Omega-shaped metamaterial lens design for microstrip patch antenna performance optimization at 12 GHz

Bilal TÜTÜNCÜ[1] and Hamid TORPİ[2]

[1, 2] Department of Electronic and Communication Engineering, Faculty of Electric and Electronic, Yıldız Technical University, İstanbul, Turkey
bilal1334@gmail.com [1], hamidtorpi@gmail.com [2]

Abstract

Generally high antenna gain and directivity are required for satellite based communication systems. This study proposes improving the directivity and gain of microstrip patch antenna at Ku-Band (12 GHz). In order to optimize these parameters, Omega-Shaped metamaterial (OSM) is designed as a flat lens in front of Microstrip Patch Antenna (MPA) that tuned to 12 GHz resonance frequency. Computer simulation technology Microwave Studio (CST MWS) was used for modeling and simulation. The permeability and permittivity of the designed metamaterial are extracted from the S parameters by using Matlab.

1. Introduction

Metamaterials are a new type of materials that is not found in nature but could be artificially designed. If both the permeability (μ) and the permittivity (ϵ) parameters are set negative at the same frequency so that the electromagnetic wave is inversely refracted and inverse refraction results in focusing [1]. These materials are called double negative materials (DNG) or metamaterial. If the electromagnetic wave can be focused instead of transmitting omnidirectional, the directivity and so the gain will be increased [1]. For that reason in order to improve antenna performance; metamaterial structures are used on the antenna substrate [2, 3], on direct antenna geometry [4, 5] or as a lens (superstrate) [6, 7].

In this study, Omega-Shaped metamaterial (OSM) was used as a lens to optimize reference antenna performance at Ku band (12 GHz). Rectangular Microstrip Patch Antenna (MPA) was used as reference antenna and fed by microstrip line. Using the relevant formulas and with a few experiments at CST the operating frequency of Rectangular MPA was set to 12 GHz. For impedance matching, two adjacent parallel slits were extended until the desired resonance input impedance value (50 Ω) was achieved [8]. Modeling, scaling and simulation were done by CST MWS program. The "robust method" was utilized to extract the effective permittivity and permeability from S parameters for to analyze whether the metamaterial structure was DNG at 12 GHz [9].

2. Reference antenna (Rectangular MPA) design

The reference antenna (rectangular MPA) was modeled as being etched through a copper-coated dielectric substrate Rogers RO4350B from Rogers Corp. (www.rogerscorp.com) by using CST MWS. The relative dielectric constant is 3.48, the dielectric loss tangent is 0.0037 and the thickness is 0.762 mm. The width (*W*) and length (*L*) of the substrate were taken as twice the size of patch. The thickness of coppers was taken 0.035 mm. Patch width (*Wp*), patch length (*Lp*) and the effective dielectric constant ϵ_{reff} of the rectangular MPA were calculated by equations (1), (2), (3) and (4) [8].

$$Wp = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r+1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}} \quad (1)$$

$$Lp = \frac{\lambda}{2} - \Delta L = \frac{1}{2f_r\sqrt{\epsilon_{reff}}\sqrt{\mu_0\epsilon_0}} - 2\Delta L \quad (2)$$

And normalized extension ΔL is given by;

$$\Delta L = 0.412\, h\, \frac{(\epsilon_{reff}+0.3)\,(\frac{Wp}{h}+0.264)}{(\epsilon_{reff}-0.258)\,(\frac{Wp}{h}+0.8)} \quad (3)$$

Effective dielectric constant for $Wp / h > 1$ is given by;

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[1+12\frac{h}{Wp}\right]^{-1/2} \quad (4)$$

For substrate thickness $h = 0.762$ mm, free space light velocity $v0$ = 3.18 m/sn and resonance frequency fr = 12 GHz; the patch width (*Wp*) was calculated as 8.35 mm and the patch length (*Lp*) as 6.38 mm.

2.1. MPA feed line and impedance matching

The width of the feed line "*wf*" was calculated as 1.7 mm by the "calculate impedance" feature on the "macros" menu of the CST MWS for to set the input impedance value to 50 Ω. There are several different methods for MPA impedance matching [8]. We used the two parallel slit model in this study. Equation (5) that obtained from [10] was used to find "*y*" the feed line extension of the patch.

$$y = 10^{-4}\{0.001699\epsilon_r^{\,7} + 0.13761\epsilon_r^{\,6} - 6.1783\epsilon_r^{\,5} + 93.187\epsilon_r^{\,4} - 682.69\epsilon_r^{\,3} + 2561.9\epsilon_r^{\,2} - 4043\epsilon_r + 6697\} \quad (5)$$

From equation (5) "*y*" was calculated 1.91 mm and gap of parallel slit was taken as half of wf ($g = wf / 2 = 0.85$ mm) [8]. Reference MPA antenna shape is shown in Fig. 1.

To excite the rectangular MPA, waveguide port that is placed just below the feed line, was used. "Macros" component of CST Studio helps to set up the waveguide port size for planar transmission. Time domain solver was used for simulation on CST and S_{11} return loss curve was obtained as shown in Fig. 2.

The minimum of return loss is at - 25.21 dB and the center frequency at this value is 12.08 GHz. In order to see the increase in gain and directivity, far field patterns of MPA without metamaterial lens were obtained at 12 GHz and the gain and directivity were found respectively as 4.66 dB and 6.33 dBi (Fig. 3.) Also as seen in Fig. 2 the bandwidth is 380 MHz.

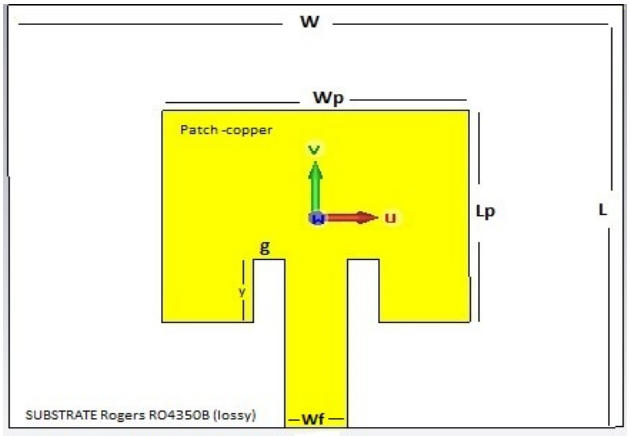

Fig. 1. The shape of the reference (rectangular) MPA

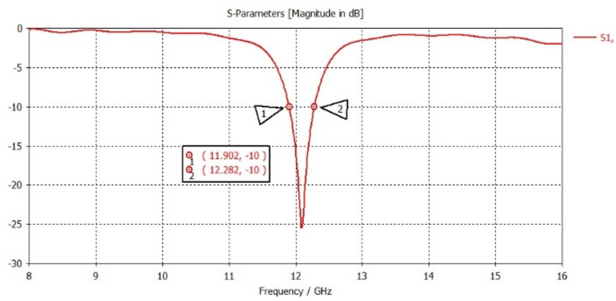

Fig. 2. Return loss (S11) curve of rectangular MPA

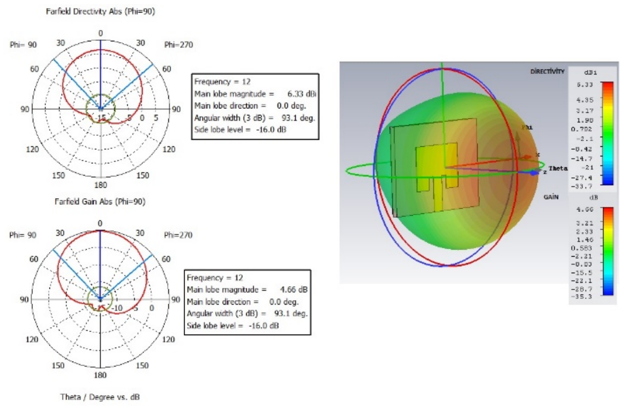

Fig. 3. Far field radiation patterns of rectangular MPA

3. OSM Unit dell design and Simulation setup

In this metamaterial unit cell, same substrate with predefined characteristics and dimensions was used. There is an omega structure on the front side of the substrate and on the backside there is symmetry of this structure with respect to the *X*-axis [11]. To set the resonance frequency to 12 GHz a "*k*" multiplier is defined on the parameter list on CST MWS. The inner radius of the OSM structure was set to 1.87 mm, the outer radius was set to 2.53 mm and the gap was set to 0.88 mm. The foot length of the unit cell is 5.6 mm. The shape of the designed OSM is shown in Fig. 4.

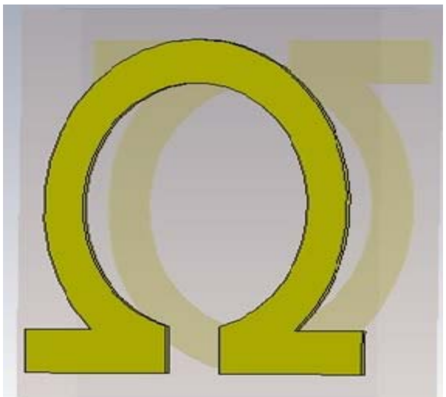

Fig. 4. OSM shape

For high frequency measurements, time domain method is considered the best method for simulations (since it was faster and more reliable), [11] so the measurements were made in this domain. The simulation setup was designed similar to the free space dielectric measurement setup. This free space model requires electromagnetic radiation in TEM mode [12]. For that reason, electromagnetic waves within the metamaterial were excited in TEM mode and the simulation setup is similar to the material placed in a waveguide environment that propagates in the Z-axis. The boundary conditions of the program was set so that the perfect electrical conductor (PEC) along the *X*-axis and the perfect magnetic conductor (PMC) along the *Y*-axis. Owing to these boundary conditions, metamaterial unit cell was excited by TEM waves. Also, for correct transmission and reflection calculation, two waveguide ports were placed at a distance of six times the perimeter lengths of the unit cell of the OSM.

3.1. Extraction of effective parameters of OSM

There are several different methods such as Nicholson-Ross-Weir (NRW) and Robust Method to obtain the media parameters (ε and μ) from the S parameters. In this study, we chose the "robust method" and encoded the formulas given by this method and obtained the results graphically by MATLAB. [9, 13].

S parameters of OSM were obtained from CST STUDIO and saved to an excel file. S_{11} and S_{21} values were taken for the relevant frequency values. By defining a matrix in Matlab; the primary column was defined as the frequency, the secondary column as S_{11}-real, the third column as S_{11}-imaginary, the fourth column as S_{21}-real, and the fifth column as S_{21}-imaginary. S values were placed in the columns of the excel file in the same order. The refractive index "n" and the impedance "z" were calculated with the help of the following equations [9, 13];

$$e^{jnkod} = \frac{S_{21}}{1 - S_{11}\frac{z-1}{z+1}} \quad (6)$$

$$n = \frac{1}{kod}\left(\left[ln\left(e^{jnkod}\right)\right]'' - i\left[ln\left(e^{jnkod}\right)\right]'\right) \quad (7)$$

$$z = \pm\sqrt{\frac{(1 + S_{11})^2 - {S_{21}}^2}{(1 - S_{11})^2 - {S_{21}}^2}} \quad (8)$$

The above equations (6), (7) and (8) were defined in MATLAB. In equation (7), (.') is real part and (.") refers imaginary part. "*k*" is the wave constant and "*d*" is substrate length. In the excel file of S parameters, the real and imaginary parts were recorded in separate columns. After all; ϵ_{eff} and μ_{eff} were computed from refractive index "n" and the impedance "z" [13] by following equations (9),(10) and also the ϵ_{eff} and μ_{eff} curves were drawn by MATLAB as shown at Fig. 5.

$$\epsilon_{eff} = \frac{n}{z} \quad (9)$$

$$\mu_{eff} = n.z \quad (10)$$

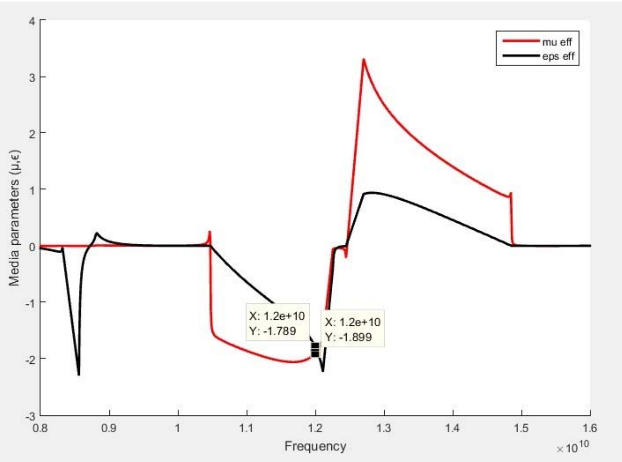

Fig. 5. Media parameters (μ, ϵ) of OSM

4. Use of OSM as lens

Metamaterial unit cell of OSM whose effective parameters are confirmed to be negative at 12 GHz, have to be converted into a periodic structure to use as a lens for a significant increase. Parametric studies was carried out in different dimensions and different quantities for the periodic structure to obtain optimal return loss and optimal radiation parameters and a 2×2 periodic structure at 12 mm×12 mm dimensions was noted optimal and used .

The metamaterial lens can be used as one or more layers. We used only one layer at a half-wave distance ($\lambda 0$ / 2 = 12.49 mm) to the reference antenna. Boundary conditions were set to "open (add space)" in all direction. This option is recommended for antenna problems and adds some extra space for far field calculation. It accepts "free space" behind their boundary plane that means the electromagnetic fields are absorbed at these boundaries with virtually no reflections (www.cst.com).

5. Results and Conclusions

2×2 periodic structure was used as a lens in front of the reference MPA and was simulated under the conditions that given in section 3 and the results were obtained. Fig. 6 shows the antenna layout and the far field directivity and gain at 12 GHz for OSM lens that loaded in front of the patch antenna. Enhancement and change on the gain, directivity and bandwidth were given in the Table 1. As can be seen, there is a 2.24 dBi increase in directivity and a 2.86 dB increase in gain. But as directivity increases, the bandwidth drops in the same order.

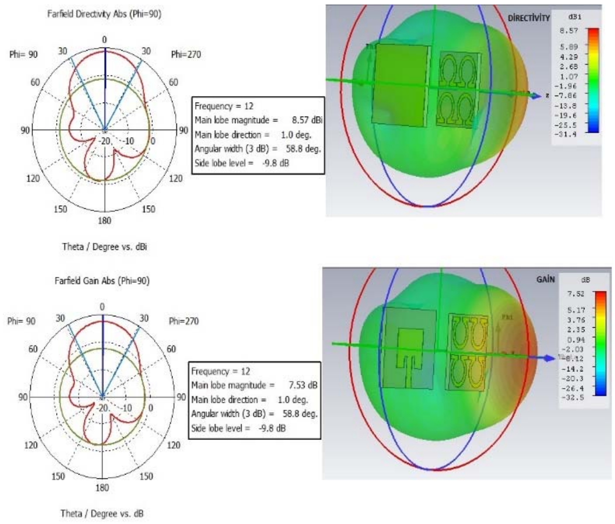

Fig. 6. Layout and radiation patterns of MPA with OSM

Table 1. Changes on the gain, directivity and bandwidth

	Directivity	Gain	Bandwidth
Only MPA	6.33 dBi	4.66 dB	380 MHz
MPA with OSM	8.57 dBi	7.53 dB	164 MHz
CHANGE	+2.24 dBi	+2.86 dB	-216 MHz

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