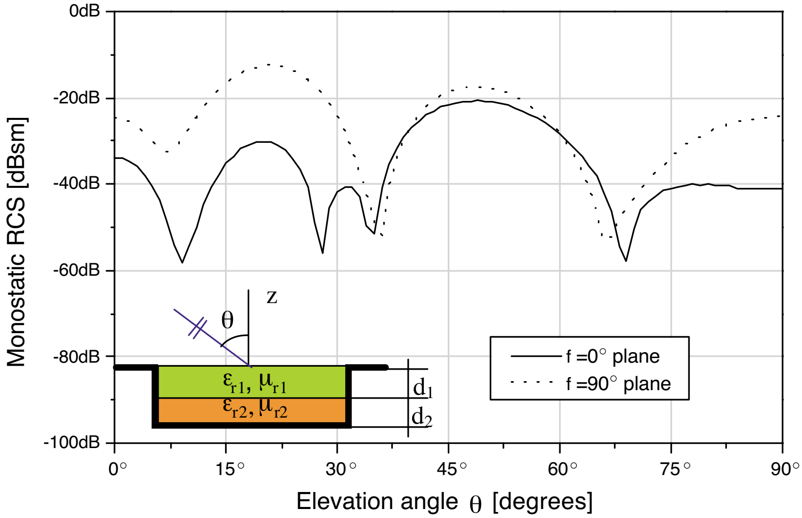

Figure 5. Monostatic RCS $\sigma_{\theta\theta}$ for a φ-polarized incident plane wave at $f = 10\,\text{GHz}$. The cavity dimensions are: $10\,\text{cm} \times 10\,\text{cm} \times 1.5\,\text{cm}$; while the slab parameters are: $d_1 = 1.02\,\text{cm}$, $d_2 = 1.02\,\text{cm}$, $\varepsilon_{r1} = 9.957$, $\mu_{r1} = 0.037$, $\varepsilon_{r2} = 5.747$, $\mu_{r2xx} = \pm 0.283$, $\mu_{r2yy} = -0.283$, $\mu_{r2zz} = 0.283$.

analyze the variation of the RCS for the same DPS material as in Figs. 3 and 4, but now for the second medium we assume a metamaterial whose permeability tensor is anisotropic having positive diagonal terms along the x and z axes, but negative along the y axis. The permittivity of this metamaterial is assumed to be scalar. This can represent metamaterials whose negative parameters are due to resonant inclusions (e.g., split ring resonators) all oriented in the same direction (e.g., all normals to the rings are supposed to be in the y direction). In this case, due to their particular orientation, the inclusions are supposed to affect only the y component of the magnetic field ($\mu_{r2yy} < 0$), while the other two diagonal entries of the permeability tensor (μ_{r2xx} and μ_{r2zz}) are positive. Therefore, when a θ-polarized plane wave impinges on the cavity, the magnetic field is parallel to the aperture plane and, if it is directed along the y-axis, it couples well with the negative parameter of the anisotropic material resulting in a monostatic RCS similar to the one presented in Fig. 4. Actually, the overall monostatic RCS levels are somehow reduced with respect to the isotropic case (Fig. 4), implying the contribution from the cross polarized waves due to the finite size of the cavity. This result is not presented here for sake of brevity. Instead, the more relevant result is presented in Fig. 5. Here the monostatic RCS is calculated in the particular case where a φ-polarized plane wave impinges on the structure.

The electric field is parallel to the aperture and the magnetic field is in the yz plane when the plane of incidence is the $\varphi = 90°$ plane. However, if the plane of incidence is the $\varphi = 0°$ plane, the incident magnetic field will be in the xz plane. In the former case, part of the magnetic field may interact with the negative permeability of the anisotropic material, while in the latter its magnetic field does not couple directly with the negative permeability. These physical considerations may explain why in Fig. 5 the overall monostatic RCS is lower in the $\varphi = 0°$ case than the one for the $\varphi = 90°$ case.

4. CONCLUSION

The numerical analysis of some anomalous properties of scattering from cavities partially filled with metamaterials has been presented in this paper. A hybrid numerical formulation based on the Finite Element Method (FEM) and on the Boundary Integral (BI) has been utilized in order to verify the backscattering behavior in this structure. In particular, it has been found that cavities filled with properly chosen pairs of metamaterial layers with "*resonant*" features exhibit unusual scattering properties, namely, with properly chosen constitutive parameters for these layers the "transparency" effect or significant backscattering RCS from such cavities are resulted. Some physical insights into the findings have also been provided.

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Filiberto Bilotti was born in Rome, Italy, on April 25, 1974. He received the *Laurea* degree (*summa cum laude*) and the Ph.D. degree both in Electronic Engineering from the University of Roma Tre, Rome, Italy, in 1998 and 2002, respectively. Since 2002 he has joined the Department of Applied Electronics of the University of Roma Tre, Rome, Italy as an Assistant Professor in Electromagnetic Field Theory. His interest areas are in microwave and millimeter-wave planar and conformal structures, in complex materials for circuits and for radiation components, in numerical methods for a fast solution of electromagnetic problems, and in artificial engineered surfaces. Dr. F. Bilotti is a member of IEEE.

Andrea Alù was born in Rome, Italy, on September 27, 1978. He received the *Laurea* degree (*summa cum laude*) in Electronic Engineering in 2001 from the University of Roma Tre, Rome, Italy. As the recipient of an AEI (Italian Electrical and Electronic Society) grant, he has been working in 2002 at the University of Pennsylvania, Philadelphia, PA, on the characterization of left handed materials. He is currently working towards his MS degree at the University of Roma Tre, Rome, Italy. His main interest areas are in integrated planar and conformal antennas and in circuit microwave components loaded by complex materials and in metamaterial applications at microwave frequencies.

Nader Engheta is a Professor of Electrical and Systems Engineering at the University of Pennsylvania. He received the B.S.E.E. degree from the University of Tehran in 1978, and the M.S. and the Ph.D. degrees in electrical engineering from Caltech in 1979 and 1982, respectively. After spending one year as a postdoctoral research fellow at Caltech and four years as a Senior Research Scientist at Kaman

Sciences Corporation's Dikewood Division, he joined the faculty of the University of Pennsylvania, where he is currently a Professor. He is also a member of the Mahoney Institute of Neurological Sciences, and a member of the Bioengineering Graduate Group at the University of Pennsylvania. He was the graduate group chair of electrical engineering from July 1993 to June 1997. He is a Guggenheim Fellow, a recipient of the IEEE Third Millennium Medal, a Fellow of IEEE, a Fellow of the Optical Society of America, and was an IEEE Antennas and Propagation Society Distinguished Lecturer in 1997–1999. He is an Associate Editor of *IEEE Antennas and Wireless Propagation Letters*. In addition, he has been the recipient of the UPS Foundation Distinguished Educator Term Chair in 1999–2000, the Fulbright Naples Chair award in 1998, a NSF Presidential Young Investigator (PYI) award in 1989, the S. Reid Warren, Jr. Award for distinguished teaching (two times) from UPenn's School of Engineering and Applied Science, the Christian F. and Mary R. Lindback Foundation Award in 1994, and the W. M. Keck Foundation's 1995 Engineering Teaching Excellence Award.

Lucio Vegni was born in Castiglion Fiorentino, Italy on June 20, 1943 and he received the degree in Electronic Engineering from the University of Rome, Rome, Italy. After a period of work at the Standard Elektrik Lorenz in Stuttgart (Germany) as an antenna designer, he joined the Istituto di Elettronica of the University of Rome, Italy, and then the University of Rome Tre where he is a Full Professor of Electromagnetic Field Theory. His research interests are on microwave and millimeter-wave circuits and antennas. Prof. L. Vegni is a member of IEEE and of the Italian Electrical and Electronic Society (AEI).