High Gain, Low Cost, Low Profile Transmitarray Antenna

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***Abstract*— This paper presents a double layer double ring unit cell for circular polarization transmitarrays. The proposed unit cell is evaluated with Rogers 4003 and FR4 substrates. Both models are applied to the design of a 13 x 13 elements transmitarray with a log spiral feeder at 10 GHz. Results show that the transmitarray achieves a directivity of 20.7 dBi and 20.0 dBi at the boresight, with Rogers 4003 and FR4 substrates, respectively, which is nearly 12 dB above the log spiral gain. The results of the proposed transmitarray are compared with a horn antenna and a toroidal plasma lens. When compared with solutions that present equivalent boresight directivity, the proposed transmitarray achieves significantly reduced profile, showing to be a high gain low cost, low profile and easy to prototype solution.**

Keywords*— *Transmitarray, antenna, metamaterials.

I. Introduction

High gain, high frequency and circular polarization are antenna characteristics generally obtained by complex and costly waveguide based solutions. A planar element combined with dielectric lenses may represent a cheaper solution for some applications [1]. In this context, a transmitarray is a promising alternative to high gain antennas, such as dielectric lenses, parabolic reflectors and phased arrays. A transmitarray is the combination of a feeding antenna and an array of unit cells, as shown in Fig. 1. The unit cell is composed of conventional materials, such as metals and dielectrics, arranged in a specific geometric pattern. The array of unit cells forms the electromagnetic metamaterial [2]. The ability to control the electromagnetic wave properties, with different metamaterial structures, had significant impact on the development of advanced microwave devices in the last years [3-8].

The transmitarray is basically a phase-shifting surface capable of focusing the electromagnetic (EM) wave by means of constructive interference, producing a high gain beam [9-11]. Each unit cell compensates the phase delay of the incident EM wave, according to its spatial position in the array, in such a way that the EM waves transmitted by each unit cell element are in phase, forming a coherent beam. Thus, ideally, the unit cells should be able to shift the phase of the transmitted EM wave in the full range of 2π radians.

The array of unit cells is placed in front of the feeding antenna. The phase of the EM wave which impinges each unit cell of the array is shifted by a specific value [11]. The unit cells are generally composed by resonant elements, typically inspired by metamaterials and frequency selective surfaces, and it works similarly to dielectric lenses [9]. Low profile, low mechanical complexity, compactness, no feeding network and simplicity in prototyping are some advantages of transmitarrays when compared to dielectric lenses, parabolic reflectors and phased arrays.

In this context, this paper presents a double layer double ring unit cell for circular polarization. The proposed unit cell is evaluated with low loss Rogers 4003 substrate and low cost FR4 substrate. Both models are then applied to a 13 x 13 transmitarray with a log spiral feeder at 10 GHz. Results show that the transmitarray achieves a gain of 20.7 dBi and 20.0 dBi at the boresight, with Rogers 4003 and FR4 substrates, respectively, which is nearly 12 dB above the log spiral gain. The results of the proposed transmitarray are compared with a horn antenna and a toroidal plasma lens. The comparison shows that, with equivalent gain, the transmitarray presents significantly reduced profile, showing to be a low cost and easy to prototype solution.

The rest of this paper is organized as follows: Section II shows the proposed unit cell. The developed transmitarray antenna is presented in Section III. Section IV compares the results and Section V brings the conclusions.

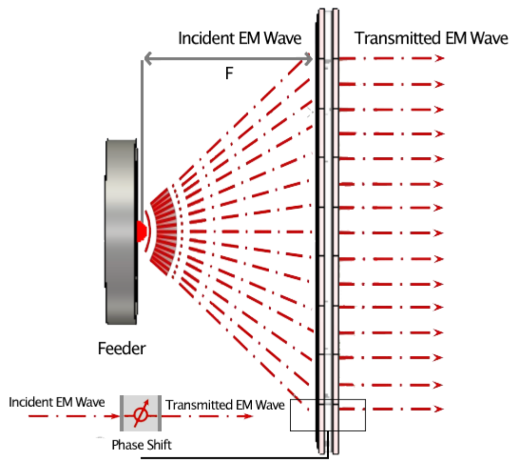

Fig. 1. Transmitarray working principle.

II. Proposed Unit Cell

The proposed unit cell is a double layer circularly polarized cell that applies the element rotation method for the phase shift. Each layer is composed by two concentric rings printed on a dielectric substrate. The inner ring is a split-ring and the rotation of the ring gap on the substrate plane controls the phase shift of the transmitted EM wave. The layers are separated by air and the printed rings are placed face to the face, to the internal side of the unit cell, as shown on Fig. 2. The unit cell has been modeled and simulated using finite-difference time-domain (FDTD) simulation algorithm.

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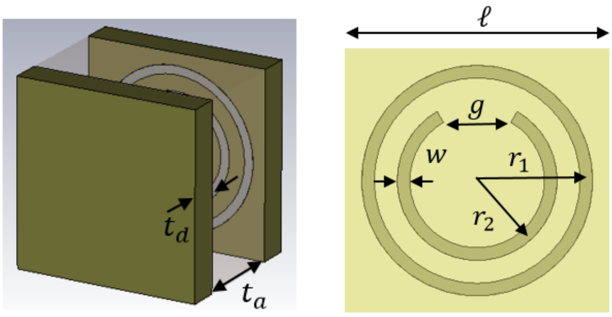


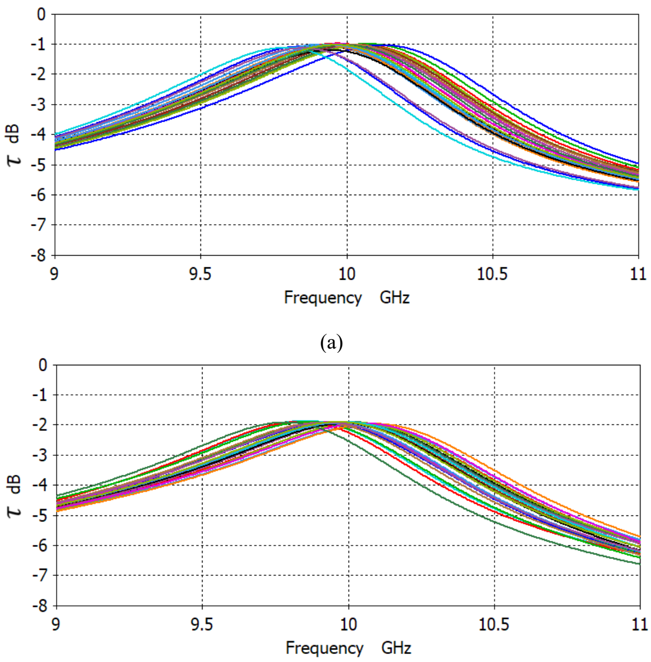
(a) (b)

Fig. 2. (a) Unit cell perspective view; (b) Detailed view of the double ring faces.

The unit cell behavior has been evaluated with Rogers 4003, low loss dielectric (loss tangent $\tan\delta = 0.0027$) and FR4, higher loss ($\tan\delta = 0.025$), low cost and easy to buy dielectric.

The dimensions of the proposed structure have been optimized at 10 GHz by using genetic algorithm, aiming to reduce the insertion loss. The resulting dimensions are presented in Table I. ℓ is the cell width, r_1 and r_2 are the outer and inner ring radius, respectively, w is the rings width, g is the inner ring gap, t_d is the dieletric thickness and t_a is the air layer thickness. The optimized cell width ℓ resulted in approximately 0.42λ at 10 GHz.

Fig. 3 presents the transmission coefficient τ versus frequency. Each curve refers to an inner ring rotation angle α. Fig. 4 presents the phase shift of the transmitted electromagnetic wave versus the rotation of inner split-ring on the substrate plane, given by angle α, obtained with Rogers 4003 and FR4 dielectrics.



(b)

Fig. 3. Transmission coefficient τ using (a) Rogers 4003; (b) FR4. Each curve refers to an inner ring rotation angle α.

TABLE I. Unit Cell Parameters

	ℓ		r_1	r_2	w	g	t_d	t_a	ϵ_r
Rogers 4003	12.5		5.7	3.9	0.45	3.74	1.5	2.5	3.55
FR4	12.5		5.7	3.9	0.54	4.07	1.5	2.0	4.3

* *All parameters are in millimeters*

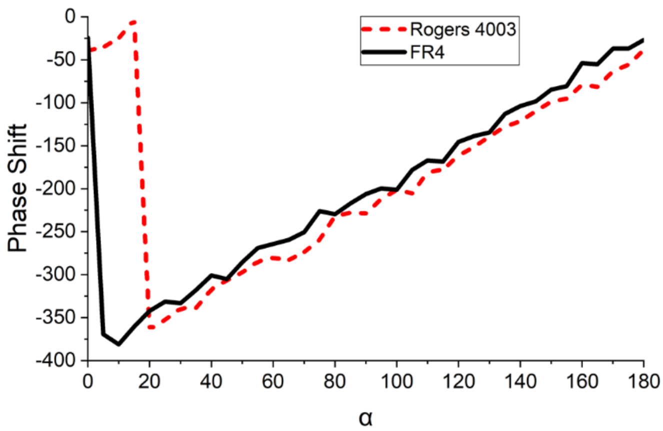


Fig. 4. Phase shift of the transmitted electromagnetic wave versus the rotation of inner split-ring on the substrate plane.

As expected, the results obtained with Rogers 4003 are slightly superior than the results obtained with FR4. τ presents maximum values of -0.99 dB and -1.90 dB for Rogers 4003 and FR4, respectively, which means that FR4 presents approximately 1 dB increase in insertion loss. Observe that τ is minimally affected by the inner split-ring rotation angle α. The unit cell bandwidth is reduced when applying FR4: Rogers 4003 presents 9.0% bandwidth while for FR4 it is reduced to 6.0%. Both structures present quite linear phase shift of the transmitted EM wave. Note that it is possible to reach the phase shift range from 0º to 360º with a gentle phase slope, which allows minimizing manufacturing errors.

III. TRANSMITARRAY ANTENNA

The proposed unit cell presented in Section II has been applied to the design of a 13 x1 3 elements transmitarray. The inner split-ring rotation φ_i of the i^{th} unit cell, which controls the phase shift of the transmitted EM wave, is the phase difference between the phase of the incident EM wave of the i^{th} unit cell θ_i and the incident EM wave of central unit cell θ_c of the array. φ_i and θ_i are given by

$$\varphi_i = \theta_i - \theta_c$$

$$\theta_i = R_i\beta - r_0\beta$$

where, R_i is the distance from the feeder to the i^{th} unit cell element, given by $R_i = \sqrt{r_i{}^2 + r_0{}^2}$, where r_i is the distance between the central element and the i^{th} element, which is given by $r_i = \sqrt{x^2 + y^2}$, where x and y are the coordinates of the i^{th} element, considering that the central element is located at coordinates $x = 0, y = 0$. The distance between the feeder and the central element of the transmitarray is represented by r_0. β represents to the propagation constant in the free space, given by

$\beta = 2\pi/\lambda$, where $\lambda = c/f$ is the wavelength. Fig. 5 shows the required phase shift of each array element.

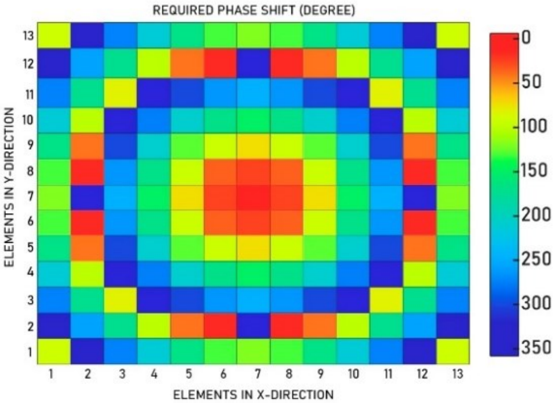
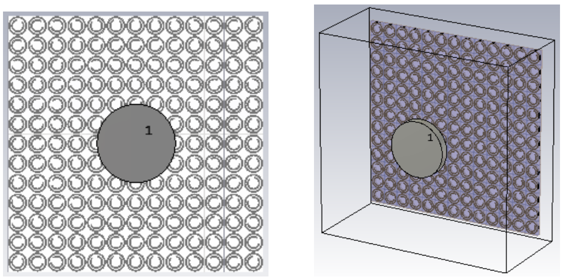


Fig. 5. Required phase shift of each unit cell of the Transmitarray.

The feeder is a log spiral antenna, placed at a distance $F =$ 50mm from the array plane. Fig. 6 presents the transmitarray model. Note the inner split-ring rotation of each unit cell, which controls the phase shift of the transmitted EM wave.



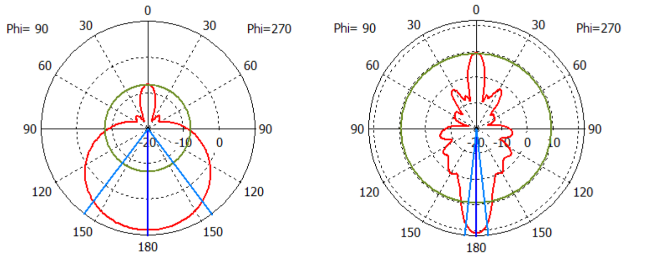
(a) (b)

Fig. 6. (a) Transmitarray front view; (b) Transmitarray perspective view.

Fig. 7 compares the radiation pattern of the log spiral antenna and the radiation pattern of the transmitarray with Rogers 4003 substrate, both operating at 10 GHz. Note that the transmitarray presents 20.7 dBi boresight directivity, -11.3 dB side lobe level (main lobe gain in dB minus maximum secondary lobe gain in dB) and 12.2º angular width (3 dB), while for the log spiral antenna the boresight directivity is only 8.41 dBi, the side lobe level is -16.2 dB and the angular width is 73.7 º.

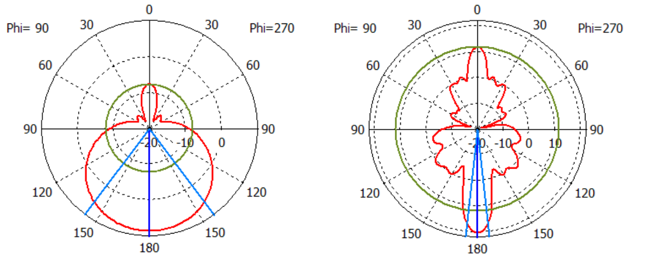
Fig. 8 compares the radiation pattern of the log spiral antenna and the radiation pattern of the transmitarray with FR4 substrate, both operating at 10 GHz. The transmitarray presents 20.0 dBi boresight gain, -8.3 dB side lobe level and 12.1º angular width (3 dB). Thus, the transmitarray efficiently adjusted the phase of the incident waves from log spiral source so that the re-irradiated waves interfere constructively, increasing the beam gain in approximately 12.3 dB and 11.6 dB with Rogers 4003 and FR4 substrates, respectively.

Fig. 9 presents the transmitarray antenna gain over frequency (losses included). Fig. 9 (a) presents the results for Rogers 4003 substrate and Fig. 9 (b) for FR4 substrate. The evaluated transmitarrays present 14.5% bandwidth (Rogers 4003) and 17% bandwidth (FR4).



(a) (b)

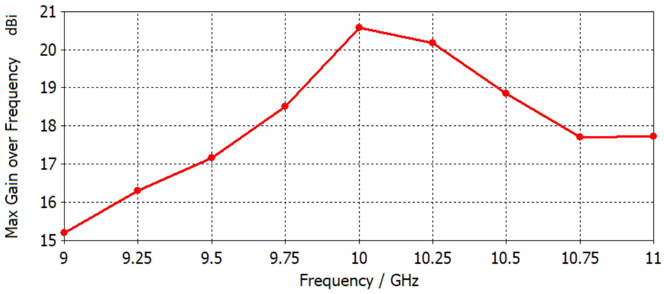
Fig. 7. Antennas directivity at 10 GHz (a) Log spiral antenna: boresight directivity = 8.41 dBi; angular width (3 dB) = 73.7°; side lobe level = -16.2 dB; (b) Rogers 4003 substrate transmitarray: boresight directivity = 20.7 dBi; angular width (3 dB) = 12.2°; side lobe level = -11.3 dB



(a) (b)

Fig. 8. Antennas directivity at 10 GHz (a) Log spiral antenna: boresight directivity = 8.41 dBi; angular width (3 dB) = 73.7°; side lobe level = -16.2 dB; (b) FR4 substrate transmitarray: boresight directivity = 20.0 dBi; angular width (3 dB) = 12.1°; side lobe level = -8.3 dB.

The transmitarray performance with Rogers 4003 and FR4 resulted similar in terms of boresight directivity and angular width. Rogers 4003 substrate achieved approximately 3 dB reduced side lobe and up to 2 dB higher antenna gain compared to FR4 substrate. On the other hand, FR4 substrate reaches larger bandwidth than Rogers 4003 substrate.



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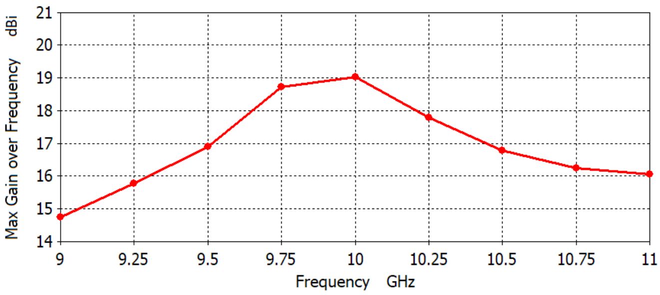

(b)

Fig. 9. Transmitarray maximum gain over frequency: (a) Rogers 4003 substrate; (b) FR4 substrate.

IV. Results Comparison

A widely adopted solution for circular polarization and high gain applications is the horn antenna [1]. The toroidal plasma lens (TPL) is an alternative solution that presents low profile and low radar cross section [13]. Thus, the results of the proposed transmitarray are compared with the horn antenna and TPL.

The transmitarray profile is evaluated considering the antenna volume, i.e., the volume of a box into which the whole antenna fits exactly. The transmitarray dimensions are $16.25\ \text{cm} \times 16.25\ \text{cm} \times 6.3\ \text{cm}$, resulting in approximately $1.66 \times 10^3 \text{cm}^3$.

As for the overall physical size, the transmitarray presents significantly smaller length and volume when compared to a conical horn of same gain. A conical horn optimized for 20 dBi at 10 GHz has a diameter of 133 mm and a length of 185 mm [12]. Actually, in practice, the horn will have a larger length when considering the coaxial-to-waveguide adapter, polarizer, and the waveguide connections. Thus, the conical horn has approximately three times the length of the transmitarray, and its volume is approximately 2.5 times larger than the transmitarray volume. Therefore, the proposed transmitarray presents a significantly smaller profile, keeping the same gain of a larger profile conical horn antenna.

Comparing the 19.9 dBi TPL [13] profile with the 20 dBi transmitarray profile, the TPL overall physical size is larger than the transmitarray size. TPL is approximately 15% wider than transmitarray, 60% longer and its volume is more than two times the transmitarray volume.

V. Conclusion

This paper presents a double layer double ring unit cell for circular polarization that applies the element rotation method to control the phase shift of the transmitted wave. The unit cell has been modeled and optimized for 10 GHz operating frequency. The model has been evaluated with low cost FR4 substrate and with low loss Rogers 4003 substrate. Results show that Rogers substrate achieves nearly 1 dB insertion loss reduction and larger bandwidth when compared to FR4.

Based on the proposed unit cell model, a 13×13 transmitarray has been designed, modeled and simulated. The feeder element is a log spiral antenna. The metamaterial transmitarray achieves 20.7 dBi and 20.0 dBi boresight directivity with Rogers 4003 and FR4 substrates, respectively, which is approximately 12 dB above the log spiral antenna directivity. The results obtained from Rogers 4003 and FR4 are similar in terms of boresight directivity and angular width. The FR4 transmitarray achieves larger bandwidth than Rogers 4003 transmitarray. Rogers 4003 substrate achieved approximately 3 dB reduced side lobe and up to 2 dB higher antenna gain compared to FR4 substrate. The results show that FR4 is an attractive solution due to its low cost and good performance.

The transmitarray results are compared to horn antenna and a toroidal plasma lens. Achieving similar boresight directivity, the transmitarray has significantly reduced profile when compared to the horn and TPL. Thus, the proposed transmitarray shown to be a high gain, compact and low cost and solution with the advantage of having a simple manufacturing process.

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