Dynamical Chiral Metamaterial with Giant Optical Activity and Constant Chirality Over a Certain Frequency Band

F. Karadağ [1], İ. Çömez [1], F. Dinçer [2], M. Bakır [3], and M. Karaaslan [4]

[1] Department of Physics
Cukurova University, Adana, 01030, Turkey
fkaradag@cu.edu.tr, icomez2003@yahoo.com

[2] Department of Electrical Engineering
Kilis 7 Aralık University, Turkey
furkandincer@kilis.edu.tr

[3] Department of Informatics
Mustafa Kemal University, Turkey
mbakir@mku.edu.tr

[4] Department of Electrical and Electronic Engineering
Iskenderun Technical University, Turkey
muharrem.karaaslan@iste.edu.tr

Abstract ─ We demonstrate numerically and experimentally a dynamical chiral metamaterial that uniaxially creates giant optical activity and circular dichroism. In addition, the structure gives a high negative refractive index due to the large chirality. The proposed chiral metamaterial includes four L attached cross (FLAC) wire strips and offers a simple geometry, flexibility and more efficient results for chiral metamaterial applications such as polarization rotator, EM filter and so on. The experimental results are in a good agreement with the numerical simulation. It can be seen that FLAC wire strips based chiral metamaterial can also be used to achieve natural-small chirality with a constant value in a wide frequency range between 3.5-4.5 GHz. This is also another crucial feature of the structure. Therefore, the proposed chiral metamaterial with constant chirality value can be used to design novel EM devices such as polarization converter, anti-reflection filters for a certain frequency range.

Index Terms ─ Dynamical chiral metamaterials, natural-small chirality, optical activity, wide band.

I. INTRODUCTION

Metamaterials (MTMs) are defined as artificial electromagnetic (EM) materials that are rapidly developing as a research area due to having many potential application areas such as diffraction-limit breaking [1], cloaking [2], super lens [3], sensing [4, 5], absorber [6] and chiral metamaterial [7, 8]. Chiral media have received considerable attention in the recent years due to their potential applications in the fields of electromagnetic, microwave, and millimeter wave frequencies. The reason is that the chiral media shows exotic and individual properties such as giant optical activity and negative refraction. They are also MTMs made up of unit cells without mirror symmetry planes [9-14]. Giant optical activity is also realized by using gold nanostructures in the visible frequency range [15]. The broadband achievement of large optical activity is demonstrated in microwave regime by metamaterial with hybrid elements composed of twisted pairs of cross-shaped meta-atoms and their complements [16]. Conditions for the phase velocity to be directed opposite to the direction of power flow in a Faraday chiral medium are investigated and derived for a plane wave propagation in an arbitrary direction. It is observed that the phase velocity can be directed in the reverse direction to the power flow which provides that the gyrotropic parameter of the ferrite component medium is sufficiently large compared with the corresponding nongyrotropic permeability parameters [17]. It is also demonstrated that bright-bright, dark-dark, and dark-bright vector solitons can be formed in a spectral subregime in which one of the two Beltrami components exhibits a negative real refractive index when nonlinearity is ignored and the chirality parameter is sufficiently large [18, 19]. The optical theorem for an obstacle excited by a plane and a spherical wave mixed radiation-scattering theorems expressing the extinction cross section by means of the

Submitted On: February 1, 2016
Accepted On: April 14, 2016

secondary Beltrami field at the dipole's location is investigated [20]. In all these studies, general properties of chiral medium are theoretically derived dislikeness with the proposed structure in this study. The proposed study gives opportunities to the researchers to realize the mentioned theoretical outputs.

The major advantage of chiral MTMs over natural materials is that the macroscopic parameters can be designed to have desired values [14, 21]. This advantage provides the ability to control electromagnetic waves. Chiral media have different responses for a left circularly polarized (LCP, -) wave and a right circularly polarized (RCP, +) wave due to the intrinsic chiral asymmetry of the medium refractive index. This phenomenon is caused by the cross-coupling effect between the electric and magnetic fields through a chiral medium. These two circularly polarized waves then combine at the chiral-end and propagate out from the chiral media as an elliptically polarized wave based on circular dichroism. This ability is called as optical activity. κ describes chirality parameter and the strength of the cross-coupling effect, so that it is one of the constitutive relations of a chiral medium. Basically, chirality parameter is defined as the geometric property of a structure onto its mirror image. Chirality is also connected to the refractive index,

$$n^{\pm} = \sqrt{\varepsilon_r \mu_r} \pm \kappa. \quad (1)$$

They are characterized by the quantity of chirality,

$$\kappa = (n_+ - n_-)/2, \quad (2)$$

where n_+/n_- is the refractive index of the RCP or LCP waves and high chirality leads to negative refractive index. Furthermore, there are some studies on chiral metamaterials in literature [22-34]. Natural like chirality over a certain frequency band and strong optically active chiral metamaterials are also investigated in literature with different types of inclusions [31, 32]. Small chirality is achieved by rectangular split ring resonators in the same frequency band with the proposed metamaterial in this study but it doesn't demonstrate that the same resonators can be used to obtain huge values of chirality admittance [31].

In this study, we designed both numerically and experimentally FLAC wire strips based chiral MTM. In conventional chiral metamaterial studies, chirality based negative index of refraction, giant optical activity and very large circular dichroism is the main subject. The object of these studies is to realize both huge polarization conversion and negative refraction by using metamaterials with high chirality admittance. Unlike the mentioned conventional chiral metamaterial studies in literature, the suggested structure has very flexible feature because of its dynamical properties which provide mechanical tunability and present natural-small chirality with constant value in a wide frequency range between 3.5-4.5 GHz together with other conventional metamaterial potentials such as negative index of refraction, giant optical activity and very large circular dichroism. This is also another crucial feature of the structure comparing to the other literature studies. This provides to design novel EM devices such as polarization converter, anti-reflection filters for a certain frequency range [25-29]. Firstly, we designed a dynamical chiral MTM structure. When we changed arm-lengths of the structure, we observed that our dynamic chiral MTM structure has very flexible feature and it can also be used as a frequency shifter (because of the mechanical tunability). The parametric study is then realized by CST Microwave Studio (based on finite integration technique) to get the dimensions necessary for giant chirality between the frequency ranges of 1-6 GHz. Secondly, we measured the fabricated chiral MTM structures for 1-6 GHz by Rohde & Schwarz vector network analyzer (VNA) and microwave horn antennas. We evaluated and compared the simulation and experimental results. Obtained results show that experimental results are in a good agreement with the numerical simulation. Besides, the strong chirality and negative refractive index due to this strong chirality are obtained. In addition, the proposed dynamical chiral metamaterial has natural-small chirality with a constant value at a wide range of frequency between 3.5-4.5 GHz.

The organization of this paper is as follows. In Section II, the experiment and simulation of the chiral MTM structure based on FLAC wire strips-based chiral structure is proposed, the experimental and simulation methods are presented. In Section III, generalization of the idea and designs of chiral structures are introduced. Finally, summary and conclusions are provided in Section IV.

II. EXPERIMENT AND SIMULATION SETUP

The resonant behavior of the proposed structure is achieved by the geometry dependent capacitive elements such as gaps and strips. EM interaction between strips and gaps can be arranged by playing with the geometrical configuration of the structure such as shape and size. This provides mechanical tunability for the suggested structure to obtain well optical activity as desired. The main purpose of this geometry is to provide simpler structure that offers more flexibility and reliability on the control of incident EM wave polarization and simplifies the manufacturing process.

Designed structure consists of wire strips and their mirror image which are patterned at the front and back side of a host dielectric substrate, respectively. In the present work the selected host material is FR-4; a high frequency laminate with a thickness of 1.6 mm, relative permittivity of 4.2, relative permeability of 1 and loss tangent of 0.02. The cross wire strip-shapes are made of copper with a thickness of 0.036 mm and electrical conductivity of $5.8x10^7\ S/m$. The dimensions of the structure are presented in Fig. 1 (a). After the designing phase, we fabricated dynamic chiral MTM sample structure with print circuit board technique as shown in Fig. 1 (b). Samples are simulated with a commercial full-wave EM solver, CST Microwave Studio (Computer Simulation Technology GmbH, Darmstadt, Germany), which uses a finite integration technique to determine reflection and transmission properties. In addition, boundary conditions are assigned as unit-cell (side surfaces) and open add space (front and back surfaces) boundary conditions in the simulation.

The experimental measurement setup consists of a VNA and two microwave horn antennas as shown in Fig. 1 (c). Two microwave horn antennas are connected to the VNA to measure the S-parameters. In the measurements, one horn acts as a transmitter and the other one detects the transmitted or reflected wave. Firstly, free space measurement without the chiral structure is carried out and this measurement used as the calibration data for the VNA. The structure is then inserted into the experimental measurement setup and S-parameter measurements are performed as co-polar and cross-polar reflection/ transmission coefficients. Initially, the distance between the horn antennas and chiral slab is kept sufficiently large to eliminate unwanted near-field effects.

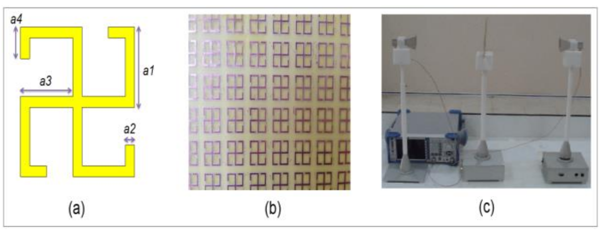


Fig. 1. (a) Schematic representation dimensions of one unit cell of the proposed resonator (a1=5.8 mm, a2=0.8 mm, a3=4.6 mm, a4=3.3 mm), (b) picture of the front side of the fabricated sample, and (c) a picture from the measurement setup.

III. NUMERICAL AND EXPERIMENTAL RESULTS OF THE PROPOSED STRUCTURE

Figure 2 shows the simulation and experimental results of the reflection coefficient (R), and transmission coefficients ($T+, T-$), as a function of frequency, respectively. The experimental results agree well with the numerical simulation. The transmission results for RCP ($T+$) and LCP ($T-$), split into two curves are obtained. There are two different resonance peak points in our structure. Dynamic structure of our chiral MTM provides this feature. It can be seen that the resonances are observed around the frequency of 3.1 and 5.6 GHz for transmission and reflection coefficients. The differentiation of the $T+$ and $T-$ provides optical activity, i.e., dynamical chirality due to the asymmetric resonance properties of the proposed structure.

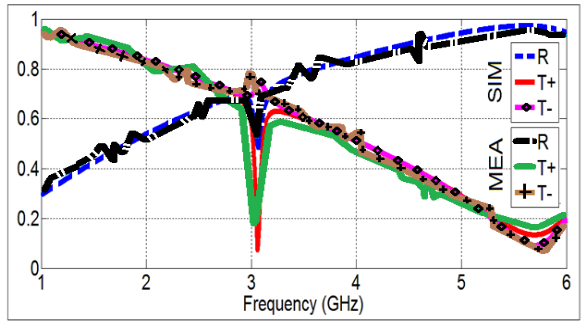


Fig. 2. Numerical and experimental results for $Abs\ (R)$, $Abs\ (T+)$, and $Abs\ (T-)$.

From the following retrieval results [22-34], the difference between the phases of RCP and LCP transmitted wave is characterized as the polarization azimuth rotation angle θ which is calculated by:

$$\theta = \frac{1}{2}[\arg(T_+) - arg(T_-)], \quad (3)$$

and demonstrated in Fig. 3 for simulation and experimental results, in order. Furthermore, we conclude that only at the resonance frequencies, the transmission spectra for the RCP and LCP waves are significantly different. This difference is due to the unmatched transmission behavior of RCP and LCP waves. Beside this, minor difference between RCP and LCP waves can be seen in the frequency range of 3.1-4.5 GHz. The small difference results in both minor asymmetric transmission and natural-small chirality. This difference between the amplitudes of two transmissions is characterized by ellipticity of the transmitted wave by the equation:

$$\eta = 0.5\tan^{-1}(|T_+|^2 - |T_-|^2)/(|T_+|^2 + |T_-|^2), \quad (4)$$

as shown in Fig. 4.

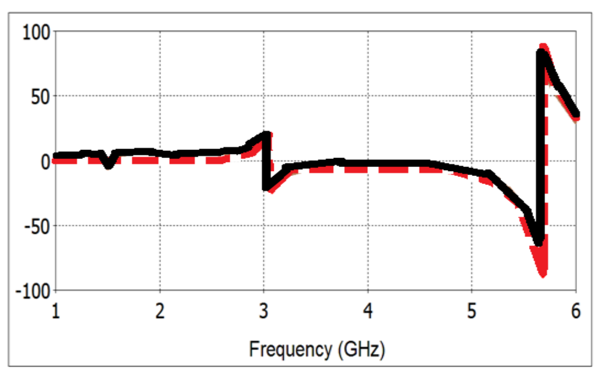


Fig. 3. Numerical (red-line) and experimental results (black-line) for theta ($\theta -$ degree).

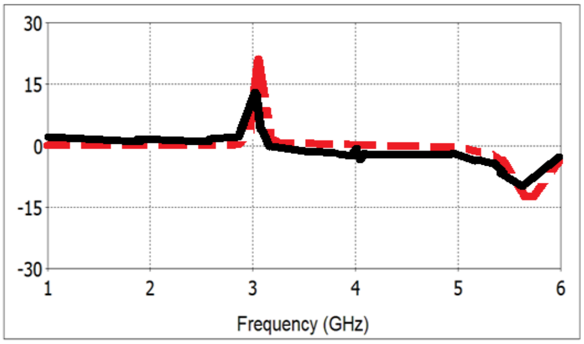


Fig. 4. Numerical (red-line) and experimental results (black-line) for ellipticity (η − degree).

Effective constitutive parameters are also evaluated using transmission and reflection parameters with retrieval formulas. These formulas can also be used to obtain chirality of the effective media from the RCP and LCP elements of the transmitted wave. The chirality κ can be obtained directly from the transmissions as:

$$Re(\kappa) = [\arg(T+) - \arg(T-) + 2m\pi]/(2k_0 d), \quad (5)$$

where k_0 is the wave vector in the vacuum, d is the thickness of the structure and m is an integer which guarantees the result to be physically meaningful. T_+ and T_- values are restricted by $-\pi < \arg(T_+) - \arg(T_-) + 2m\pi < \pi$ [22-34].

The average refractive index,

$$n = (n_L + n_R)/2, \quad (6)$$

and the impedance z can be obtained by using the traditional retrieval procedure by:

$$n_\pm = \frac{i}{k_0 d}\left\{\log\left[\frac{1}{T_\pm}\left(1 - \frac{\zeta-1}{\zeta+1}R\right)\right] \pm 2m\pi\right\}, \quad (7)$$

[25, 26] after taking the geometric average of transmission components with RCP and LCP transmitted wave ($T = \sqrt{T_+T_-}$). In addition, the impedance can be extracted by:

$$\zeta = \pm\sqrt{\frac{(1+R)^2 - T_+T_-}{(1-R)^2 - T_+T_-}}. \quad (8)$$

The other retrieval parameters can then be calculated by $n_\pm = n \pm \kappa$, $\varepsilon = n/\zeta$, and $\mu = n\zeta$ [30-36]. Figures 5-7 show the retrieval results.

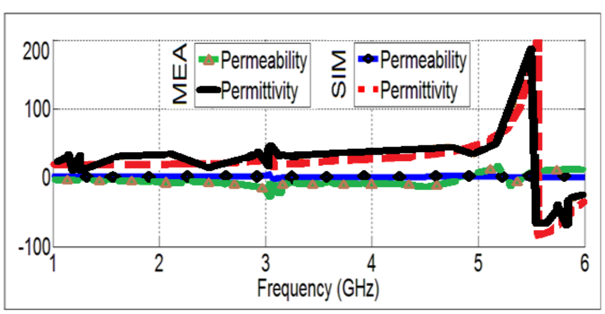


Fig. 5. Numerical and experimental results for permittivity and permeability values.

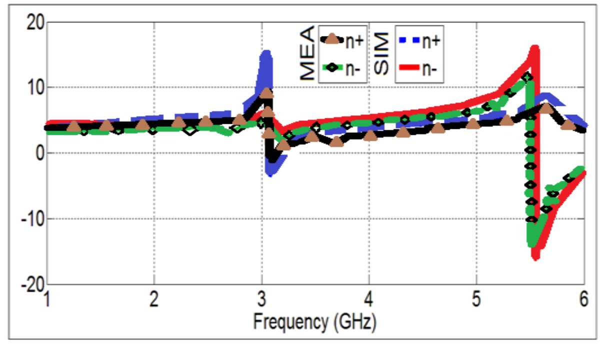


Fig. 6. Numerical and experimental results for n(+) and n(-) values.

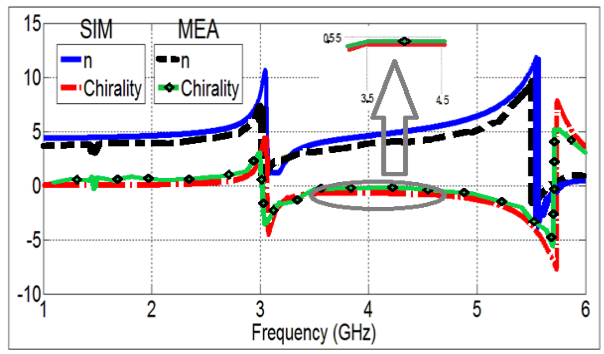


Fig. 7. Numerical and experimental results for n and chirality values.

It is clearly shown that the relative permeability is around 1 and small changes are observed around resonance frequencies. Besides, relative permittivity has also ripples around the resonance frequencies. The relative permittivity reduces to -95 at around the second resonance frequency. The RCP and LCP elements of effective index are shown in Fig. 6. The difference between them proves the asymmetric phenomena and optical activity of the overall structure.

The effective refractive index and chirality are shown in Fig. 7. Although the effective permittivity and permeability are not simultaneously negative at the second resonance frequency, the effective refractive index is negative. This is caused by the strong chirality at the same frequency. Beside this, another important phenomenon is the small-natural chirality observed between 3.1-4.5 GHz. A small-natural chirality phenomenon for chiral metamaterials has not been studied so far in the literature. The observed chirality is very small as natural chiral substances. Hence, this structure can be used in many applications such as polarization conversion, anti-reflection filter and so on. If the geometry of the dynamic chiral metamaterial is reduced to nanoscale, the proposed structure can be easily used as chiral sensor. One another advantage of the proposed structure is constant value (~0.55) of the chirality for a wide range of frequency (3.5-4.5 GHz) (Inset in Fig. 7). Therefore, the proposed structure supposes polarization conversion with in all the frequencies in the range.

In order to show physical mechanism, we investigated the resonance electric field and surface current distributions for both resonance frequencies as presented in Figs. 8 and 9, respectively. As shown in Fig. 8, especially electric field distribution is strongly concentrated at the resonance frequency of 5.68 GHz according to the first resonance. However, electric field distributions are concentrated around the gaps due to EM interaction between layers. Moreover for Fig. 9, it can be seen that the magnetic field strongly concentrates at the resonance frequency of 3.08 GHz according to the second resonance frequency of 5.68 GHz. This situation verifies the character of the resonances as magnetic ones as indicated above. In addition, the intensity of the current is highly strengthened at the surface of the center resonators at the resonance. The surface current distribution at 5.68 GHz is particularly given to show their different characters.

It is well known that a material can only have chirality characteristics if it shows both electric and magnetic responses. It means that when electric field component is incident towards the structure, it results in magnetic response and vice versa. Since EM wave includes both electric and magnetic field components, it is not possible to decide exactly to the response of the structure. The magnetic response of the structure can be estimated by following the continuous current paths between front and backside inclusions of chiral metamaterial. Whereas the current distributions along centers of both front and back sided inclusions at 3.08 GHz is higher than that of 5.68 GHz, these currents are along the same direction. Therefore, this orientation does not contribute to the chirality admittance as well oriented inclusions. Whereas, the magnitude of the current is not high as the first one, both orientations are continuous and demonstrate instructive effect for 5.68 GHz. Hence, the chirality admittance is higher at this frequency value.

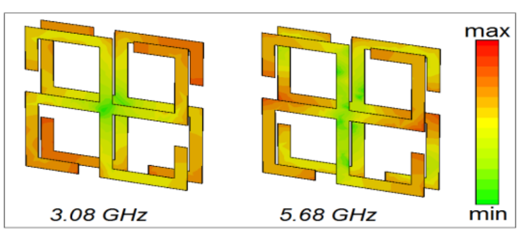


Fig. 8. Electric field distributions at the resonance frequencies.

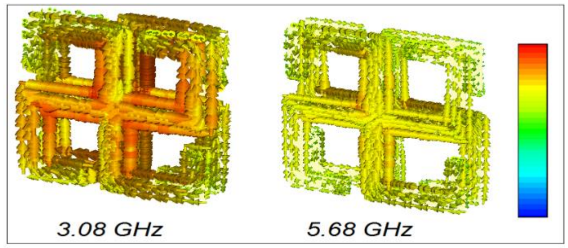


Fig. 9. Surface current distributions at the resonance frequencies.

IV. CONCLUSION AND DISCUSSION

In summary, we numerically and experimentally designed and studied a dynamical chiral MTM based on four L attached cross (FLAC) wire strips which has very simple geometry and features of wide-band chirality and mechanical tunability. The presented dynamic chiral design offers a much more efficient fabrication because of the feasible geometry. The experimental results are in a good agreement with the numerical simulation. This chiral MTM has very adaptable properties, including negative index of refraction due to chirality, giant optical activity and very large circular dichroism. Besides, the proposed chiral structure offers a natural-small chirality with a constant value at a wide frequency range between 3.5-4.5 GHz. This advantageous is the crucial point of the study. By using this property, it is possible to design polarization converter with constant amount in a wide range of frequency. In addition, the structure can be used as a sensor of chiral substances by placing between two layers of it. Therefore, the suggested dynamical chiral MTM has many potential applications in order to create configurable polarization rotator, sensors and so on.

ACKNOWLEDGMENT

This work is supported by the TUBITAK under Projects No: 113E290. One of the authors M. K. also acknowledges partial support from the Turkish Academy of Sciences.

REFERENCES

[1] J. S. Lih, J. S. Wang, M. C. Lu, Y. C. Huang, K. H. Chen, J. L. Chern, and L. E. Li, "Experimental realization of breaking diffraction limit by planar negative-index metamaterials in free space," *Europhys. Lett.*, vol. 69, pp. 544-549, 2005.

[2] J. B. Pendry, "A chiral route to negative refraction," *Science*, vol. 306, pp. 1353-1355, 2004.

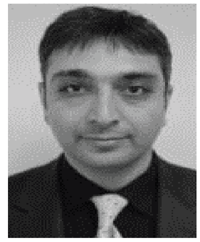
[3] S. Tretyakov, I. Nefedov, A. Sihvola, S. Maslovski, and C. Simovski, "Waves and energy in chiral nihility," *J. Electromagn. Waves Appl.*, vol. 17, pp. 695-706, 2003.

[4] C. Monzon and D. W. Forester, "Negative refraction and focusing of circularly polarized waves in

optically active media," *Phys. Rev. Lett.*, vol. 95, pp. 123904-123908, 2005.
[5] S. Tretyakov, A. Sihvola, and L. Jylha, "Negative refractions and backward waves in biaxially anisotropic chiral media," *Phys. Condens. Matter.*, vol. 3, pp. 107-112, 2005.
[6] V. Yannopapas, "Circular dichroism in planar nonchiral plasmonic metamaterials," *J. Phys. Condens. Matter*., vol. 18, pp. 6883-6890, 2006.
[7] Z. Shuang, P. Yong-Shik, L. Jensen, L. Xinchao, Z. Weili, and Z. Xiang, "Negative refractive index in chiral metamaterials," *Phys. Rev. Lett*., vol. 102, pp. 023901-023908, 2009.
[8] F. Dincer, C. Sabah, M. Karaaslan, E. Unal, M. Bakir, and U. Erdiven, "Asymmetric transmission of linearly polarized waves and dynamically wave rotation using chiral metamaterial," *Progress In Electromagnetics Research*, vol. 140, pp. 227-239, 2013.
[9] K. Delihacioglu and S. Uckun, "Power reflection and transmission coefficients for meander L line polarizers with chiral slab," *ETRI Journal*, vol. 25, no. 1, pp. 41-48, 2003.
[10] D. Zarifi, M. Soleimani, and V. Nayyeri, "Dual- and multiband chiral metamaterial structures with strong optical activity and negative refraction," *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 334-337, 2012.
[11] C. Sabah and H. G. Roskos, "Design of a terahertz polarization rotator based on a periodic sequence of chiral-metamaterial and dielectric slabs," *Progress In Electromagnetics Research*, vol. 124, pp. 301-314, 2012.
[12] C. Sabah, "Multiband metamaterials based on multiple concentric open-ring resonators topology," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 19, pp. 8500808, 2013.
[13] F. Karadag and M. Karaaslan, "Artificial diamagnetic metamaterial loaded sub-wavelength waveguide with reduced bianisotropic effect: Design, fabrication and characterization," *Optoelectronics and Advanced Materials Rapid Communications*, vol. 3, no. 6, pp. 574-7, 2009.
[14] J. Zhou, J. Dong, B. Wang, T. Koschny, M. Kafesaki, and C. M. Soukoulis, "Negative refractive index due to chirality," *Physical Review B*, vol. 79, pp. 121104, 2009.
[15] M. Kuwata-Gonokami, et al., "Giant optical activity in quasi-two-dimensional planar nanostructures," *Phys. Rev. Lett*., vol. 95, 227401, 2005.
[16] K. Hannam, D. A. Powell, I. V. Shadrivov, and Y. S. Kivshar, "Broadband chiral metamaterials with large optical activity," *Phys. Rev. B*, vol. 89, 125105, 2014.
[17] T. G. Mackay and A. Lakhtakia, "Plane waves with negative phase velocity in Faraday chiral mediums," *Phys. Rev. E*, vol. 69, 026602, 2004.
[18] N. L. Tsitsas, A. Lakhtakia, and D. J. Frantzeskakis, "Vector solitons in nonlinear isotropic chiral metamaterials," *J. Phys.*, vol. 44, 435203, 2011.
[19] A. Lakhtakia, "Beltrami fields in chiral media," *World Scientific*, Singapore, 1994.
[20] C. Athanasiadis and N. L. Tsitsas, "Radiation relations for electromagnetic excitation of a layered chiral medium by an interior dipole," *J. Math. Phys.*, vol. 49, 013510, 2008.
[21] B. Wang, T. Koschny, and C. M. Soukoulis, "Wide-angle and polarization-independent chiral metamaterial absorber," *Physical Review B*, vol. 80, pp. 033108-4, 2009.
[22] R. Marques, L. Jelinek, and F. Mesa, "Negative refraction from balanced quasi-planar chiral inclusions," *Microw. Opt. Technol. Lett*., vol. 49, pp. 2606-9, 2007.
[23] F Dincer, M Karaaslan, O Akgol, E Unal, E Demirel, and C Sabah, "New generation planar chiral metamaterials with small and constant chirality over a certain frequency band," *Modern Physics Letters B*, vol. 29, no. 01, pp. 1450257, 2015.
[24] J. D. Baena, L. Jelinek, and R. Marques, "Towards a systematic design of isotropic bulk magnetic metamaterials using the cubic point groups of symmetry," *Phys. Rev. B.*, vol. 76, pp. 245115, 2007.
[25] C. Akturk, M. Karaaslan, E. Ozdemir, V. Ozkaner, F. Dincer, M. Bakir, and Z. Ozer, "Chiral metamaterial design using optimized pixelated inclusions with genetic algorithm," *Optical Engineering*, vol. 54 no. 3, pp. 035106-035106, 2015.
[26] R. Zhao, T. Koschny, and C. M. Soukoulis, "Chiral metamaterials: Retrieval of the effective parameters with and without substrate," *Optics Express*, vol. 18, no. 14, pp. 14553-67, 2010.
[27] I. Comez, M. Karaaslan, F. Dincer, F. Karadag, and C. Sabah, "Systematic analysis on the optical properties of chiral metamaterial slab for microwave polarization control," *Applied Computational Electromagnetics Society Journal*, vol. 30, no. 5, pp. 478-487, 2015.
[28] Z. Wu, B. Q. Zhang, and S. Zhong, "A double-layer chiral metamaterial with negative," *J. Electromagn. Waves Appl*., vol. 24, no. 7, pp. 983-992, 2010.
[29] F. Dincer, M. Karaaslan, E. Unal, O. Akgol, and C. Sabah, "Flexible chiral metamaterials with dynamically optical activity and high negative refractive index," *Modern Physics Letters B*, vol. 29, no. 18, pp. 1550087, 2015.
[30] M. C. K. Wiltshire, J. B. Pendry, and J. V. Hajnal, "Chiral swiss rolls show a negative refractive index," *Journal of Physics: Condensed Matter*, vol.

21, pp. 292201-5, 2009.
[31] Z. Li, R. Zhao, T. Koschny, M. Kafesaki, K. B. Alici, E. Colak, H. Caglayan, E. Ozbay, and C. M. Soukoulis, "Chiral metamaterials with negative refractive index based on four "U" split ring resonators," *Applied Physics Letters*, vol. 97, pp. 081901-3, 2010.
[32] F. Dincer, M. Karaaslan, O. Akgol, E. Unal, and C. Sabah, "Dynamic and tunable chiral metamaterials with wideband constant chirality over a certain frequency band," *Optik-International Journal for Light and Electron Optics*, vol. 126, no. 24, pp. 4808-4812, 2015.
[33] R. Zhao, L. Zhang, J. Zhou, T. Koschny, and C. M. Soukoulis, "Conjugated gammadion chiral metamaterial with uniaxial optical activity and negative refractive index," *Physical Review B*, vol. 83, pp. 035105, 2011.
[34] Z. Li, K. B. Alici, E. Colak, and E. Ozbay, "Complementary chiral metamaterials with giant optical activity and negative refractive index," *Applied Physics Letters*, vol. 98, pp. 161907-3, 2011.
[35] C. Sabah, F. Dincer, M. Karaaslan, O. Akgol, E. Demirel, and E. Unal, "New-generation chiral metamaterials based on rectangular split ring resonators with small and constant chirality over a certain frequency band," *IEEE Trans. Antennas Propagat.*, vol. 62, pp. 5745-5751, 2014.
[36] F. Dincer, M. Karaaslan, E. Unal, O. Akgol, and C. Sabah, "Chiral metamaterial structures with strong optical activity and their applications," *Optical Engineering*, vol. 53, 107101, 2014.

İbrahim Comez received the M.S. degree in Physics Department from the University of Cukurova, Adana, Turkey. He is currently studying Metamaterials and Chiral Media as a Ph.D. student. His research interests are metamaterials, solid state physics, cihral, and anisotropic media.



Muharrem Karaaslan received the Ph.D. degree in Physics Department from the University of Cukurova, Adana, Turkey, in 2009. He is the co-author of about 70 scientific contributions published in journals and conference proceedings. His research interest are applications of metamaterials, analysis and synthesis of antennas, and waveguides.

Faruk Karadag received the Ph.D. degree in Physics Department from the University of Çukurova, Adana, Turkey, in 2002. He is the co-author of about 25 scientific contributions published in international journals and conference proceedings. His research interest includes the applications of metamaterials, solid state physics, and anisotropic media.

Furkan Dincer received the B.Sc., M.Sc., and Ph.D. degrees in Electrical and Electronics Engineering from Sutcu Imam, Yuzuncu Yil and Mustafa Kemal Universities, Turkey. His research interests are related with the functional microwave structures and metamaterials.