



Luo, Y., Qin, F. X., Scarpa, F., Carbonell, J., Ipatov, M., Zhukova, V., ... Peng, H. X. (2017). Left-handed metacomposites containing carbon fibers and ferromagnetic microwires. *AIP Advances*, 7(5), [056110]. DOI: 10.1063/1.4978404

Publisher's PDF, also known as Version of record

License (if available):
CC BY

Link to published version (if available):
[10.1063/1.4978404](https://doi.org/10.1063/1.4978404)

[Link to publication record in Explore Bristol Research](#)
PDF-document

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/pure/about/ebr-terms.html>

Left-handed metacomposites containing carbon fibers and ferromagnetic microwires

Y. Luo, F. X. Qin, F. Scarpa, J. Carbonell, M. Ipatov, V. Zhukova, A. Zhukov, J. Gonzalez, L. V. Panina, and H. X. Peng

Citation: *AIP Advances* **7**, 056110 (2017); doi: 10.1063/1.4978404

View online: <http://dx.doi.org/10.1063/1.4978404>

View Table of Contents: <http://aip.scitation.org/toc/adv/7/5>

Published by the [American Institute of Physics](#)

HAVE YOU HEARD?

Employers hiring scientists and
engineers trust

PHYSICS TODAY | JOBS

www.physicstoday.org/jobs



Left-handed metacomposites containing carbon fibers and ferromagnetic microwires

Y. Luo,¹ F. X. Qin,^{2,a} F. Scarpa,¹ J. Carbonell,³ M. Ipatov,⁴ V. Zhukova,⁴ A. Zhukov,⁴ J. Gonzalez,⁴ L. V. Panina,⁵ and H. X. Peng^{2,b}

¹*Advanced Composite Centre for Innovation and Science, Department of Aerospace Engineering, University of Bristol, University Walk, Bristol BS8 1TR, United Kingdom*

²*Institute for Composites Science and Innovation (InCSI), School of Materials Science and Engineering, Zhejiang University, Hangzhou 310027, China*

³*Wave Phenomena Group, Universitat Politècnica de Valencia, Camino de Vera s/n, 46022 Valencia, Spain*

⁴*Dpto. de Física de Materiales, Fac. Químicas, Universidad del País Vasco, San Sebastian 20009, Spain*

⁵*School of Novel Materials and Nanotechnology, National University of Science and Technology MISiS, Moscow 119049, Russia*

(Presented 4 January 2016; received 22 September 2016; accepted 6 December 2016; published online 8 March 2017)

We investigate the microwave behavior of polymer-based metacomposites containing ferromagnetic microwires and carbon fibers. A notable transmission window is observed from the metacomposite containing 3mm spaced parallel microwire array in 1-7 GHz, verifying a left-handed behavior. In the hybrid metacomposites containing both parallel wires and carbon fibers, such transmission window is preserved with a much higher transmittance due to the improved impedance match and hence decreased reflection loss. The introducing of continuous carbon fibers leads to a remarkable anisotropic behavior: left-handed properties are turned on/off by rotating the electric excitation by 90 degrees. The proposed metacomposites are promising for microwave cloaking and sensing applications for aerospace-graded structural components. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). [<http://dx.doi.org/10.1063/1.4978404>]

I. INTRODUCTION

The beauty of left-handed metamaterials is their peculiar electromagnetic properties that are not available from natural materials. Today metamaterials with double negative (DNG) properties have enabled a range of scientific concepts and engineering applications such as invisibility cloaking,¹ perfect metamaterial absorber,² perfect lenses,³ mechanical metamaterials.⁴ However, conventional design of metamaterials involves the structure-dependent characteristics of the building blocks yet with less focus on their intrinsic materials' properties. Also one cannot ignore the complex geometries in the modern metamaterials in order to host DNG features that lead to the increasing use of nanomaterials synthesis technologies with added capital costs involved.⁵

We recently have proposed and developed a metacomposite with DNG features which is made from Fe-rich ferromagnetic microwires and glass fiber reinforced polymer-based composites.^{6,7} This design has a simpler geometry of building blocks and related DNG properties are revealed in a real piece of engineering material rather a merely functionalized structure. Most recently, as an effort to ameliorate left-handed properties, Co-rich microwires are hybridized into the Fe-rich wires-enabled metacomposites and key findings of tunable, dual-band and band-stop DNG features have been reported in the microwave regime.⁸

^aCorrespondence should be addressed to: faxiangqin@zju.edu.cn (Faxiang Qin)

^bhxpengwork@zju.edu.cn (Hua-Xin Peng)

So far the left-handed DNG features have been reported and well expounded in the microwires-contained glass-fiber reinforced polymer (GFRP) composites.⁶⁻⁸ From the engineering standpoint, the carbon fiber reinforced polymer (CFRP) composites are extensively employed in automobile and aerospace industries due to the light weight, high structural strength and excellent corrosion resistivity of carbon fibers (CFs).⁹ It is therefore very necessary to blend CFs into our microwire-metacomposite system and to explore the possibility of DNG features. The electrically conductive nature of CFs will help improve the impedance match of the microwires-enabled metacomposites by decreasing the reflection loss. Therefore, exploring the topological arrangement of CFs and wires would be very intriguing.

II. EXPERIMENTAL PROCESS

Amorphous glass-covered $\text{Fe}_{77}\text{Si}_{10}\text{B}_{10}\text{C}_3$ microwires (TAMAG, Spain) manufactured by the modified Taylor-Ulitovskiy technique¹⁰ and CFs-contained prepregs (HexPly, IM8552) were embedded into 913 E-glass prepregs (GFRC) with the in-plane size of $500 \times 500 \text{ mm}^2$.¹¹ Microwires have average diameter of $20 \mu\text{m}$ coated with a thin glass layer of $1.7 \mu\text{m}$. Carbon fibers were manufactured with good industry-standard quality with average diameter of approximately $8 \mu\text{m}$. Three geometries were designed for the manufacture of composites: (i) metacomposite containing 3 mm-spaced parallel Fe-rich microwires; (ii) metacomposite containing short-cut CF-prepreg patches and 3 mm-spaced Fe-rich microwires; (iii) metacomposite containing a full-sized CF prepreg ($500 \times 500 \text{ mm}^2$) as the insertion to the 3 mm spaced parallel metacomposite according to a theoretical study.¹² CFs were arranged in perpendicular to the direction of microwires to minimize the reflection loss. The microwave characterization was conducted by the free-space measurement in the 0.7-17 GHz range with the electric component (E_k) placed along the glass fibres.^{13,14} An external dc magnetic (H_{ex}) bias up to 3000 A/m was applied to track the field-tunable response of metacomposites.

III. RESULTS AND DISCUSSIONS

A. Parallel metacomposites containing Fe-rich microwires

The transmission spectra of parallel wire composites under external fields up to 3k A/m are presented in Fig. 1. Notably, a transmission window is identified in the absence of H_{ex} (Fig. 1), together with dips in reflection and absorption spectra corresponding to the frequency band of 1 to 7 GHz (not shown here). The full width at half maximum (FWHM) of the ‘window’ of transmission coefficient, S_{21} , is identified as 4.1 GHz at zero magnetic bias. This indicates that the observed

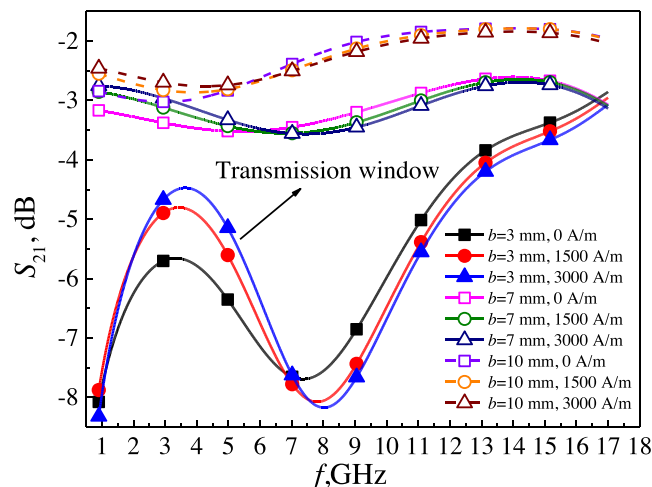


FIG. 1. Frequency dependence of transmission coefficients (S_{21}) of parallel metacomposites containing $\text{Fe}_{77}\text{Si}_{10}\text{B}_{10}\text{C}_3$ microwires with the wire periodicity, respectively, $b=3, 7$ and 10 mm .

transmission windows reveal an abnormal S -parameters dispersion and the ferromagnetic microwires behave as transmitting components in this wire-composite medium. However, it should be emphasized that the abnormal transmission enhancement can be induced in either double positive (DPS) or DNG medium, suggesting permittivity and permeability would have either simultaneous positive or negative values.

To further explore the electromagnetic nature of the proposed parallel metacomposites, an easiest way is to present direct evidence of the effective electric permittivity ϵ and magnetic permeability μ of the wire-composites. However, the measurement of the magnetic permeability is problematic when using the conventional Nicolson-Ross-Weir extraction from the S -parameters obtained in a free-space measurement, which is normally adopted for traditional lossy split ring resonator (SRRs)-based metamaterials.¹⁵ Our microwire composite, nevertheless, possesses limited magnetic response and permeability which make difficult to extract useful experimental values. Alternatively, another physical term could help verify the double negative features, i.e., the phase velocity, which is a prerequisite to obtain double negative metamaterials.¹⁶⁻¹⁹ In a normal wave-matter interaction, according to classic solid state physics, waves are considered to propagate in a double positive

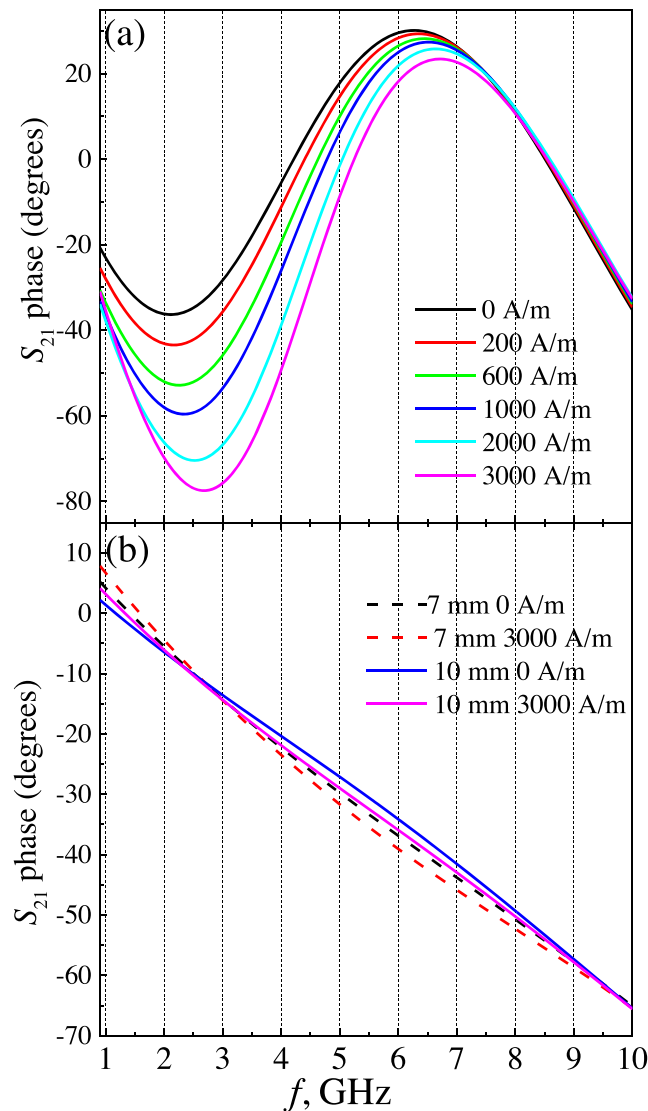


FIG. 2. Frequency dependences of transmission (S_{21}) phase of (a) 3mm parallel metacomposite and (b) wire-composites containing parallel wires spaced by 7 and 10 mm under external fields up to 3000 A/m.

medium (ε and μ are both positive) and their propagation phase velocity is regarded as positive values, i.e., waves are moving forward. However, when ε and μ are both negative, phase velocity is expected to enter into negative zone, rendering a ‘backward’ propagation of waves. Herein, Fig. 2 presents the transmission phase results of 3 mm spaced parallel microwire-composite in 1-10 GHz. Evidently, the transmission phase velocity (slopes of phase curves) of our 3 mm parallel wire-composite shows negative values in the 2-6.5 GHz. This characteristic indeed substantiates the double negative indices. The presence of DNG feature in the microwire-composite system can be explained by the plasmonic behavior of the parallel wire medium and ferromagnetic resonance of microwires which induce a negative ε and a negative μ , respectively.^{6,7} Note that in the S_{21} spectra, transmission window is located in 1-7 GHz. The small deviation in terms of abnormal bandwidth between the transmission coefficients and their phase results may be induced by the measurement errors.

B. Microwires metamaterials containing short-cut carbon fibers

Figure 3(a) gives the transmission results of wires/CFs hybridized metamaterials. Clearly, transmission windows are preserved after the addition of CFs with a bandwidth of 1-6 GHz which coincides with the result of 3 mm parallel metamaterial. This confirms that the DNG characteristic is obtained in the carbon fibers contained wire-metamaterial due to the magnetic response of microwires and their periodical alignment. Of particular note is that the transmittance level is enhanced after the insertion of carbon fibers, e.g., the highest transmittance increases from -5.6 dB (52.5%) to -1.6 dB (83.2%) at zero field (*cf.* Figs. 1 and 3(a)). As is well documented, the transverse conductivity amongst CFs in the unidirectional CFPR composites is rather poor due to the electrically unconnected fibres.²⁰ Note that the E_k is placed perpendicularly to the carbon fibers (E_k is along the glass fibers and microwires). As a consequence, the permittivity magnitude of wire-composites should be decreased

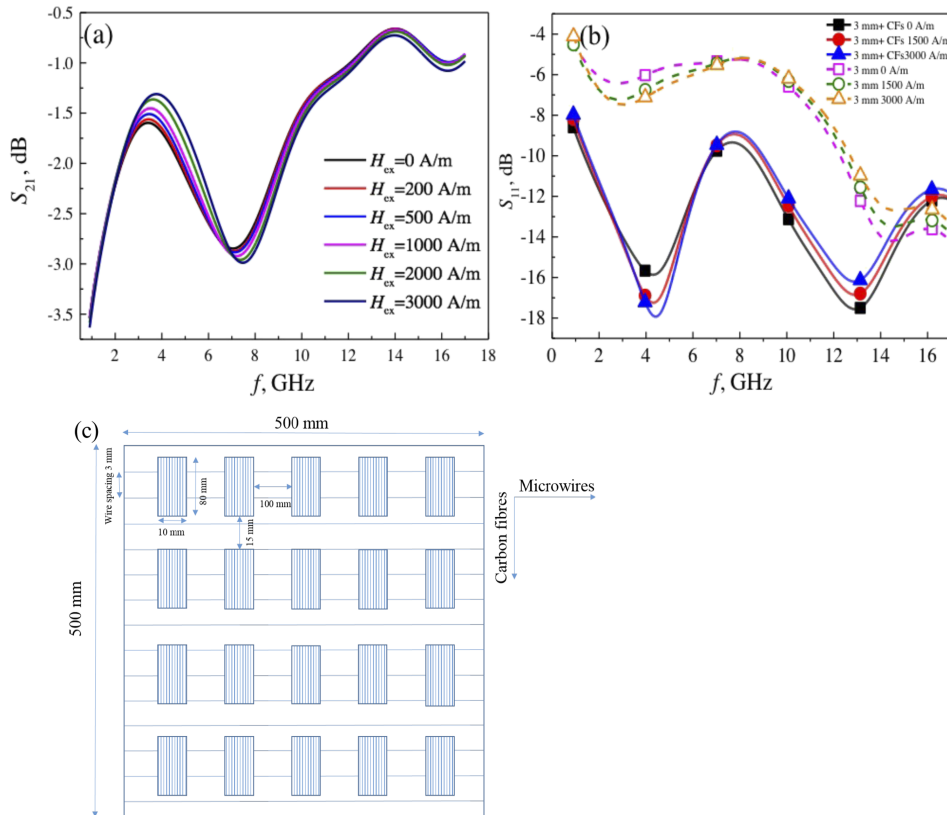


FIG. 3. Frequency dependences of (a) transmission coefficients S_{21} and (b) reflection coefficients (S_{11}) of the metamaterial containing short-cut carbon fibers and microwires in 0.7-17 GHz. (c) gives the geometry of such carbon fiber/wire composite.

with the insertion of CFs and hence the impedance is increased as per Eq. 1. In this sense, the transmittance of metamaterial containing CFs is increased accordingly.

$$Z = (\mu/\epsilon)^{1/2} \quad (1)$$

Moreover, the metamaterial containing CFs indicates much lower reflection coefficients in the frequency range where transmission windows are realized as opposed to the 3 mm Fe-rich parallel metamaterial (Fig. 3(b)). Now, one can conclude that the low transverse conductivity of the CFs patches (in the direction perpendicular to CFs) is helpful in reducing the reflective signals in their wire-composite. This further assures a meaningful interaction among transmitted waves and the microwire composite which benefits their DNG response.

C. Microwires metamaterials containing continuous carbon fibers

From above analysis, placing CFs perpendicularly to microwires is found to be beneficial of increasing transmission level of composites. This encourages us to investigate whether replacing the CF patches with continuous CFs is physically feasible in terms of obtaining DNG features.

Figures 4(a) and (c) present the transmission and its phase coefficients of the proposed continuous CFs contained metamaterials when the electric excitation is along the microwires. A series of transmission windows are obtained under different magnetic fields (Fig. 4(a)) in addition to the observation of negative phase velocity and permittivity (insets of Figs. 4(a) and 4(c)). This verifies the DNG property of the proposed composite. The transmittance level, however, is decreased compared

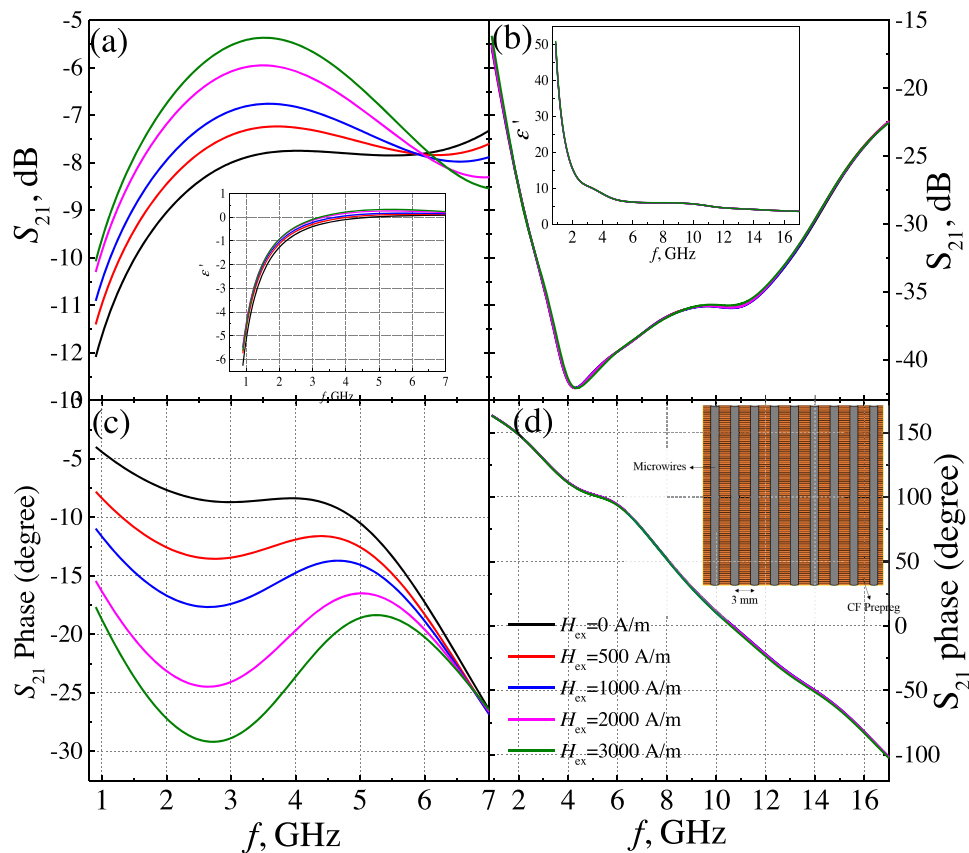


FIG. 4. Frequency dependences of transmission spectra of continuous carbon fibers contained hybrid metamaterials with E_k placed (a) along and (b) perpendicularly to microwires. Frequency plots of transmission phase of the same composite in (a)/(b) with E_k (c) along and (d) perpendicular to microwires. The insets in (a) and (b) are the frequency dependences of their ϵ' when E_k is along and perpendicular to microwires, respectively. The inset in (d) provides the geometry of continuous carbon fiber contained metamaterial.

with the 3mm Fe-rich parallel metacomposite, e.g., from -5.6 (52.5%) to -7.8 dB (40.7%) (See in Fig. 1) at zero field due to the integration of massive amount of conductive carbon fibers.

Notably, with the increase of external fields, the observed windows are received with linearly enhanced amplitudes, i.e., the waves can be quantitatively controlled to pass the microwire metacomposite by an application of magnetic bias (Fig. 4(a)). The maximum amplitude variation under different fields reaches 2.4 dB at 3.5 GHz which equals to 78.5 % of the total incident microwave signals. From scientific standpoint, embedding microwires into the CF reinforced composites still preserves the DNG properties, providing microwires are overlapped with CFs in an orthogonal manner.

On the other hand, neither evident field-tunable nor DNG features is indicated when organizing E_k along the CFs (Figs. 4(b) and (d)). First of all, the transmittance of the composites is rather low, e.g., the lowest transmission is obtained as -41.9 dB (0.8 %) as is seen in Fig. 4(b). The transmission phase and permittivity results also suggest a nature of double positive medium of the composite (inset of Fig. 4(a) and Fig. 4(d)). This anisotropic effect of the metacomposites containing continuous CFs induced by the direction change of electrical excitation field is reminiscent of the orthogonal microwire metacomposites.⁷ However, the reason of the disappearance of DNG properties of the former is the absence of microwires along the electrical excitation direction.

IV. CONCLUSIONS

The left-handed microwave properties of metacomposites containing ferromagnetic microwires and carbon fibers have been systematically investigated. Double negative results are identified in 1-7 GHz in the composite containing a parallel array of Fe-rich microwires verified by the negative transmission phase velocity. With the incorporation of short-cut CFs, the transmission windows are preserved together with a much lower reflectance as compared to the 3 mm parallel metacomposite thanks to their increased dielectric impedance. The introduction of continuous CFs in the composite induces an anisotropic effect in terms of their DNG properties: arranging E_k along the microwires leads to the tunable DNG properties of the composite in sharp contrast to the observation of a significantly decreased transmittance together with the suppression of the left-handed/field-tunable characteristic by placing E_k perpendicularly to microwires. All these results open up potentials in the invisibility cloaking of the next-generation aircrafts and airborne vehicles.⁶⁻⁸

ACKNOWLEDGMENTS

Yang Luo would like to acknowledge the financial support from University of Bristol Postgraduate Scholarship and China Scholarship Council. FXQ would like to thank the support from Natural Science Foundation of China (NSFC) under Grant no. 51501162.

- ¹ J. B. Pendry, D. Schurig, and D. R. Smith, *Science* **312**, 1780 (2006).
- ² N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, *Phys. Rev. Lett.* **100**, 207402 (2008).
- ³ J. B. Pendry, *Phys. Rev. Lett.* **85**, 3966 (2000).
- ⁴ Z. G. Nicolaou and A. E. Motter, *Nat. Mater.* **11**, 608 (2012).
- ⁵ V. M. Shalaev, "Optical negative-index metamaterials," *Nat. Photon.* **1**, 41 (2007).
- ⁶ Y. Luo, H. X. Peng, F. X. Qin, M. Ipatov, V. Zhukova, A. Zhukov, and J. Gonzalez, *Appl. Phys. Lett.* **103**, 251902 (2013).
- ⁷ Y. Luo, H. X. Peng, F. X. Qin, M. Ipatov, V. Zhukova, A. Zhukov, and J. Gonzalez, *J. Appl. Phys.* **115**, 173909 (2014).
- ⁸ Y. Luo, F. X. Qin, F. Scarpa, J. Carbonell, M. Ipatov, V. Zhukova, A. Zhukov, J. Gonzalez, L. V. Panina, and H. X. Peng, *J. Magn. Magn. Mater.* **416**, 299 (2016).
- ⁹ S. Chand, *J. Mater. Sci.* **35**, 1303 (2000).
- ¹⁰ V. S. Larin, A. V. Torcunov, A. Zhukov, J. Gonzalez, M. Vazquez, and L. Panina, *J. Magn. Magn. Mater.* **249**, 39 (2002).
- ¹¹ F. X. Qin and H. X. Peng, *Prog. Mater. Sci.* **58**, 183 (2013).
- ¹² L. Liu, L. Kong, G. Lin, S. Matitsine, and C. Deng, *IEEE Trans Magn.* **44**, 3119 (2008).
- ¹³ D. Makhnovskiy, A. Zhukov, V. Zhukova, and J. Gonzalez, *Adv. Sci. Technol.* **54**, 201 (2008).
- ¹⁴ D. P. Makhnovskiy, L. V. Panina, C. Garcia, A. P. Zhukov, and J. Gonzalez, *Phys. Rev. B* **74**, 064205 (2006).
- ¹⁵ D. Smith, S. Schultz, P. Markoš, and C. Soukoulis, *Phys. Rev. B* **65**, 195104 (2002).
- ¹⁶ H. García-Miquel, J. Carbonell, V. Boria, and J. Sánchez-Dehesa, *Appl. Phys. Lett.* **94**, 054103 (2009).
- ¹⁷ H. García-Miquel, J. Carbonell, and J. Sánchez-Dehesa, *Appl. Phys. Lett.* **97**, 094102 (2010).
- ¹⁸ G. Dolling, C. Enkrich, M. Wegener, C. M. Soukoulis, and S. Linden, *Science* **312**, 892 (2006).
- ¹⁹ A. Grbic and G. V. Eleftheriades, *J. Appl. Phys.* **92**, 5930 (2002).
- ²⁰ N. Athanopoulos and V. Kostopoulos, *Compos. B.* **42**, 1578 (2011).