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2-D Isotropic Effective Negative Refractive Index Metamaterial in Planar Technology

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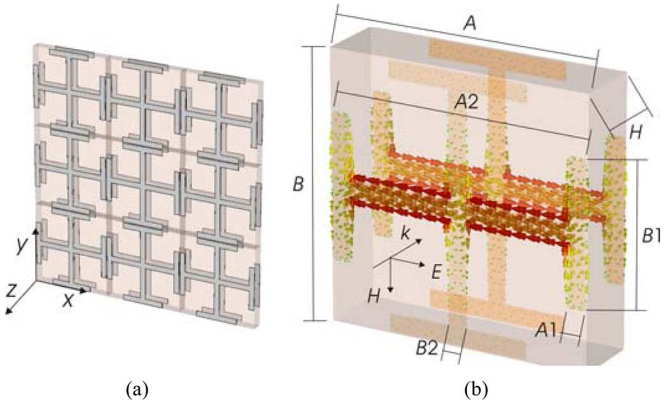
***Abstract*—We present a fully printable effective negative refractive index (NRI) metamaterial responsive to arbitrarily linearly polarized incident waves. The proposed metamaterial is composed of a periodic array of *tightly coupled Jerusalem cross conductor pairs* printed on the opposite sides of a dielectric substrate. Each pair supports both symmetric and antisymmetric resonance modes, whose superposition can lead to an effective NRI of the composite medium. A thorough characterization of the transmission properties of such metamaterial is performed, and conclusive evidences of the medium exhibiting effective NRI properties and impedance matching to free space are presented for a range of the structure parameters.**

***Index Terms*—Left-handed media, negative permeability, negative permittivity, negative refractive index (NRI), polarization independence.**



(a) (b)

Fig. 1. (a) Layer of the 2–D isotropic metamaterial formed by a periodic array of tightly coupled JCPs, which can exhibit an antisymmetric (magnetic) resonance for arbitrary linearly polarized incident wave. (b) The antisymmetric surface current distribution in the JCP unit cell with $H = 2\ \mathrm{mm}$ at $f = 6.4\ \mathrm{GHz}$, near the magnetic resonance.

I. INTRODUCTION

FIRST realizations of metamaterials exhibiting an effective negative refractive index (NRI) were based upon a combination of split-ring resonators (SRRs) and continuous wires [1], [2], which provided negative effective magnetic permeability and electric permittivity over a common frequency range. As an alternative to the SRRs, pairs of finite-length wires have been recently proposed as constitutive particles of the NRI medium [3], [4]. The pairs of coupled conductor wires exhibit both a magnetic resonance (antisymmetric mode) and an electric resonance (symmetric mode) that can be properly tuned to the specified frequency by adjusting the wire length. As a result, different periodic arrangements of paired wires and stripes have been proposed for NRI realizations at microwave and optical frequencies [5], [6]. It is noteworthy that, unlike SRR and continuous wire media, the cut-wire pair composites are fully compatible with planar fabrication technology and assembly.

Most of previously designed NRI media are anisotropic, i.e., their properties are polarization dependent, which is undesirable in certain potential applications, e. g., in "perfect lens". As an alternative, fully printable NRI metamaterials responsive to arbitrary linear incident polarization have been proposed in [7], as an extension of the cut-wire pair structure, and in [8], [9] by modification of the "fishnet" design.

In this Letter, we propose a new type of an isotropic NRI medium composed of a periodic array of *tightly coupled Jerusalem cross pairs* (JCP) *of conductors* printed on the opposite sides of a dielectric substrate, Fig. 1(a). This arrangement is conceptually linked to the "dogbone" pairs [5], [6], which provide better control of the particle resonances as compared to the cut-wire pairs and fishnet. Indeed, a pair of Jerusalem crosses can be represented as an assembly of two orthogonal "dogbone" pairs, which form a symmetric planar structure. Thus owing to the unit cell symmetry, the proposed metamaterial exhibits an isotropic NRI response to arbitrary linearly polarized incident wave. This is in contrast to the dogbone structure [6], where the composite medium is sensitive to a single polarization only. While the Jerusalem cross geometry has been extensively used in frequency selective surfaces (FSS) [10], it is shown in this Letter that the arrays of tightly coupled JCPs exhibit fundamentally different properties that enable the realization of a new type of 2–D isotropic NRI metamaterials with superior performance. The sub-wavelength size of the constitutive particles and the additional control of the geometrical parameters and enhanced design flexibility make this metamaterial an attractive alternative to the SRR-based [2] and fishnet [9] structures. Also it is shown that the substrate losses have negligible impact on the effective medium characteristics provided the magnetic resonance is reasonably broadband.

II. METAMATERIAL STRUCTURE

The proposed isotropic metamaterial is composed of a doubly periodic array of face-coupled pairs of Jerusalem cross shaped

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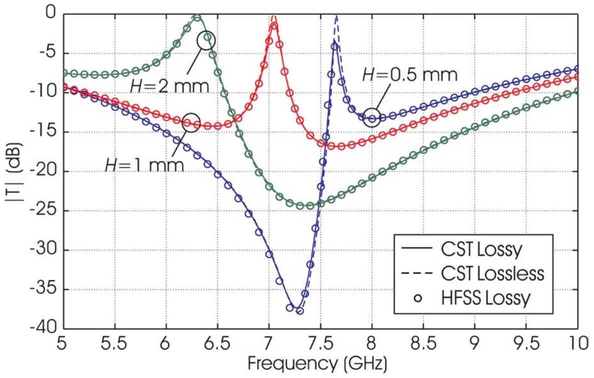

Fig. 2. Transmission coefficients vs. frequency for the JCP periodic arrays (Fig. 1) at different thicknesses H of the dielectric substrate separating the printed JCP conductors. Solid and dashed lines correspond to CST simulations of lossy and lossless structures, respectively; circles represent HFSS results for the respective lossy structure only.

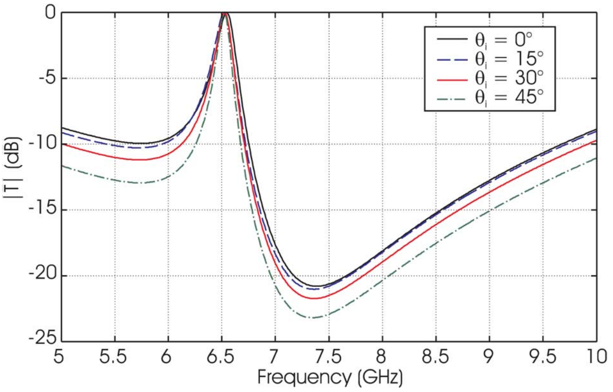

Fig. 3. Transmission coefficients vs. frequency for the JCP periodic arrays with $H = 1.5$ mm (Fig. 1(a)) illuminated by a TE plane waves incident normally ($\theta_i = 0°$) and at slant angles $\theta_i = 15°$, 30°, 45°.

conductors, as shown in Fig. 1. Owing to the unit cell symmetry, such a metamaterial provides an isotropic response to any linearly polarized incident wave. The conductor pairs are made of 10 μm thick copper foils printed on opposite sides of a dielectric substrate with permittivity $\epsilon_r = 2.2$ and loss tangent 0.0009 (such microwave laminates are commercially available, e.g., Rogers RT/Duroid 5880 or Taconic TLY-5). The constitutive unit cell of the array has a square shape with side lengths $A = B = 7.5$ mm, whereas the periodicity C in the z-direction (for periodically stacked layers) and the thickness H of the dielectric substrate are variable parameters. The other default dimensions are $A1 = B2 = 0.5$ mm, $A2 = 7.4$ mm and $B1 = 4$ mm.

Since each JCP can be seen as the superposition of two orthogonal dogbone shaped conductor pairs [6], the phenomenology of the particle response is very similar for both structures (except the polarization sensitivity). Indeed, at any orientation of the incident magnetic field, its x- and y- components induce the currents in the perpendicularly oriented central sections of the JCPs. The current distribution in the JCP unit cell with $H = 2$ mm is shown in Fig. 1(b) at the frequency $f = 6.4$ GHz, just above the transmission peak at $f = 6.3$ GHz (cf. Fig. 2). It clearly demonstrates that the currents on the two conductors are antisymmetric and form a loop, which represents an equivalent magnetic dipole. The associated magnetic moment is responsible for the artificial magnetism of the JCP particle, and therefore such a resonance is referred to as a magnetic resonance, similarly to the case of dogbone pairs [6].

The JCPs also exhibit an electric resonance (typical of FSS structures [10]) due to the excitation of co-directional currents in the central parts of JCPs. This latter resonance can be associated with an effective negative permittivity. When both magnetic and electric resonances occur in the same frequency band, the composite medium exhibits an effective NRI behavior.

III. NRI PERFORMANCE OF JCP ARRAYS

The JCP based metamaterial structure shown in Fig. 1(a) has been simulated with the commercial software CST Microwave Studio and the results have been compared with those obtained with Ansoft HFSS. The data obtained with these two packages, which employ completely different methods, are in total agreement (cf. Fig. 2), and this validates the presented results.

The characteristics of the JCP periodic array are obtained by modeling a single unit cell with doubly periodic boundary conditions along the x- and y-directions. Without loss of generality, it is sufficient to analyze a single linear polarization of electric field E along the x-direction because, owing to the structure symmetry, the response to a wave with the orthogonal y-polarized E is identical. Therefore arbitrary linearly polarized waves at normal incidence can be represented by a superposition of two waves with orthogonal polarizations. Magnitudes of the transmission coefficient $|T|$ at normal incidence at three thicknesses of the dielectric substrate $H = 0.5$, 1, 2 mm are shown in Fig. 2 for both lossy and lossless structures. The resonance transmission peaks in Fig. 2 are associated with the antisymmetric current distributions in the JCP shown in Fig. 1(b). Therefore they are attributed to the magnetic type resonances. Such a response of the JCP particles is similar to that of the "dogbone" pairs [6] where the transmission resonance also occurs at low frequencies and has broader bandwidth for thicker substrates.

It is important to note that lower transmission and higher attenuation are observed in the structures with thinner substrates. This is the result of a closer field confinement to the substrate between the conductors that, in turn, causes an increased dissipation of the incident wave by the lossy conductors and dielectric substrate. However as illustrated in Fig. 2, the effect of losses at microwave frequencies is rather insignificant at larger H and does not alter the fundamental features of the JCP characteristics. Therefore, only lossless structures are considered in remainder of the letter.

To evaluate the effect of oblique incidence, the transmission characteristics of the JCP array have been calculated for a transverse-to-z electric (TE) polarized plane wave impinging onto the array at angles varying from $\theta_i = 0°$ to $\theta_i = 45°$. The simulation results in Fig. 3 reveal a remarkable feature of the JCP array, that its transmission resonance frequency is nearly independent of the incidence angle. This implies that the JCP arrays have the potential to provide a NRI response in a broad range of incidence angles.

In order to obtain further evidences that the transmission characteristics discussed above are associated with the NRI phenomenon, we have retrieved an effective refractive index n from the

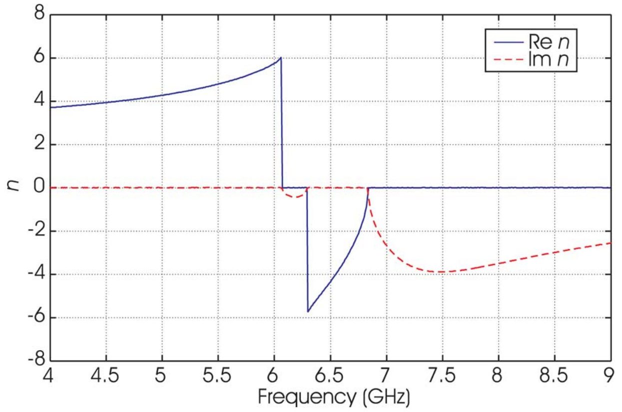

Fig. 4. Real (solid line) and imaginary (dashed line) parts of the retrieved effective refractive index n for a JCP array with $H = 2$ mm and effective layer thickness $C = 4$ mm.

simulated transmission and reflection characteristics for a single layer JCP array, using the procedure proposed in [11]. The plots in Fig. 4 for a JCP array with $H = 2$ mm (Fig. 1(a)) and an effective layer thickness $C = 4$ mm along the z-direction confirm that a NRI band does exist between 6.3 and 6.8 GHz, separated from the transmission band with positive refractive index at lower frequencies by a narrow bandgap where transmission is forbidden.

The existence of an effective NRI band has been further corroborated by analyzing the dispersion characteristics of the eigenmodes in the infinite structure comprised of the planar JCP arrays (Fig. 1) stacked with period C along the z-axis. Fig. 5 shows the calculated one-dimensional dispersion diagram for the Bloch propagation wavenumber k_M along the z-direction, normalized to the period $C = 4$ mm (the other parameters are the same as in Fig. 2). The negative slope of the dispersion curves at frequencies above 6.3 GHz conclusively confirms backward type of wave propagation at all three thicknesses of the dielectric substrate. The dispersion characteristics for $H = 2$ mm, in particular, are fully consistent with the retrieved refractive index in Fig. 4. Also, one should note that with $C = 4$ mm, the NRI passband increases at larger H. The dependence of the central frequency of the NRI passband on H deduced from these dispersion diagrams is shown in Fig. 6 at a few values of C. As apparent from these plots, the passband progressively shifts toward lower frequencies at larger H while $H \leq C/2$, and then it moves upward at larger H. It is found that $H \cong C/2$ generally provides the largest NRI bandwidth along with the lowest magnetic resonance frequency.

Finally, it is important to emphasize that in the NRI passband, the lattice constant A of JCP arrays is of an order of $A \approx \lambda/6$. This implies that JCP particles are of subwavelength size. Therefore they are amenable to the homogenization procedures, and such an obtained effective NRI represents a meaningful phenomenological characteristic of the JCP based composite medium.

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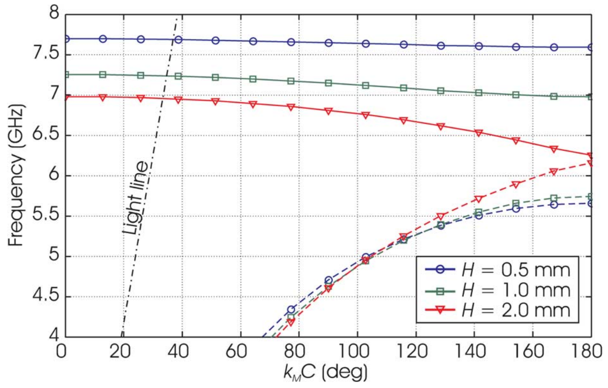

Fig. 5. Dispersion diagram for a wave propagating with wavenumber k_M along the z-direction in the infinite periodic (period $C = 4$ mm) stack of planar JCP arrays of Fig. 1. The JCP parameters are the same as in Fig. 2. The light line (dashed-dot) is given by $\omega = k_M c$, where c is the speed of light.

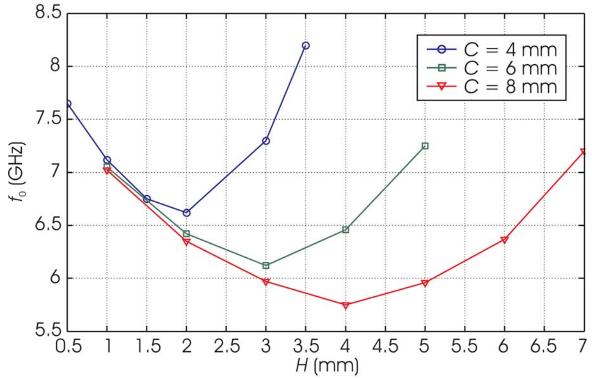

Fig. 6. Centre frequency f_0 of the NRI transmission band (shown in Fig. 5) vs. thickness H of dielectric substrate at a few values of period C along the propagation direction z.

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