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Circular Polarized Patch Antenna Generating Orbital Angular Momentum

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Abstract—The recent extension of the orbital angular momentum (OAM) concept from optical to microwave frequencies has led some researchers to explore how well established antenna techniques can be used to radiate a non-zero OAM electromagnetic field. In this frame, the aim of the present paper is to propose a new approach to generate a non-zero OAM field through a single patch antenna. Using the cavity model, we first analyze the radiated field by a standard circular patch and show that a circular polarized (CP) TM_{nm} mode excited by using two coaxial cables generates an electromagnetic field with an OAM of order $\pm(n-1)$. Then, in order to obtain a simpler structure with a single feed, we design an elliptical patch antenna working on the right-handed (RH) CP TM_{21} mode. Using full-wave simulations and experiments on a fabricated prototype, we show that the proposed antenna effectively radiates an electromagnetic field with a first order OAM. Such results prove that properly designed patch antennas can be used as compact and low-cost generators of electromagnetic fields carrying OAM.

1. INTRODUCTION

The concept of Orbital Angular Momentum (OAM) is well known at optical frequencies, where it has found application in trapping and manipulating of microscopic particles, imaging and communication systems [1–4]. Recently, it has been shown that an electromagnetic (EM) field with a non-zero OAM can be also generated in the microwave range using standard antenna systems [5]. Starting from this first demonstration, several systems generating EM fields with non-zero OAM have been proposed [5–9]. Such systems are based on two different approaches. The first one consists of a circular antenna array in which the different elements are fed with signals having the same amplitude and a progressive phase shift, such that the total delay between the first and the last element is an integer multiple l of 2π [5, 6]. A variant of this approach is presented in [7] and makes use of a time-switched array. The second approach consists of using a reflector with a helical phase profile achieved by mechanically modifying a spiral [8] or parabolic [9] reflector.

However, both these approaches have some inherent drawbacks. In fact, the first approach requires the design and the implementation of a transmission line network to properly feed the array elements. On the other hand, the fabrication of a reflector with a helical phase profile is not easily replicable. Moreover, both solutions require considerable space occupancy, weight, and costs.

In contrast, at optical frequencies there are different techniques used to generate OAMs. As an example, the higher order laser modes of a laser cavity, also known as Laguerre-Gauss (LG) laser modes, have a non-zero OAM and can be either directly generated [10] or obtained by properly combining two Hermite-Gauss (HG) laser modes [11]. This means that, for instance, a LG_0^1 laser mode can be generated combining two orthogonal HG_{10} and HG_{01} modes with a $\pi/2$ phase delay between them [1].

Inspired by this technique, we may think of properly combine orthogonal higher order modes of resonant antennas to generate OAMs at microwave frequencies.

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In this paper, in order to obtain an EM field with a non-zero OAM at microwave frequencies, we propose to use a single patch antenna. In particular, we show that the higher order modes of a circularly polarized patch antenna can be used to generate different OAM states. This solution is clearly cheaper, lighter and more compact compared to the ones already proposed [5–9]. Moreover, although OAM cannot be used to improve the performances of a communication system except in very particular cases [12], the proposed solution can be useful to experimentally investigate the properties of the OAM or to extend to microwave frequencies imaging and identification techniques based on OAM and developed in the optical regime [13].

The structure of the paper is as follows. In Section 2, we report the analytical study of a circular patch antenna and show that an EM field with non-zero OAM can be generated if we make this component working on higher order circularly polarized (CP) modes. In Section 3, we present the design procedure and the results of the full-wave simulations for an elliptical patch antenna generating a helical far-field radiation pattern with circular polarization. In Section 4, we validate these results through the characterization of the radiating and matching properties of a fabricated prototype. Finally, in Section 5, we draw the conclusions.

2. ANALYTICAL STUDY OF A CIRCULAR PATCH ANTENNA GENERATING AN EM FIELD WITH A NON-ZERO OAM

A patch antenna, in its general form, consists of a metallic patch placed on a grounded dielectric slab [14]. Over the last decades, patch antennas with different geometries have been proposed to satisfy several design constraints (see, for instance, [15–18]). Let's consider the circular patch antenna depicted in Fig. 1. In some applications, this type of patch antenna is preferred to the rectangular one due to its greater flexibility in terms of achievable radiation patterns.

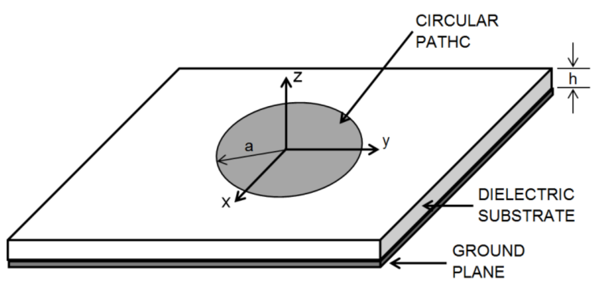

Figure 1. Geometrical sketch of a circular patch antenna. The main geometrical parameters are the radius of the patch a and the thickness of the dielectric substrate h.

In order to evaluate the radiating performances of a patch antenna, different analysis methods can be used. In our case, we have chosen the cavity model that is a good compromise between accuracy of the obtained results and complexity of the model. This approximate model is based on considering the antenna to be a dielectric loaded resonant cavity.

In the case of a circular patch antenna, the radiated electric field components by a TM_{nm} mode can be derived by using the cavity model in cylindrical coordinates and are expressed as [19]:

$$\begin{aligned} E_{\theta n} &= j^n \frac{V k_0 a}{2} \frac{e^{-jk_0 r}}{r} \cos n\varphi \left[J_{n+1}(\gamma) - J_{n-1}(\gamma)\right] \\ E_{\varphi n} &= j^n \frac{V k_0 a}{2} \frac{e^{-jk_0 r}}{r} \cos\theta \sin n\varphi \left[J_{n+1}(\gamma) + J_{n-1}(\gamma)\right] \end{aligned} \tag{1}$$

where $V = hE_0 J_n(ka)$ is the edge voltage at $\varphi = 0$, h the thickness of the dielectric substrate, E_0 the value of the electric field at the edge of the patch, $\gamma = k_0 a \sin\theta$, a the radius of the patch, and J_i the Bessel function of the first kind and order i.

As anticipated in the introduction, we now investigate the use of CP higher order modes of a patch antenna in order to produce an EM field with non-zero OAM. Circular polarization can be obtained by using two coaxial cables with proper angular spacing such that two orthogonal modes with a proper phase shift are excited. Therefore, the total radiated field by a CP TM_{nm} mode can be considered as the superposition of the individual electric fields produced by the two orthogonal modes and obtained from (1):

$$\begin{aligned} E^t_{\theta n} &= E^1_{\theta n}(\phi,\theta) + jE^2_{\theta n}(\phi+\alpha,\theta) \\ E^t_{\varphi n} &= E^1_{\varphi n}(\phi,\theta) + jE^2_{\varphi n}(\phi+\alpha,\theta) \end{aligned} \tag{2}$$

where superscripts 1 and 2 correspond to the fields generated by the two coaxial cables, respectively, α is the angular spacing of the probes depending on the mode order [20], while the phase shift has been chosen equal to $\pi/2$ in order to obtain a right-handed circular polarized (RHCP) field.

From these expressions, we can derive the x and y components of the total radiated field:

$$\begin{aligned} E_x &= -j^n \frac{e^{-jk_0 r}}{2r} a\,h\,k_0\,J_n(a\,k_0\sqrt{\epsilon_r})\left[\mathrm{e}^{-\mathrm{j}(n-1)\,\phi} J_{n-1}(\gamma) - \mathrm{e}^{-\mathrm{j}(n+1)\,\phi} J_{n+1}(\gamma)\right]\cos[\theta] \\ &= \mathrm{A}\,\mathrm{e}^{-\mathrm{j}(n-1)\,\phi} - B\,\mathrm{e}^{-\mathrm{j}(n+1)\,\phi} \\ E_y &= j^{n+1} \frac{e^{-jk_0 r}}{2r} a\,h\,k_0\,J_n(a\,k_0\sqrt{\epsilon_r})\left[\mathrm{e}^{-\mathrm{j}(n-1)\,\phi} J_{n-1}(\gamma) + \mathrm{e}^{-\mathrm{j}(n+1)\,\phi} J_{n+1}(\gamma)\right]\cos[\theta] \\ &= -j\left[\mathrm{A}\,\mathrm{e}^{-\mathrm{j}(n-1)\,\phi} + B\,\mathrm{e}^{-\mathrm{j}(n+1)\,\phi}\right] \end{aligned} \tag{3}$$

where:

$$\begin{aligned} A &= -j^n \frac{e^{-jk_0 r}}{2r} a\,h\,k_0\,J_n(a\,k_0\sqrt{\epsilon_r})\cos[\theta]\,J_{n-1}(\gamma) \\ B &= -j^n \frac{e^{-jk_0 r}}{2r} a\,h\,k_0\,J_n(a\,k_0\sqrt{\epsilon_r})\cos[\theta]\,J_{n+1}(\gamma) \end{aligned} \tag{4}$$

From (3), we note that the x-component (y-component) consists of the difference (the sum) of the same two terms, having phase evolutions of the forms $e^{-j(n-1)\varphi}$ and $e^{-j(n+1)\varphi}$, respectively.

However, for a patch antenna with typical geometrical and EM parameters, the amplitude of the second term is always significantly smaller than the one of the first term. In fact, the amplitude of the two terms differs only in the order of the Bessel function and, for small values of the argument, the higher the order of the function, the lower its value. This aspect has been also verified through several full-wave simulations, whose results are not reported here for sake of brevity. Moreover, as shown in Fig. 2 for the case of a patch antenna working in the CP TM_{21} mode, increasing the dielectric permittivity of the substrate the first term becomes increasingly dominant. In the case of a circular polarized TM_{nm} mode we can thus consider only the term proportional to $e^{-j(n-1)\varphi}$, which corresponds to an EM field carrying an OAM of order $n-1$.

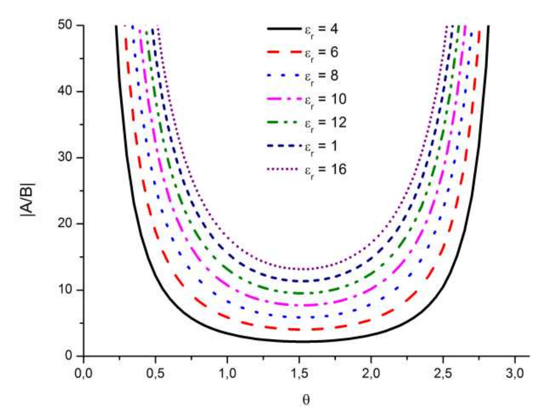

Figure 2. Ratio between the amplitude of the terms A and B in the case of a circular patch antenna working in a CP TM_{21} mode for different values of substrate permittivity.

Therefore, for the first resonant mode of a circular patch antenna (TM_{11}) the OAM is equal to zero. However, for the higher order modes with $n > 1$, the radiated EM field is characterized by a non-zero OAM. This is confirmed by the phase patterns reported in Fig. 3, where we can observe that the electric fields produced by TM_{21} and TM_{31} modes have the rotating phase front expected by a non-zero OAM [21]. On the contrary, the TM_{11} mode has a phase pattern independent of φ, which corresponds to a zero OAM. Moreover, the conical radiation patterns of a circular patch antenna working at higher order modes [20] are also in agreement with the presence of an EM field with non-zero OAM, which has, as another peculiar aspect, an amplitude null in the propagation direction.

Finally, note that, reassessing Equations (2)–(4) for a $-\pi/2$ phase shift between the two coaxial cables, we obtain a left-handed CP field with a dominant phase term $e^{j(n-1)\varphi}$ and, therefore, an OAM state with an opposite sign.

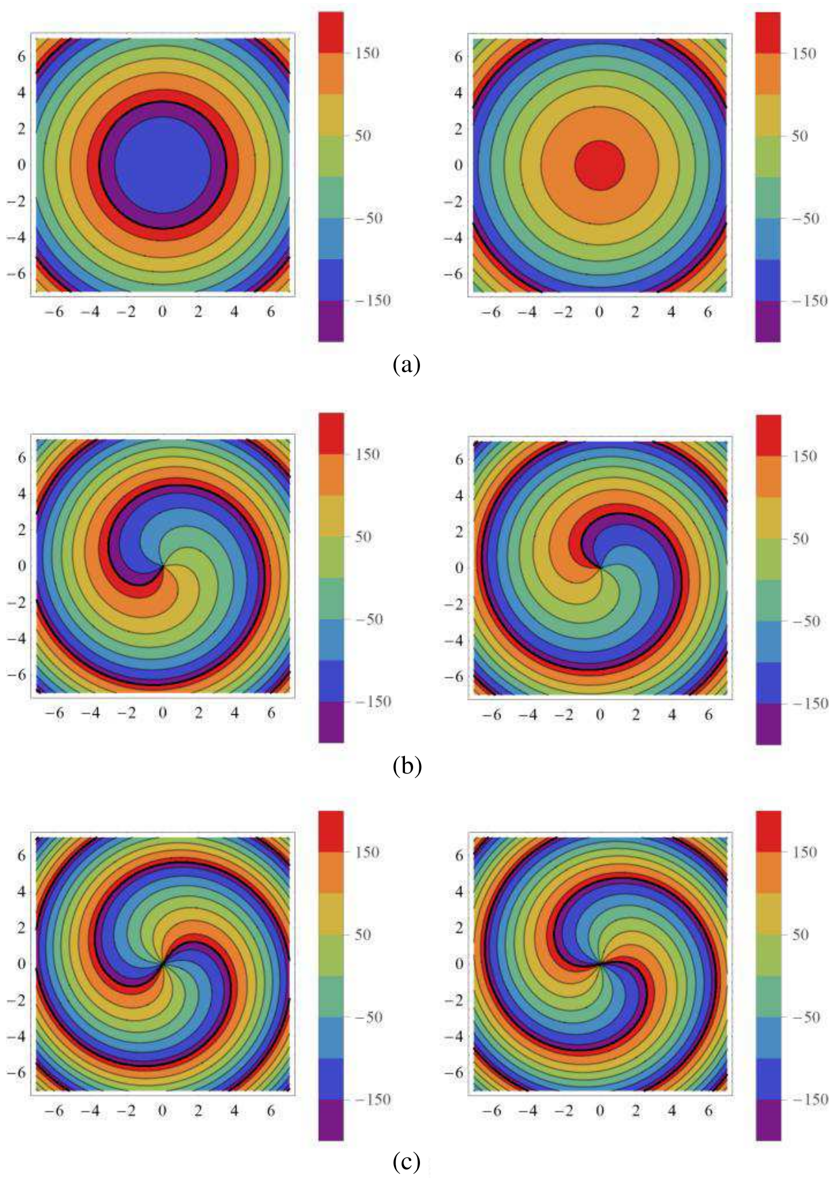

Figure 3. Phase patterns (in degree) of the x (left) and y (right) component of the radiated electric field in the case of: (a) RHCP TM_{11} mode; (b) RHCP TM_{21} mode; (c) RHCP TM_{31} mode.

3. VALIDATION THROUGH FULL-WAVE NUMERICAL SIMULATIONS

As analytically shown in the previous Section, the CP TM_{nm} modes of a circular patch antenna radiate an EM field with OAM of order $\pm(n-1)$. Such a structure, even if simpler and more compact than those ones proposed in the literature, can be further simplified. In fact, circular polarization can be obtained also through a single coaxial feed. A possible solution consists of introducing a proper asymmetry in the geometrical structure in such a way that two degenerate modes are excited [22, 23].

Therefore, in order to obtain a patch antenna with a single feed that generates OAM states, we have transformed the circular patch into an elliptical one, as shown in Fig. 4. The elliptical metallic patch is placed on a square 0.787 mm thick Rogers Duroid$^{\mathrm{TM}}$ RT5870 ($\varepsilon_r = 2.33$, $\tan\delta = 0.0012$). The dimensions of the two main axes of the elliptical patch have been properly chosen to obtain two almost overlapped resonant frequencies and, therefore, a CP TM_{21} mode around 2.4 GHz. Moreover, the 50 Ω coaxial cable has been properly positioned to obtain a good impedance matching of the two degenerate modes. The main geometrical dimensions of the structure are reported in Fig. 4.

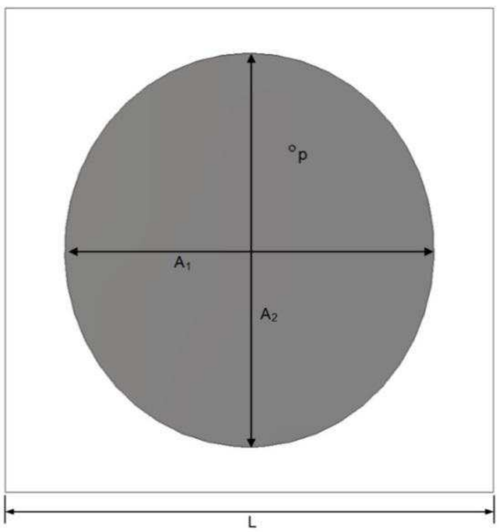

Figure 4. Top view of the elliptical patch antenna. The inner conductor of the coaxial cable is connected to the point p ($x = 8.75$ mm; $y = 21$ mm). The origin of the reference system is at the shape centre. Antenna dimensions are: $A_1 = 75.2$ mm, $A_2 = 81.6$ mm, and $L = 100$ mm.

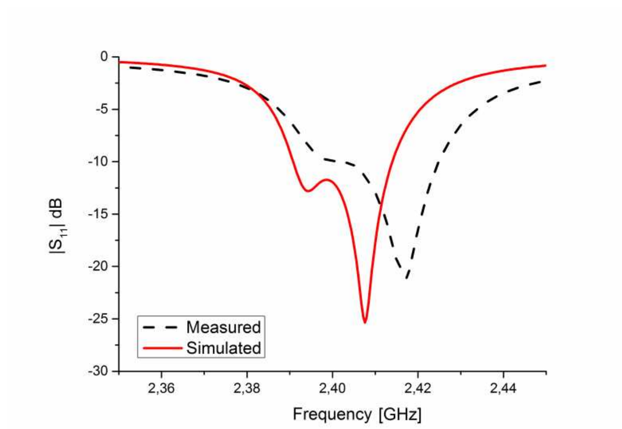

Figure 5. Simulated (red-solid line) and measured (black-dashed line) reflection coefficient amplitude of the proposed elliptical patch antenna shown in Fig. 4.

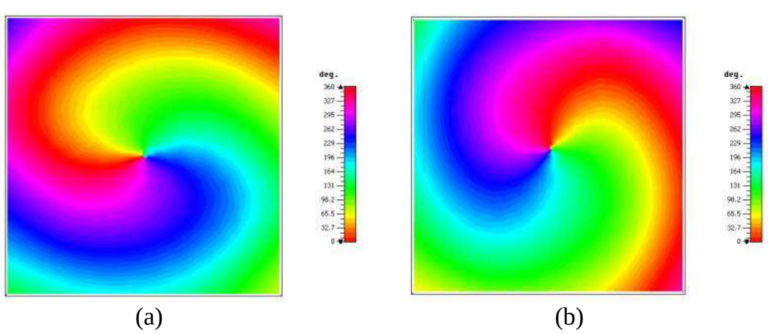

Figure 6. Phase patterns at 2.4 GHz of the (a) x and (b) y component of the radiated electric field by the elliptical patch antenna, shown in Fig. 4, working in a RHCP TM_{21} mode.

Using the full-wave numerical solver CST Microwave Studio [24], we have simulated the radiating and matching properties of the proposed structure. From Fig. 5, we can see that the proposed antenna is well matched around two slightly different resonant frequencies, as required to generate a circular polarized TM_{21} mode. Furthermore, in order to verify the actual generation of a non-zero OAM, the phase patterns of the x and y components of the radiated electric field are shown in Fig. 6. As readily apparent, these phase patterns have a helical profile with a 2π phase change in one turn, corresponding to a phase term $e^{-j\varphi}$. Therefore, the proposed antenna effectively radiates a circular polarized EM field with an OAM of the first order. This result is also confirmed by the simulated phase of radiation patterns, reported in Fig. 7, that show a spiral variation with the azimuthal angle. Finally, please note that the 3-D directivity pattern, reported in Fig. 8, shows an amplitude null in the propagation direction, as expected due to the helical phase profile.

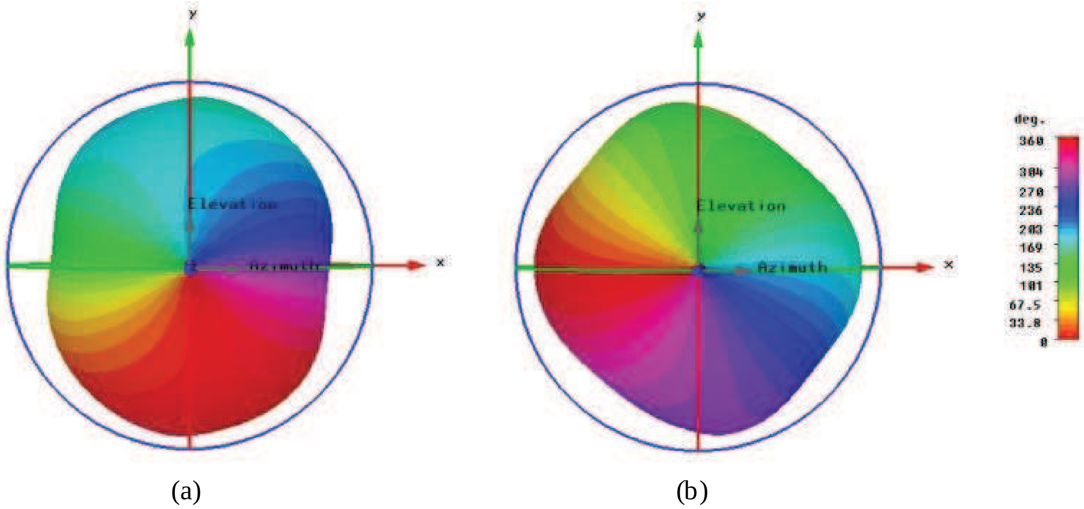

Figure 7. (a) Simulated Azimuth and (b) elevation radiation phase patterns at 2.4 GHz of the elliptical patch antenna, shown in Fig. 4, working in a RHCP TM_{21} mode.

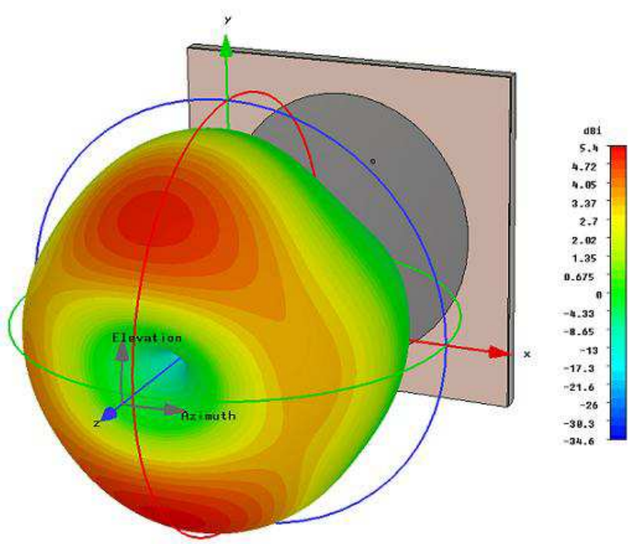

Figure 8. 3-D directivity pattern at 2.4 GHz of the elliptical patch antenna, shown in Fig. 4, working in a RHCP TM_{21} mode.

Figure 9. Photograph showing the realized elliptical patch antenna with the dimensions given in Fig. 4.

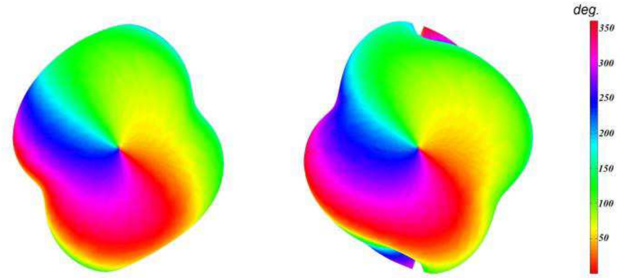

Figure 10. (a) Measured Azimuth and (b) elevation radiation phase patterns at 2.4 GHz of the prototype shown in Fig. 9.

4. MEASUREMENTS

The proposed antenna with the dimensions given in Fig. 4 has been manufactured with a LPKF Protomat-S milling machine. An SMA connector with characteristic impedance of 50 Ω has been used to feed the prototype antenna (see Fig. 9). Then, the matching and radiating properties have been measured by using a vector network analyzer and a near-field antenna measurement system.

The measured magnitude of the S_{11} parameter, reported in Fig. 5, is in good agreement with the simulated one. In particular, the antenna is well matched around 2.41 GHz and shows two almost overlapped resonant frequencies. The slight shift in frequency between the simulated and measured results, due to manufacturing tolerances, does not affect the antenna operation and the proof of concept we wanted to give. In fact, the far-field phase patterns of the elevation and azimuth components at 2.4 GHz, reported in Fig. 10, show the expected helical profile of the OAM of the first order.

These results, thus, confirm that an elliptical patch antenna, if properly designed, can be used to generate an EM field with non-zero OAM.

5. CONCLUSIONS

We have presented a novel approach to generate an EM field with non-zero OAM at microwave frequencies. At first, we have analytically studied the EM field produced by a circular patch antenna in order to show that a CP TM_{nm} mode generates an OAM of order $\pm(n-1)$. For this purpose, the circular patch antenna can be excited with two properly spaced coaxial cables with the same signal amplitudes but with a $\pm\pi/2$ phase shift.

Then, we have shown that an EM field with non-zero OAM can be also generated with a single coaxial feed by using an elliptical patch antenna. In fact, the geometrical asymmetry of this structure allows generating two orthogonal modes that produce a CP EM field. In particular, we have designed an elliptical patch antenna working in a RHCP TM_{21} mode. By using CST Microwave Studio, we have numerically demonstrated that this structure radiates a RHCP EM field with an OAM of the first order around 2.4 GHz.

Finally, we have realized and tested a prototype of the proposed elliptical patch antenna and the measured results validate the predicted characteristics. The final message is that a standard patch antenna, if properly designed, can be employed to generate OAM states. Compared to the other solutions already proposed in the literature, based on either antenna arrays or complex reflector antennas, the proposed one is cheaper, lighter, and more compact.

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