Abstract: A dual-band artificial magnetic material and then a dual-band double-negative metamaterial structure based on symmetric spiral resonators are presented. An approximate analytical model is used for the initial design of the proposed structures. The electromagnetic parameters of the proposed metamaterial structure retrieved using an advanced parameter retrieval method based on the causality principle show its dual-band nature at microwave frequencies. The proposed double negative metamaterial structure with unit cells with transverse dimensions of 2.5 mm × 2.5 mm has two negative refractive index regions around 6 GHz and 8 GHz. The designed structure can be scaled to other frequencies and is also suitable for planar fabrication.

Keywords: Artificial Magnetic Materials, Dual-Band Structures, Double Negative Metamaterials.

1 Introduction
The artificial materials have been the subject of great interest for many worldwide research groups and scientists over the years. Recently, a new class of artificial materials, the so-called metamaterials (MTMs), has been studied extensively owing to its peculiar physical properties and novel applications, which do not occur or might not be readily realizable in nature. The most interesting physical phenomenon of MTMs is the Negative Refractive Index (NRI) [1]. The first implementation of NRI was reported in Smith’s experiments using a composite structure, consisting of Split Ring Resonators (SRRs) and continuous wires [2]. Afterwards, while the negative permittivity is still simply obtained from continuous wires, various types of artificial magnetic structures, such as cut-wire pair, H-shaped and π-shaped configurations have been introduced [3-5]. Negative refraction and, in general, electromagnetic wave propagation in NRI media are still controversial subjects and have generated many intense debates. Based on the interesting and unique properties of MTMs, many applications have been proposed for them, such as antennas [6-11], superlenses [12, 13], filters [14-16], and other devices [17-21]. More recently, chiral MTMs have been introduced as an alternative route for achieving NRI media [22-26].

In this study, a dual-band artificial magnetic material and MTM structures are proposed, using symmetric spiral resonators. Briefly, in Sec. 2, the analytical and numerical analysis of dual-band artificial magnetic materials are presented. In Sec. III the application of proposed structure for designing double-negative MTMs is introduced. Finally, summary and conclusions are provided in Sec. 4.

The most significant advantage of the proposed dual-band MTM structure in this study is that its dimensions are similar to the well-known single-band MTM structures [27]. However, the common techniques of realizing dual-band MTMs such as combination of unit cells with different transverse dimensions [28, 29] and using multilayer printed circuit boards [30, 31] causing enlargement of the unit cell dimensions, are totally avoided.

2 Dual-Band Artificial Magnetic Material using Symmetric Spiral Resonators
Figure 1 illustrates the unit cell of proposed dual-band artificial magnetic structure. The unit cell with transverse dimensions of 2.5 mm × 2.5 mm, consisting of two symmetric spiral resonators, with width $w = 0.1$ mm and thickness $t = 0.018$ mm and other geometric parameters $s = 0.05$ mm, $l_1 = 1.15$ mm, $l_2 = 1.05$ mm, $l_3 = 2.4$ mm, and $l_4 = 2.3$ mm were patterned on one side of an FR-4 dielectric board with the dielectric constant $\varepsilon_r = 4.4$, dielectric loss tangent $\tan \delta = 0.025$, and thickness $h = 0.25$ mm. Note that the use of two symmetric spiral resonators is to achieve a dual-band structure.
The analytic model of single-band artificial magnetic material structures were in [32, 33]. We may now study the behaviour of the proposed dual-band magnetic material structure. Observe that when the structure is exposed to an external magnetic field (according to Faraday’s Law) the change in the magnetic flux enclosed by the resonators induces an electromotive force in the square copper rings resulting a current in them. Thus, the induced current and resultant magnetic dipole moment is the source of the resultant effective permeability generated only in the direction. If only the upper symmetric spiral resonator exists, the effective relative permeability of the structure is given by [33]:

$$
eff = 1 + \frac{\varepsilon_r - 1}{2} \frac{K(k)K(\sqrt{1-k^2})}{K(k)K(\sqrt{1-k^2})},$$

(4)

$$k = \frac{s}{s+2w}, \quad k_i = \frac{\sinh(\pi s/4h)}{\sinh(\pi(s+2w)/4h)}$$

where $\varepsilon_{eff}$ and $K$ are the effective relative permittivity and complete elliptic integral of the first kind, respectively. In order to compute the total capacitance of the resonator’s strips, the per-unit-length capacitance of coplanar strips, $C_{pul}$ should be multiplied by the average length of adjacent strips, $l_i$. In addition, $R_{ohmic}$ and $G_{eff}$ corresponding to the ohmic loss of copper strips and the loss of substrate, respectively are given by:

$$R_{ohmic} = \frac{l_i}{w} \sqrt{\frac{\sigma}{2\pi}}, \quad G_{eff} = \omega \varepsilon_r \varepsilon_{eff} l_i \tan \delta \frac{K(\sqrt{1-k^2})}{K(k)}$$

(5)

where $l_i$ is the total length of copper strips of the resonator.

The unit cell of proposed dual-band artificial magnetic structure is now considered. Two symmetric spiral resonators with different dimensions generate two distinct resonant frequencies, between which there is clearly no magnetic coupling. By neglecting the effect of electric coupling between resonators, the effective relative permeability of this configuration can be expressed by:

$$\mu_r = \frac{j \omega L^{(1)}_{eff} A^{(1)}}{d_y d_x \left( R_{ohmic} + \frac{1}{G_{eff} + j \omega C_{eff}} + j \omega L^{(1)}_{eff} \right)} - \frac{j \omega L^{(2)}_{eff} A^{(2)}}{d_y d_x \left( R_{ohmic} + \frac{1}{G_{eff} + j \omega C_{eff}} + j \omega L^{(2)}_{eff} \right)}$$

(6)

where Eqs. (1) and (2) superscripts correspond to the upper and lower resonators, respectively. Due to the considerable width of strips and many corners in the structure, considering of the exact values of effective area enclosed by each resonator, total length of each resonator and the average length of adjacent strips is almost impossible. It can be seen that the effective area enclosed by each resonator, total length of each resonator and the average length of adjacent strips in each resonator are approximately given by:

$$A^{(1)} = \sum_{k=1}^{N} \left[ l_i - (2k)w - (2k - 1)s \right]^2$$

(7)

$$I^{(1)} = (4N^2 l_i - (2N)w - (2N - 1)s)$$

(8)

$$I^{(2)} = 4(N-1)l_i - 4N(N-1)w - 4(N-1)^2s$$

(9)

where $i$ may be set equal to 1 or 2, and $N \geq 2$ is the number of turns of each square spiral structure in a symmetric spiral resonator.
In general, for compact structures, where the space between non-adjacent strips is comparable to the space between adjacent strips, the presented model gives an approximate value for the relative permeability, which can be used to initiate a design. However, we can, once again, perform a more accurate analysis by using a commercial electromagnetic simulator to accurately compute the exact value of the resonance frequencies and the relative permeability of the proposed structure. However this procedure would only provide some fine adjustment.

The resonance frequencies of the proposed symmetric spiral resonators and the resultant structure using the proposed analytical model are calculated and reported in Table 1. Observe that the resonance frequencies of the complete resultant structure are close to those of each resonator. The small shift between them is mainly due to the electric coupling among the resonators.

In order to evaluate the presented analytical model, a full-wave analysis is required. Numerical simulations are performed by using time domain analysis of CST Microwave Studio. The resonance frequencies obtained from simulation are also presented in Table 1. Due to the aforementioned approximations, exact agreement cannot be expected. However, the reasonable agreement among the results shows the adequacy of the proposed approximate model.

### Table 1. Resonance frequencies obtained from simulation and approximated analytical model.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Resonance Frequency (Simulation)</th>
<th>Resonance Frequency (Analytical Model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonator (1)</td>
<td>6.1 GHz</td>
<td>5.5 GHz</td>
</tr>
<tr>
<td>Resonator (2)</td>
<td>8 GHz</td>
<td>7 GHz</td>
</tr>
<tr>
<td>Dual-Band</td>
<td>6 GHz &amp; 7.9 GHz</td>
<td>5.5 GHz &amp; 7 GHz</td>
</tr>
<tr>
<td>Structure</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The simulation results of transmission (S21) and reflection (S11) coefficients in a frequency range of 4 to 9 GHz are illustrated in Fig. 3. It can be easily shown that the impedance and refractive index of the MTM slab are given by:

\[
z = \pm \sqrt{\left(1 + S_{11}\right)^2 - S_{21}^2} \left(1 - S_{11}\right) - S_{21}^2 \left(1 + S_{11}\right)
\]

(10)

\[
n = \frac{i}{k_d} \ln \left[ \frac{1 - z - 1}{z + 1} S_{11} \right]
\]

(11)

The sign of square root in Eq. (10) should be chosen according to the energy conversation principle by the fact that the real part of \(z\) is positive. Since complex logarithmic function is a multi-branch one, the refractive index cannot be uniquely determined using Eq. (11); and so, the branch selecting problem is the challenge of MTM structures. It is clear that the imaginary part of refractive index can be unambiguously determined using Eq. (11). Considering this fact, Kramers-Kronig relations [35]:

\[
\text{Re}\{n(\omega)\} = 1 + \frac{2}{\pi} PV \int_0^\infty \frac{u \text{Im}\{n(u)\}}{u^2 - \omega^2} du
\]

(12)

\[
\text{Im}\{n(\omega)\} = -\frac{2\omega}{\pi} PV \int_0^\infty \frac{\text{Re}\{n(u)\} - 1}{u^2 - \omega^2} du
\]

(13)

which connect the real and imaginary parts of the refractive index based on the causality principle were applied for solving the branch selecting problem [36]. In the above equations, Pv refers to the principal value of integral. However, in simulations and experiments, S-parameters are measured in limited frequency ranges, sothe integrations of Eqs. (12) and (13) should be
truncated. Also, it is noticed that upper limit of integration should be truncated at a frequency at which effective medium definition is valid. Thus, these relations yield only an approximation of real and imaginary parts of \( n \). Thus, the proper branch can be selected such that the result of Eq. (11) is the closest to the K-K solution. Once \( z \) and \( n \) are unambiguously determined, effective permittivity and permeability of the structure could be identified subsequently, \( \varepsilon = n/z \) and \( \mu = nz \). The effective electromagnetic parameters of the proposed structure are retrieved and illustrated in Figs. 4-6.

The integrations in Eqs. (12) and (13) should be truncated. Also, it is noticed that upper limit of integration should be truncated at a frequency at which effective medium definition is valid. Thus, these relations yield only an approximation of real and imaginary parts of \( n \). Thus, the proper branch can be selected such that the result of Eq. (11) is the closest to the K-K solution. Once \( z \) and \( n \) are unambiguously determined, effective permittivity and permeability of the structure could be identified subsequently, \( \varepsilon = n/z \) and \( \mu = nz \). The effective electromagnetic parameters of the proposed structure are retrieved and illustrated in Figs. 4-6.

Note that, the first negative refraction region is around 6 GHz which is due to the upper symmetric spiral resonator. Besides, the second region is around 8 GHz which is due to the lower symmetric spiral resonator. The figure of merit \( \text{FoM} = |\text{Re}(n) / \text{Im}(n)| \), is relatively low compared to the well-known single-band negative index material designs such as introduced structure in [27]. Simulations show that the loss mainly originates from the lossy dielectric substrate which limits applicable frequency bands of NRIs due to the high loss of this MTM design. If low loss dielectric materials are used in the proposed design, the FoM can improve significantly. For instance, in our numerical simulations, we obtained very high FoM (larger than 50) using a dielectric board with relative permittivity of 4.4 and loss tangent of 0.001.

The proposed dual-band MTM structure can be scaled to other frequencies and is also suitable for planar fabrication using conventional printed circuit boards. In addition, as the significant advantage of the proposed structure, its dimensions are similar to that of well-known single-band MTM structure previously reported. The proposed structures may have many potential applications such as in dual-band antenna, dual-band focusing, dual-band filters, and dual-band microwave absorbers.
4 Conclusions
Symmetric spiral resonators were proposed and investigated to design dual-band artificial magnetic materials and double negative MTM structures. Also, an approximate analytical model was introduced for the initial design of dual-band artificial magnetic structures. Furthermore, the usefulness of the proposed structure for designing dual-band double negative MTMs was shown. The proposed structure has two NRI regions around 6 GHz and 8 GHz, which may be scaled to other frequencies. It seems that the proposed dual-band MTM structure which has unit cell dimensions similar to the well-known single-band microwave MTM structures can be used for improving the properties of dual-band antennas, filters, phase shiftsers, absorbers, and other microwave devices.

References


Davoud Zarifi was born in Kashan, Iran, in 1987. He received the B.Sc. degree from the University of Kashan, Kashan, Iran, in 2009 and the M.Sc. degree from the Iran University of Science and Technology (IUST), Tehran, Iran, in 2011, where he is currently working toward the Ph.D. degree, all in electrical engineering. His research interests are electromagnetic waves in complex media, numerical techniques for electromagnetics, inverse problems in electromagnetic, and applications of ordinary and chiral metamaterials.

Seyed Ehsan Hosseinejada was born in Semnan, Iran, in 1987. He received the B.Sc. degree in electrical engineering from Semnan University, Semnan, Iran, in 2009, and the M.Sc. degree in electrical engineering from the Iran University of Science and Technology (IUST), Tehran, Iran, in 2012, where he is currently pursuing the Ph.D. degree in electrical engineering. His areas of research interests include array antennas, substrate integrated circuits (SICs), numerical methods in electromagnetics, electromagnetic waves in complex media, metamaterials, plasmonics, and nanophotonics.

Ali Abdolali was born in Tehran, Iran, in 1974. He received B.S. degree from the University of Tehran, and M.S. degree from the University of Tarbiat Modares, Tehran, and the Ph.D. degree from the Iran University of Science and Technology (IUST), Tehran, Iran, all in electrical engineering, in 1998, 2000, and 2010, respectively. In 2010, he joined the Department of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran, where he is an assistant Professor of electromagnetic engineering. His research interests include electromagnetic wave scattering, Radar Cross Section (RCS), Radar Absorbing Materials (RAM), EM Waves controlling, Cloaking, Metamaterials, EM Waves in complex media (anisotropic, inhomogeneous, dispersive media, metamaterials), Frequency Selective Surfaces (FSS), Bioelectromagnetism (BEM). He has authored or coauthored over 50 articles in international journals and conferences.