

Scattering characteristics of one- and two-turn square spiral FSSs on chiral slab

K. DELİHACIOĞLU*, S. UÇKUN, T. EGE

University of Gaziantep Electrical and Electronics Engineering Department 27310 Gaziantep, Turkey

In this paper, the scattering characteristics of electromagnetic waves from Frequency Selective Surfaces (FSSs) composed of a new one- and two-turn square spiral shaped doubly periodic conductors on a chiral slab are discussed. An improved subsectional current model is proposed to approximate the induced current. The current functions in the straight sections are chosen to be overlapping Piecewise sinusoidal (PWS) while at the corners, the PWS functions are divided into two equal parts; one is in the vertical segment and the other in the horizontal segment. The co- and cross-polarized reflection and transmission coefficients are plotted with respect to frequency of the incident wave. The convergence of the numerical computations is obtained by increasing the number of Floquet modes until there is only little change in the results.

(Received February 21, 2007; accepted August 22, 2007)

Keywords: FSSs, Chiral, One-turn square spiral, Two-turn square spiral, Moment methods, Piecewise sinusoidal

1. Introduction

In the last couple decades, many numerical and experimental studies have been carried out related with chiral materials and Frequency Selective Surfaces (FSS) on dielectric slab [1, 2]. In microwave and millimeter wave regimes, chiral materials can be used to build novel devices and structures such as, polarization transformers [3], microstrip antennas [4], anti-reflection coatings [5], periodic achiral-chiral interfaces [6], chirowaveguides [7], absorbing material [8], chiro-phase shifter [9] and the reduction of target radar cross-section RCS [10] and Frequency Selective Surface (FSS) applications on a chiral slab [11].

FSSs, made of doubly periodic conductors on a chiral slab, acts as electromagnetic filters or polarization converter. They are typically used in dichroic reflectors [12] and radomes [13]. Ideally, at some frequencies an FSS completely reflects an incident plane wave, while at other frequencies the FSS is completely transparent to the incident plane wave. When designing a chiral FSS to achieve a certain spectral response, many parameters can be adjusted, such as chirality admittance, the dimensions of periodicity, element shape, dielectric thickness and relative permittivity. The dielectric or chiral slab support affects the transmission response by lowering the resonant frequency and altering the bandwidths in the arrays of three concentric rings [14]. Previously we have investigated L-shaped FSS elements on chiral slab, for a TE incident plane wave [15]. The reflection and transmission coefficients of two new FSSs which are made of L-shaped and one-turn spiral shaped conducting strips on a dielectric slab were analyzed for the first time in [16]. The two-turn square spiral FSS on a dielectric slab was also studied for the first time in [17]. In this study, the co- and cross-polarized reflection and transmission coefficients of a new one- and two-turn square spiral shaped FSS structures on a chiral slab are investigated as shown in Fig. 1(b) and 1(c). The improvement is the

replacement of the dielectric slab with a chiral one. The co- and cross-polarized reflection and transmission coefficients are analyzed for two types of square spiral FSS elements mounted on a chiral slab. Numerical results illustrate that the chirality admittance of the slab causes a significant polarization rotation of the scattered fields.

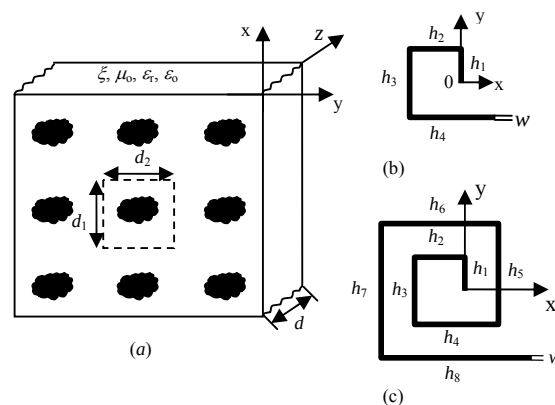


Fig. 1.(a) FSS composed of infinite doubly periodic arbitrary conductors printed on a chiral slab (b) One-turn square spiral FSS element (c) Two-turn square spiral FSS element.

2. Theory

Chiral media are known as optically active media. The special property of optically active media is that the polarization plane of linearly polarized electromagnetic wave is rotated as wave passes through the medium [1, 86]. An electric or magnetic incident field simultaneously produces both electric and magnetic polarization that exhibits magneto-electric coupling. The displacement vector D and the magnetic field H inside a chiral medium depends on both E and B . Chiral medium is characterized by the following constitutive relations for electromagnetic fields with $e^{j\omega t}$ time harmonic dependence, [1]

$$\mathbf{D} = \varepsilon \mathbf{E} - j\xi \mathbf{B} \quad (1)$$

$$\mathbf{H} = \frac{1}{\mu_o} \mathbf{B} - j\xi \mathbf{E} \quad (2)$$

where ε , μ_o , and ξ , are real values for lossless media and represent permittivity, permeability, and chirality admittance of the chiral medium, respectively. The magnitude of ξ is a measure of the degree of chirality while the sign of ξ specifies the medium handedness. When $\xi > 0$, the medium is a right handed and the sense of polarization is right handed; when $\xi < 0$, the medium is left handed and the sense of polarization is left handed; and when $\xi = 0$, the medium reduces to ordinary dielectric and there is no optical activity [18].

Inserting the constitutive relations into the source free Maxwell equations, the chiral wave equation for the electric and magnetic fields can be obtained as

$$\nabla \times \nabla \times \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix} - 2\omega\mu_o\xi\nabla \times \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix} - \omega^2\mu_o\varepsilon \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix} = 0 \quad (3)$$

The solution to the chiral wave equation consists of two partial waves, which are right hand circularly (RCP) and left hand circularly polarized (LCP) waves, whose propagation constants are given as respectively. Here k_R corresponds to a RCP and k_L to a LCP wave. When $\xi = 0$, $k_R = k_L = \omega\sqrt{\varepsilon\mu_o} = k$. The two characteristic waves propagate at different velocities in a medium, thereby causing birefringence.

$$k_R = \omega\mu_o\xi + \sqrt{\omega^2\mu_o^2\xi^2 + k^2} \quad (4)$$

$$k_L = -\omega\mu_o\xi + \sqrt{\omega^2\mu_o^2\xi^2 + k^2} \quad (5)$$

One- and two-turn square spiral FSS elements are assumed to be infinitely thin and a perfectly conducting. The periodicities (d_1 and d_2), dielectric thickness (d), and medium parameters are displayed in Fig. 1(a). The lengths (h_n) and the width (w) of one- and two-turn square spiral FSS structure are shown in Fig. 1(b) and 1(c). The FSS arrays of square spirals are illuminated by an arbitrary polarization of transverse electric (TE) plane wave incident from the free space region. Due to the periodicity of the problem, the fields are expanded into Floquet modes [19] in the air and chiral regions. The incident electric field induces currents on FSS elements which in turn are scattered in the forward and backward directions. The detailed expressions for the incident, reflected and transmitted electric fields, in air and chiral slab, can be found in [20]. The Moment Method [21] is employed by expressing the current induced on the scatterers in terms of Piecewise Sinusoidal (PWS) [22] functions. The amplitude of the scattered fields can be expressed in terms of the induced current density on the conducting elements of square spirals by using the appropriate boundary conditions as given in [16]. The Electric Field Integral

Equation (EFIE) is obtained by imposing the total electric field to be zero over the conducting area of a single periodic unit cell. Substituting basis functions into the EFIE and then integrating it over a unit cell using the Galerkin method, the EFIE is finally transformed into a complex matrix equation. The dimension of the matrix is equal to the number of basis functions used. The unknown current coefficients are then computed using matrix inversion techniques. Having computed the current coefficients, the co- and cross-polarized reflected and transmitted waves can readily be found. Four different coefficients are calculated, when a plane wave is incident on a chiral medium; R_{co} and R_{cr} are the co- and cross-polarizations of the reflected wave; T_{co} and T_{cr} are the co- and cross-polarizations of the transmitted wave, respectively. The cross-polarization for TE incidence corresponds to a transverse magnetic (TM) wave.

3. Numerical results

The numerical results of one- and two-turn square spiral FSSs backed by chiral slab has been presented for TE incident plane wave. The numerical results of one-turn square spiral FSS is illustrated in Fig. 2 and 3. The length of the first segment is $h_1 = 0.16$ cm and the other lengths can be found from the relation $h_n = n \cdot h_1$ for $n = 2, 3, 4$. The width is chosen as one tenth of the first length ($w = h_1/10 = 0.016$ cm). The inter-element spacing d_1 and d_2 are equal to 0.7 cm. The total length of the spiral is approximated by 25 PWS current function. Floquet modes used in the computations are $(2M+1)^2$, where M is equal to 12. The periodic cells are arranged in square lattice. The value of chirality admittance is varied within the range

given by the inequality $|\xi| \leq \sqrt{\varepsilon_r \varepsilon_o / \mu_o}$ [23]. The co- and cross-polarized reflection and transmission coefficients are plotted against frequency of incident wave at normal incidence for different values of chirality admittance and oblique incidences.

Fig. 2 illustrates the variation of chirality admittances at normal incidence of TE wave for one-turn square spiral FSS on a chiral slab. In Fig. 2a, at low chirality admittance (dashed curve) only one resonant frequency is seen, while at high chirality admittances two resonant frequencies exist. In the frequency region of 1–12.5 GHz, the

magnitude of R_{co}^{TE} increases, as the chirality admittance increases. The two peaks are approximately equal in terms of bandwidth for $\xi = 0.002$. The bandwidth of the first peak is very narrow than the second one for $\xi = 0.003$. As shown

in Fig. 2b, the magnitude of T_{cr}^{TM} is less than -20 dB for an achiral case ($\xi = 0$). At low chirality $\xi = 0.001$, no polarization conversion is observed. There are two anti-resonant peaks for $\xi = 0.002$ at 18 and 22 GHz. When $\xi = 0.003$, there is one anti-resonant frequency at about 15 GHz. The magnitude of T_{co}^{TE} reduces up to 19.5 GHz as the value of chirality admittance is varied from 0 to 0.002, as illustrated in Fig. 2c. The magnitude is also decreasing up to 13.5 GHz for $\xi = 0.003$ value. Some extra peaks are

seen for $\xi=0.003$ in the frequency region of 13.5-25 GHz. The magnitude of the last peak is close to unity. The magnitude of the cross-polarized reflection coefficient is very low, that is why it is not plotted.

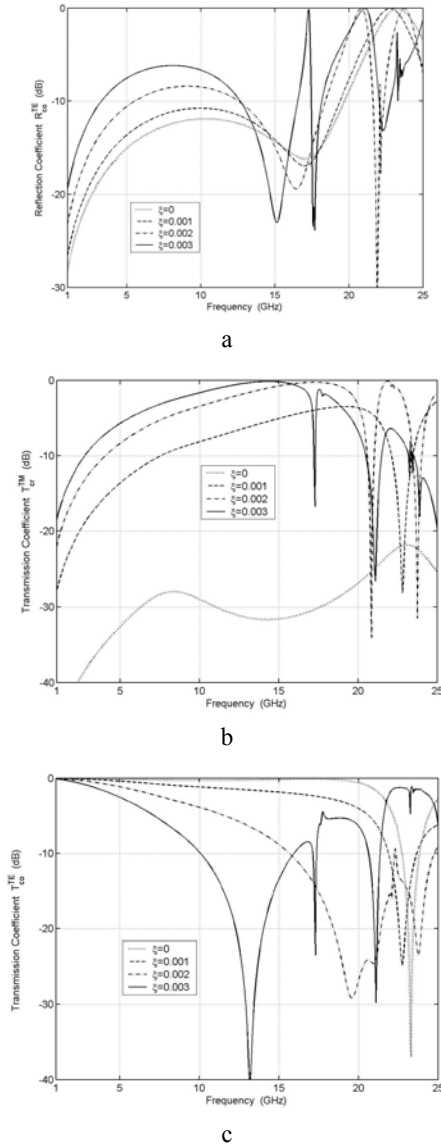


Fig. 2. Reflection and transmission coefficients of one-turn square spiral FSS on a chiral slab at different chirality admittances; TE incidence, $\theta=\phi=0^\circ$, $d=0.5$ cm, $\epsilon_r=1.6$, $w=0.016$ cm, $h_1=0.16$ cm, $h_n=n*h_1$ cm, $n=2,3,4$, $d_1=d_2=0.7$ cm, (a) Reflection Coefficient R_{co}^{TE} , (b) Transmission Coefficient T_{cr}^{TM} , (c) Transmission Coefficient T_{co}^{TE} .

The reflection and transmission coefficients of one-turn square spiral FSSs for oblique incidence variations are shown in Fig. 3. The resonant frequency occurs at around 23 GHz at normal incidence TE wave as shown in Fig. 3a. For an oblique incidence of 30° and 45° , more than one resonant frequency has been seen. The resonant frequency

shifts to lower frequency end as the angel of incidence increases. No anti-resonance is observed for obliquely incident TE wave, as can be depicted in Fig. 3b. There is a

slight decrease in the magnitude of T_{co}^{TE} up to 19 GHz, as illustrated in Fig. 3c.

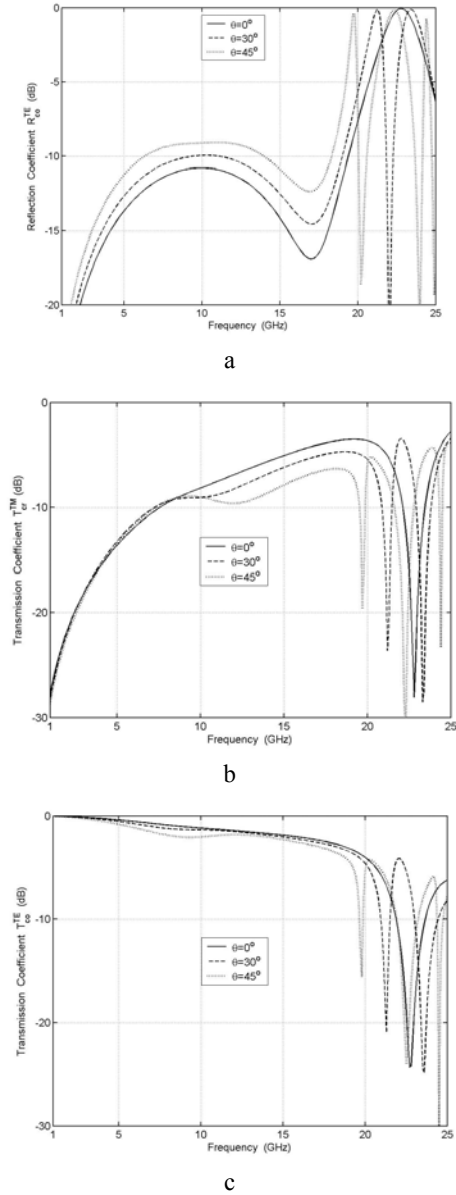


Fig. 3. Reflection and transmission coefficients of one-turn square spiral FSS on a chiral slab at different incident angles; TE incidence, $\phi=0^\circ$, $\xi=0.001$ S, $d=0.5$ cm, $\epsilon_r=1.6$, $w=0.016$ cm, $h_1=0.16$ cm, $h_n=n*h_1$ cm, $n=2,3,4$, $d_1=d_2=0.7$ cm, (a) Reflection Coefficient R_{co}^{TE} , (b) Transmission Coefficient T_{cr}^{TM} , (c) Transmission Coefficient T_{co}^{TE} .

The numerical results of FSSs comprised of periodic arrays of two-turn square spiral shaped conductors in the

case of TE incident wave are presented in Fig. 4 and 5. The length of the first segment is $h_1=0.1$ cm. The lengths of the other segments can be found from the relation $h_n=n*h_1$ for $n=2,3,\dots,8$. The overall length of the spiral is 3.6 cm. The width of the two-turn square spiral was chosen as $h_1/10$. The inter-element spacing d_1 and d_2 are 0.83 cm. The periodic cells are arranged in square dimension. The number of basis functions required to estimate the unknown current coefficients is taken as 56. The number of included Floquet modes is still $(2M+1)2$, where M is equal to 15.

Fig. 4 shows the effect of chirality admittance variations at normal incidence of TE wave. In Fig. 4a, it is seen that, two resonant frequencies exist for different values of ξ . The magnitude of R_{co}^{TE} increases for increasing values of ξ in the region of frequency from 1 to 12 GHz. In the frequency region of 11.5–13.5 GHz no change observed in the reflection curves. There is a small shift in the first resonant frequency, which happens at around 15.5 GHz. The bandwidth of second resonance is wider than the first one for $\xi=0$ and $\xi=0.001$ values. For

$\xi=0.0018$ the magnitude of T_{cr}^{TM} is seen to be unity at three different frequencies as shown in Fig. 4b. There is no polarization conversion (anti-resonance) for other chirality admittances and the magnitude of R_{co}^{TE} is very low at the anti-resonant frequency. In the frequency region of 1–15 GHz, the magnitude of T_{co}^{TE} decreases for increasing values of ξ as illustrated in Fig. 4c. The magnitude of R_{cr}^{TM} is very low in the frequency region of 1–13 GHz and it varies between -10 to -60 dB in the 15–25 GHz as can be depicted in Fig. 4d.

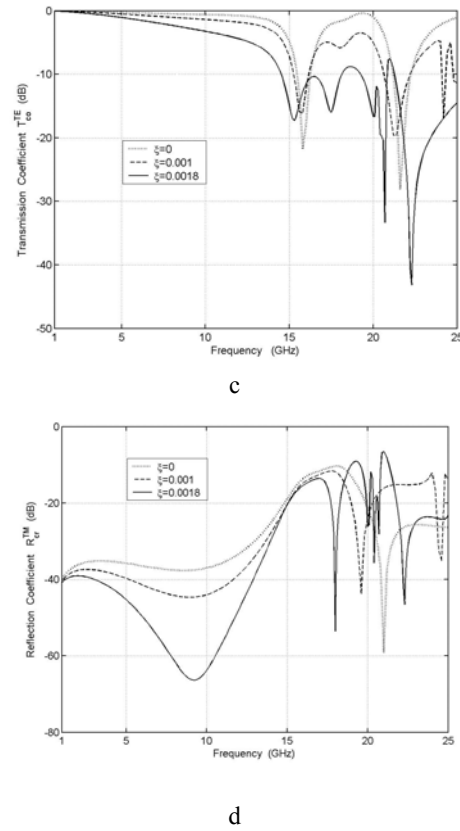
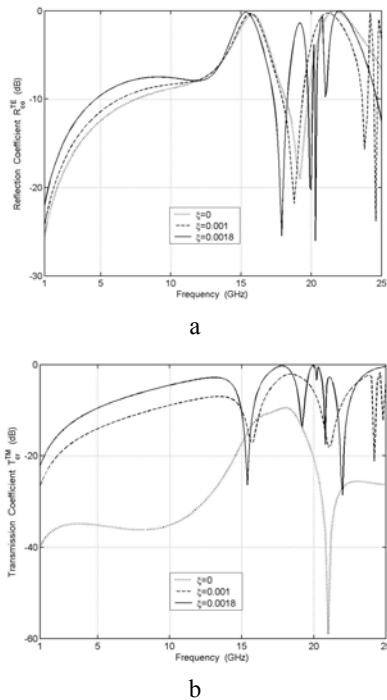


Fig. 4. Reflection and transmission coefficients of two-turn square spiral FSS on a chiral slab at different chirality admittances; TE incidence, $\theta=\phi=0^\circ$, $d=0.5$ cm, $\epsilon_r=1.6$, $w=0.01$ cm, $h_1=0.1$ cm, $h_n=n*h_1$ cm, $n=2,3,\dots,8$, $d_1=d_2=0.83$ cm, (a) Reflection Coefficient R_{co}^{TE} , (b) Transmission Coefficient T_{cr}^{TM} , (c) Transmission Coefficient T_{co}^{TE} , (d) Reflection Coefficient R_{cr}^{TM} .

The reflection and transmission coefficients of two-turn square spiral FSSs for oblique incidence variations are shown in Fig. 5. There is a small shift in resonant frequency which happens at around 16.5 GHz as illustrated in Fig. 5a. There is a gradual increase in magnitude of R_{co}^{TE} at oblique incidence variations up to resonant frequency. However, for an angle of 45° , the second resonant frequency disappears. No anti-resonance is observed for oblique incidence as shown in Fig. 5b. As illustrated in Fig. 5c, there is a small decrease in the magnitude of T_{co}^{TE} in the frequency range of 1–15 GHz and multiple peaks occur at higher frequencies.

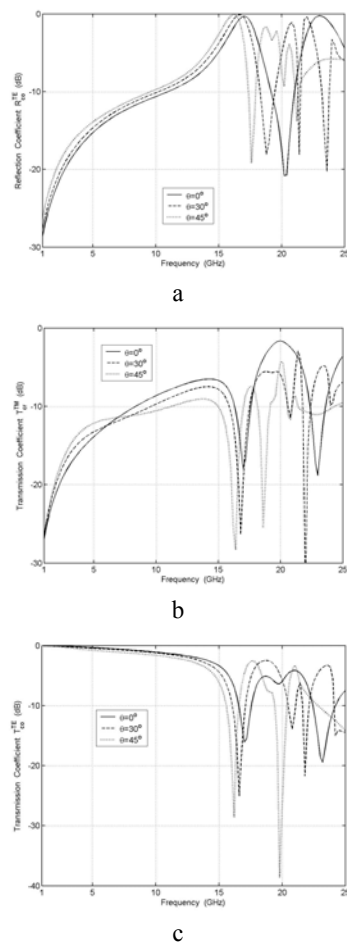


Fig. 5. Reflection and transmission coefficients of two-turn square spiral FSS on a chiral slab at different incident angles; TE incidence, $\phi=0^\circ$, $\xi=0.001$ S, $d=0.5$ cm, $\epsilon_r=1.2$, $w=0.01$ cm, $h_1=0.1$ cm, $h_n=n \cdot h_1$ cm, $n=2,3,\dots,8$, $d_1=d_2=0.83$ cm, (a) Reflection Coefficient R_{CO}^{TE} , (b) Transmission Coefficient T_{cr}^{TM} , (c) Transmission Coefficient T_{CO}^{TE} .

4. Conclusions

In this study, new FSSs, which are one- and two-turn square spiral shaped FSS elements, mounted on a chiral slab are addressed. An improved subsectional current approximation model of PWS basis functions are proposed to expand the induced current. The co- and cross-polarized reflection and transmission coefficients are plotted with respect to frequency for the variation of chirality admittance and oblique incident angle. Numerical results illustrate that the chirality admittance of the slab causes a significant polarization rotation of the scattered fields. At low chirality admittances, there is no polarization conversion. As the chirality admittance increases more resonances are observed since at high chirality admittance one wavenumber becomes high. Anti-resonances, which correspond to mode conversion, are seen in cross-polarized transmission. This feature can have potential applications in the design of novel devices such as TE to TM converters. In the reflection characteristics of FSS elements on chiral slab, the resonances are separated

with a deep minimum which shows a very good isolation between the resonances. As the oblique angle increases multiple resonances appear for one-turn square spiral FSSs. The first resonant frequency shifts to the lower end, and the second resonance disappears at oblique angle of incidence for two-turn square spiral but no anti-resonance is observed.

References

- [1] I. V. Lindell, A. H. Sihvola, S. A. Tretyakov, A. J. Viitanen, *Electromagnetic Waves in Chiral and Bi-Isotropic Media*, Norwood, MA (1994).
- [2] B. A. Munk, *Frequency Selective Surfaces: Theory and Design*. Wiley, New York (2000).
- [3] A. J. Viitanen, I. V. Lindell, *IEEE Trans. AP*, **46**, 9, 1395 (1998).
- [4] D. M. Pozar, *IEEE Trans. AP*, **40**, 1260 (1992).
- [5] H. Cory, I. Rosenhouse, *Electron. Lett.* **28**, 1051 (1992).
- [6] A. Lakhtakia, V.K. Varadan, V.V. Varadan, *J. Opt. Soc. Am. A*, **11**, 1675 (1989).
- [7] P. Pelet, N. Engheta, *IEEE Trans. AP* **38**, 1, 90 (1990).
- [8] A. M. M. Allam, 17th National Radio Science Conference, Minufiya University, Egypt, (2000).
- [9] M. M. I. Saadoun, N. Engheta, *IEEE Trans. Microw. Theory & Tech.* **42**, 9, 1690 (1994).
- [10] D. L. Jaggard, N. Engheta, *Electron. Lett.* **25**, 3, 173 (1989).
- [11] A. O. Koca, *Analysis of Frequency Selective Surfaces on Chiral Slab*. PhD Dissertation University of Gaziantep (1997).
- [12] Y. Rahmat-Samii, A. N. Tulinseff, *IEEE Trans. Antennas Propagat.* **41**, 4, 476 (1993).
- [13] R. S. Chu, *IEEE Trans. Antennas Propagat.*, **39**, 2, 164 (1991).
- [14] S. Uçkun, T. Ege, *J. Optoelectron. Adv. Mater.* **8**(1), 345 (2006).
- [15] K. Delihacıoğlu, S. Uçkun, T. Ege, *J. Optoelectron. Adv. Mater.* **8**(4), 1398 (2006).
- [16] K. Delihacıoğlu, S. Uçkun, T. Ege, *Electrical Engineering* **89**, 3, 177, (2007)
- [17] K. Delihacıoğlu, S. Uçkun, T. Ege, *Frequency selective surfaces comprised of periodic arrays of two-turn square spiral shaped conductors*, (AEÜ) *Int. J. Electron. Commun.* **61**(3), 182–185, (2007)
- [18] S. Bassiri, C.H. Papas, N. Engheta, *J. Opt. Soc. Am. A* **5**, 1450 (1988).
- [19] N. Amitay, V. Galindo, C. P. Wu, *Theory and analysis of phased array antennas*. Wiley-Interscience, New York (1972).
- [20] K. Delihacıoğlu, S. Uçkun *ETRI Journal* **25**(1), 41 (2003).
- [21] R. F. Harrington, *Field computation by moment methods*: MacMillan, New York (1968).
- [22] H. Nakano, *Helical and Spiral Antennas: A Numerical Approach*: Wiley, New York (1987).
- [23] N. Engheta, D. L. Jaggard, *IEEE AP-S Newslett.* **30**, 6 (1988).

*Corresponding author: kemal@gantep.edu.tr