HYBRID METACOMPOSITES WITH DOUBLE-NEGATIVE EFFECTS

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ABSTRACT

Metamaterials with fascinating double negative electromagnetic properties have attracted tremendous research interest in recent years. However, they are generally artificially structures rather than a true piece of material. The work proposes the concept of metacomposites that contain periodically arranged ferromagnetic microwires. Double negative properties and associated transmission features are realised in the Fe-based wires contained composites evidenced by phase velocity change. Further optimisation by donating Co-based wire arrays and carbon fibres manages to broaden such metamaterial frequency range by inducing additional magnetic resonance and reducing the reflection loss. The present work indicates promising application perspective of the microwires-enabled metacomposites such as microwave cloaking and sensors.

1 INTRODUCTION

Left-handed metamaterials possess fascinating double negative (DNG) electromagnetic (EM) properties that are unavailable from any kind of natural materials therefore attracting international research interest in recent years [1,2] Since the first lab work was reported in 2001 [3], tremendous efforts have been endeavoured to the field of metamaterials and demonstrate that such DNG properties are attainable in microwave, near-infrared, optical frequency range [4,5]. Most recently, a new class of mechanical metamaterials has been introduced into the existing metamaterial family featured with negative density, compressibility, modulus, etc [6,7]. In general, metamaterials are featured with an ordered structure by periodically arranging building blocks which are capable of generating unusual excitation when interacting with incident EM waves. Nevertheless, the conventional design of left-handed metamaterials involves the use of the overall dielectric and magnetic response of materials' meso-structures with less focus on the intrinsic properties of the metamaterials' building blocks. This renders the metamaterial practically a 'structure' rather than a real piece of material. Moreover, the increasing complexity of the topologies and designs associated to modern metamaterials leads to the increasing use of nano-materials synthesis technologies, with added higher capital costs involved [8].

Ferromagnetic microwires are considered as feasible building blocks to construct metamaterials due to their remarkable giant magnetoimpedance (GMI) effect and associated soft magnetic properties [9]. Carbonell et al have acquired double negative properties in microwave regime via arrange an array of Co-based microwires [10]. Liu proposed a microwires-enabled structure with orthogonal geometry and theoretically predicted that metamaterial characteristics are attainable [11]. However, these findings are still obtained in the metamaterial structures. We believe that incorporating microwires into a polymer-based composite context and realizing a metacomposite would be a great step forward: (i) a real piece of composite material with metamaterial properties are now realized; (ii) ultimate properties of metacomposites are not only dependent on the internal geometry but also on the intrinsic materials' properties of building blocks; (iii) metacomposites are easily manufactured via an industrial autoclave curing technique; (iv) tunable metamaterial properties can be obtained via hybridizing different microwire kinds and exerting external stimuli, e.g., magnetic bias, stress, etc.

In this work, we design and manufacture Nevertheless, actuating and tuning metamaterials is still a critical task in that conventional metamaterials are practically combined structures yet not a piece of 'true' material. We have proposed the concept of metacomposites by donating Fe-based ferromagnetic microwire arrays into glass fiber reinforced polymer composites (GFPC) and amenable double-negative metamaterial features have been proved [12,13].This work takes a bold move to hybridise different kinds of microwires and carbon fibers (CFs) into the wire-metacomposite system and explore their microwave metamaterial properties under an external dc magnetic bias. A dual-band double negative feature is obtained with the Co-based wires hybridised into the metacomposite containing parallel Fe-based wires. Such metamaterial behaviour can be magnetically tuned by introducing and arranging CFs properly in the Fe-based wire-composites.

2 EXPERIMENTAL

$Fe_{77}Si_{10}B_{10}C_3$(Fe-based) and $Fe_4Co_{68.7}Ni_1B_{13}Si_{11}Mo_{2.3}$ (Co-based) microwires(TAMAG, Spain) were selected as periodical building blocks to design and fabricate metacomposites. Three kinds of microwire-metacomposites are fabricated: a GFPC containing a parallel array of Fe-based wires (10 mm spacing), a GFPC containing hybrid parallel array of Co-based (10mm spaced) and Fe-based wires (10 mm spaced) and a GFPC containing carbon fibres reinforced polymer composite (CFPC) and a parallel array of Fe-based wires (10 mm spaced). Herein Co-based and Fe-based wires were intentionally mismatched by 1mm to avoid overlapping and further electromagnetic shielding. Experimentally, microwires were embedded into the aerospace-graded polymer-based composite prepregs (E-glass 913 for GFPC and IM8557 for CFPC) in a designed manner (Fig. 1), followed by a standard autoclave curing cycle to yield a resultant wire-metacomposite specimen with the dimensions of 500x500x1 mm^3. The technical parameters of curing process are detailed elsewhere [12]. The microwave characterisation was carried out by a free-space technique in the frequency range of 0.9 to 17 GHz with/without a dc magnetic bias up to 3000 A/m. To maximise the EM response, this bias and the electrical component of incident waves were arranged along the fibre reinforcement direction in the composites. *S*-parameters were measured and extracted to calculate the effective permittivity in the complex numbers of $\varepsilon=\varepsilon'-j\varepsilon''$ via a built-in programme, Reflection/Transmission Epsilon Fast Model [14].

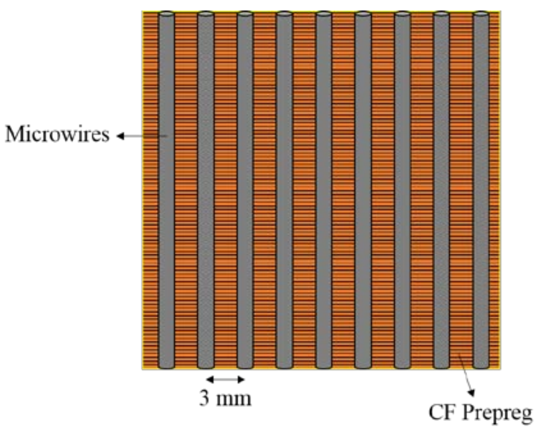

Figure 1Schematic illustration of continuous microwire-CF prepreg.

3 RESULTS AND DISCUSSION

3.1 Metacomposites containing Fe-based wires

In the composite containing parallel Fe-based wires, a transmission window is induced in the 1-7 GHz with wire spacing decreased to 3 mm (Fig. 2), suggesting double negative index (DNG) features [12]. This is also evidenced in the permittivity spectra of wire-composites where negative ε is identified in the same frequency regime [12]. The behind reasons are associated with soft magnetic nature of wires and their geometrical arrangement. Specifically, the ferromagnetic resonance (FMR) of the Fe-based occurs at 2.3 GHz, above which a negative magnetic μ is obtained, and the plasmonic behaviour of the parallel wires leads to a negative dielectric ε below plasma frequency of 16GHz. Further analysis of transmission phase velocity gives a reverse of its sign in such transmission window frequency bandwidth which is a typical evidence for DNG features. Increasing the wire spacing deactivates such double-negative behaviour due to the disappearance of negative permittivity as per Pendry's work [15]. However, such composite is filled with relatively higher wire amount, therefore generating large reflection loss hence low transmission magnitude.

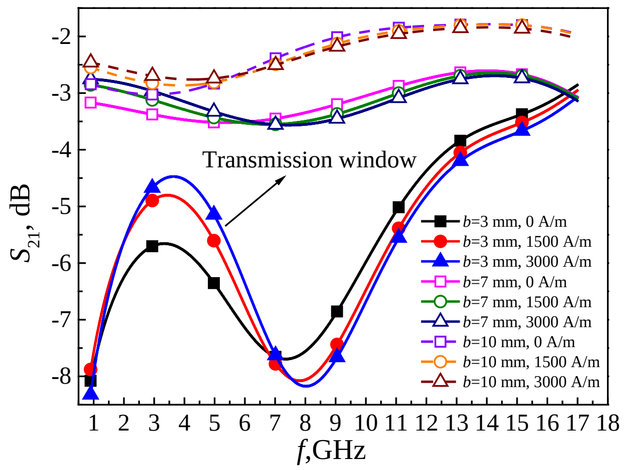

Figure 2 Frequency dependence of transmission coefficients (S_{21}) of parallel metacomposites containing $Fe_{77}Si_{10}B_{10}C_3$ microwires with the wire spacing, respectively, b=3, 7 and 10 mm.

3.2 Metacomposites containing Fe- and Co-based wires

Co-based ferromagnetic microwires are featured with a distinct giant magnetoimpedance (GMI) effect as opposed to Fe-based wires, due to their negative but vanishing magnetostriction [9], this makes their EM performance be easily modulated by external magnetic fields or mechanical stress [16]. Therefore, it is plausible to incorporate the Co-based microwire arrays into the Fe-based wire/polymer metacomposite system with the aim to obtain external stimuli-controlled DNG behaviour. Meanwhile, it is worth investigating the underlying physics behind such hybrid microwire composites when they interact with incident microwaves. In the composite containing 10 mm spaced Co/Fe-based hybrid wire arrays, a remarkable dual-band metamaterial feature is observed as verified by the transmission increase in respective 1.5-5.5 GHz (not shown here for brevity) and 7-17 GHz (Fig. 3). The low-frequency DNG band arises from the FMR of Fe-based wires whilst the high frequency band is due to the long range dipole resonance among the Fe-/Co-based wire pairs.9 It has been reported that in the Fe-based parallel metacomposite that a decrease of the wire spacing to 3 mm would induce strong dynamic wire-wire interactions and give rise to long range dipolar resonance. Note that the spacing between the layers of Fe-based wires and Co-based wires is intentionally mismatched by 1 mm in the present hybrid metacomposite. Hence, such a small inter-wire spacing can generate a similar effect and produce noticeable absorption by this magnetic interaction. At this point, it is inferred that the presence of negative permeability dispersion above the featured frequency of inter-wire magnetic resonance. Overall, the increased transmission achieved by wire misalignment/offset and the dynamic excitation from the propagating EM waves broadens the metacomposite operating frequencies in success.

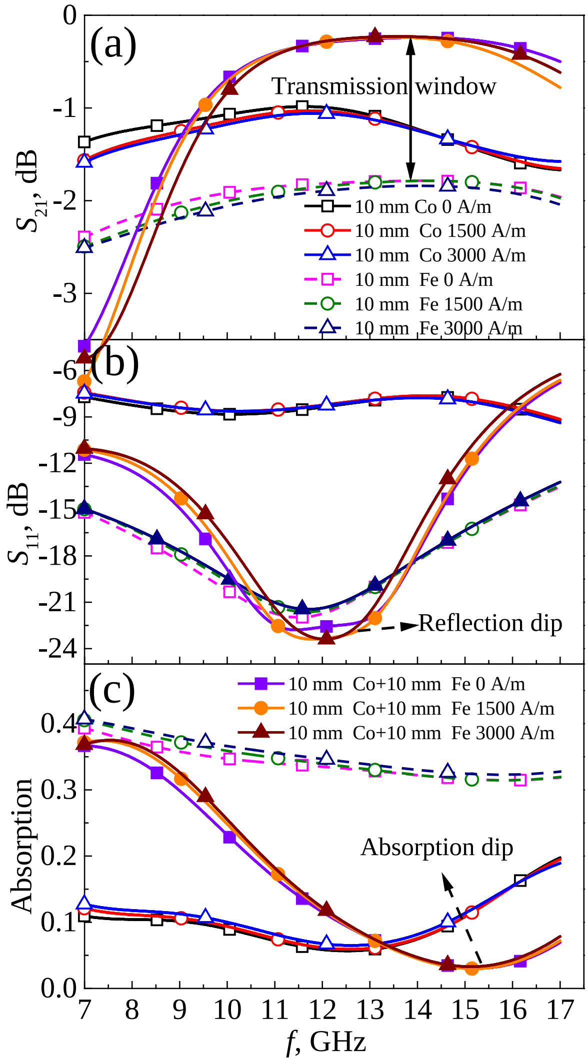

Figure 3 Frequency dependences of (a) transmission, (b) reflection and (c) absorption spectra of the Co-/Fe-based wire- composites in 7-17 GHz.

3.3 Metacomposites containing carbon fibres and Fe-based wires

Carbon fibres (CFs) are widely used in aerospace industry due to their light weight and exceptional mechanical performance. It will be interesting to integrate CFs into the existing wire-metacomposites and explore possible DNG features. A field tunable transmission window of the CFPC contained composite is shown in Fig. 3in addition to a linear increase of its magnitude. Note that 10 mm spacing is too wide to realise DNG features due to the significantly dwarfed plasma frequency (see Fig. 1). This explains why at low fields the DNG feature is not available. However, at higher fields, some dielectric coupling is generated between the carbon fibres in the matrix context and microwires. The impedance match would also be improved due to the introduction of a dielectric medium of CFPC. On the other hand, neither evident field-tunable nor DNG features is indicated with a great deal of EM losses when organising electric excitation (***E***) of waves along the CFs (Fig. 4(b) and (d)) because of the electrical conductive nature of CFs.

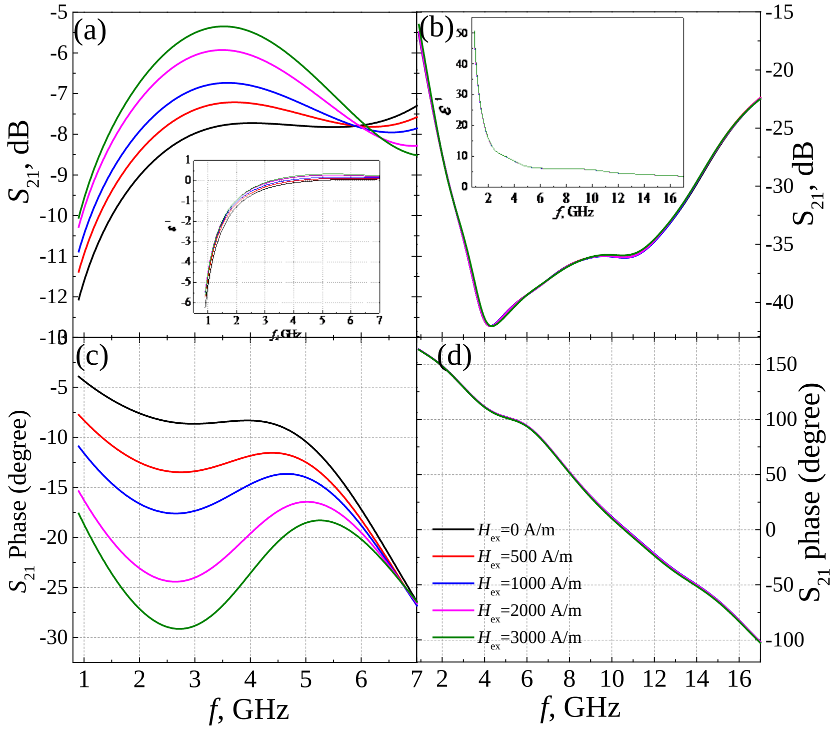

Figure 4 Frequency dependences of transmission spectra of continuous carbon fibres contained hybrid metacomposites with ***E*** placed (a) along and (b) perpendicularly to microwires. Frequency plots of transmission phase of the same composite in (a)/(b) with ***E*** (c) along and (d) perpendicular to microwires.

4 CONCLUSIONS

We design and manufacture polymer-based composites enabled by periodical arrangement of different wire array combinations, i.e., Fe-based wires, Fe- plus Co-based wires, Fe-based wires plus carbon fibres. A typical double negative feature is obtained in 1-7 GHz in the Fe-based wires enabled wires evidenced by transmission windows. Such characteristic is further optimised with a wider working frequency range by incorporating Co-based wires. An on/off mode when rotating the electric excitation direction by 90 degrees is revealed from the S-parameter spectra of carbon fibres contained composites due to the electrical anisotropy of continuous carbon fibres. The displayed results demonstrate strong engineering potential of implementing such hybrid metacomposites for microwave cloaking and radio frequency identification applications.

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