Dual-Circularly Polarized Topological Patch Antenna With Pattern Diversity

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ABSTRACT Recently, the topological properties of composite vortices, i.e., the superposition between vortex modes of a different order, have proven effective in manipulating the radiation properties of patch antennas and making them suitable for new operative scenarios. In this paper, we exploit these properties to design a multi-antenna system exhibiting both pattern- and polarization-diversity. The low mutual coupling and the possibility to steer two orthogonal polarized fields in different directions, make this radiating element an optimal candidate for antenna diversity or MIMO systems and, thus, for increasing signal quality or channel capacity of a communication system.

INDEX TERMS Patch antennas, pattern diversity, phase singularities, topology, vortex modes.

I. INTRODUCTION Wireless systems are rapidly evolving for satisfying the ever-challenging requests of their new application fields, such as Internet of Things, autonomous vehicles, or smart cities. In these complex scenarios, new technological solutions are required to achieve ultra-high channel capacity, ever lower latency and stronger resilience of the system to changing operative conditions. For this purpose, a substantial contribution can be provided by the radiating system that, using multi-antenna techniques, can improve the performance of the overall system compared to a standard single-antenna transceiver [1], [2]. In particular, the quality and the reliability of a communication system can be increased by exploiting antenna diversity between different radiating elements. In this case, the receiver is reached by multiple copies of the same signal, which is transmitted through independent channels. For maximizing the benefit of antenna diversity, the correlation between the different channels should be minimized and, thus, antenna elements with different polarization, radiation pattern and/or position are typically employed. Another possibility offered by multi-antenna techniques is to exploit the natural multipath propagation of complex operative environments for transmitting multiple signals. In this case, the different propagation channels between the multiple antenna elements at both transmitter and receiver ends can be exploited for increasing the channel capacity of the overall system. This approach, which is referred to as MIMO systems, has been further extended with the advent of 5G technologies and massive-MIMO applications [3].

The aforementioned techniques have different purposes, aiming at increasing the reliability of a single communication channel or allowing transmission of multiple channels at the same frequency. Nevertheless, they share the same enabling technology, which is based on a multi-antenna system. In particular, in both cases, the signals received by the single radiating elements should be independently manipulated for improving the overall system performance. For this purpose, multi-antenna techniques require a strong orthogonality between the different propagating channels and low mutual coupling between the radiating elements. These requirements are even more challenging as the distance between the antenna elements decreases [4].

In this framework, several solutions have been proposed for designing multi-antenna elements exhibiting spatial diversity,
polarization diversity, or radiation pattern diversity [5]–[14]. The former solution inevitably and significantly increases the space occupancy of the overall system. On the contrary, polarization and radiation pattern diversity can be also implemented in compact structures, where two or more radiating elements are placed nearby. However, most of these solutions require a non-planar structure [7], [8] or, in the case of planar patch antennas, are limited to the excitation of conical, broadside, or omnidirectional patterns with fixed shapes [10]–[14]. Due to the growing demands of wireless systems, instead, multi-antenna devices able to exploit orthogonality between different channels and, at the same time, reconfigure their response in real-time would be highly desirable.

As a possible solution for this challenging task, we propose here to exploit the topological properties of vortex modes generated by standard patch antennas [15]. In fact, vortex modes exhibit phase singularities of different order, which are inherently orthogonal between them [16] and, thus, are natural candidates for antenna diversity or MIMO systems. Moreover, phase singularity points of different order can be properly superimposed for shaping and pointing the radiation pattern of patch antennas [17], [18]. Therefore, they have also been proposed as a possible solution for reconfiguring the radiation characteristics of antennas in real-time.

In this work, by properly engineering the excitation of vortex modes, we further extend their applicative scenarios by designing a reconfigurable two-element antenna system able to radiate orthogonal field components in different directions and with reduced mutual coupling between them. This new antenna system can be used, thus, for pattern diversity and MIMO-systems requiring strong orthogonality between multiple channels.

II. THEORETICAL ANALYSIS BASED ON VORTEX MODES PROPERTIES

Vortex modes can be observed in many branches of physics and are characterized by a phase singularity point where the amplitude vanishes and phase is undefined. Such modes can be generated at microwaves by using different approaches [15]–[19] and, in particular, by exciting circular polarized (CP) higher-order modes of patch antennas [15]. Due to the inherent orthogonality between vortex modes of different order, this kind of beams has been initially proposed as a possible solution for increasing the channel capacity of a communication system. However, their applicability as a direct method for signal multiplexing has been limited to a few particular scenarios and classified as a sub-optimal case of MIMO-systems [20]. Nevertheless, vortex modes exhibit several intriguing properties, such as the robustness to external perturbations [21], which deserved further investigations. In particular, as shown in [17], [18], the superposition between vortex modes of different order, the so-called “composite vortices”, has been exploited for manipulating the radiation pattern of a simple two-element antenna array, which consists of an inner circular patch and an external annular ring. In this case, the number and the position of phase singularity points exhibited by the overall radiated beam can be analytically determined [18] and provide high degrees of freedom for pattern manipulation. In particular, for a right-handed (RH) CP TM21 vortex mode superimposed to an RHCP vortex-free TM11 mode, the following expressions have been derived [17]:

$$\phi = \delta - \frac{\pi}{2}$$
$$\sin \theta = C \tan \alpha$$

where $C$ is a constant depending on the geometrical and electric parameters of the two radiating elements [17] and $\alpha$ and $\delta$ specify the relative amplitude and phase of the two modes, respectively.

From these relations, we have observed that, on a given $z$-plane orthogonal to the antenna plane, a single phase singularity point is present, whose distance from the origin depends on $\alpha$ while its azimuth depends only on $\delta$. In particular, for $\delta = 0$, the singularity is on the negative $y$-axis and it can be moved away from the origin by increasing $\alpha$. For a fixed value of $\alpha$, instead, by increasing $\delta$ the vortex can be rotated around a fixed circle. Please note that if we repeat the analysis reported in [17] for left-handed (LH) CP fields, similar expressions can be derived:

$$\phi = -\delta + \frac{\pi}{2}$$
$$\sin \theta = C \tan \alpha$$

Comparing eqs. (1)-(2), we can thus infer that composite vortices with opposite handedness exhibit a phase singularity point in the overall radiated beam that, for $\delta = 0$ (the two modes are excited in phase), are placed in a specular position. Moreover, by increasing $\delta$, the phase singularity points rotate in opposite directions. Being these phase singularity points directly related to a null on the corresponding radiation patterns [18], we also expect that, depending on the handedness of the excitation, the composite vortices will give rise to radiation patterns pointing in different directions.

In order to validate this idea, we have evaluated the phase and amplitude patterns of the radiated field for different values of $\delta$ and opposite handedness. However, for the sake of brevity, we report in Fig. 1 only the amplitude patterns, being the position of the phase singularity points inherently related to the amplitude nulls.

From this figure, we can observe that for $\delta = 0$, the amplitude null is on the negative/positive $y$-axis when an RH/LH composite vortex is generated. Moreover, by increasing $\delta$, the amplitude null rotates clockwise or counter-clockwise for RH or LH polarizations, respectively. The corresponding radiation patterns are reported in Fig. 2, which confirm the possibility to radiate orthogonal circular polarized fields in two different directions, as well as, to dynamically control the pointing directions by simply acting on $\delta$. 
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FIGURE 1. Analytically calculated total electric energy density ($|E|^2$) distributions at a distance $\lambda_0$ from a patch radiating the superposition of a TM$_{11}$ and a TM$_{21}$ mode for different values of $\delta$ (here $\alpha = \pi/4$) and different polarization handedness.

Please note that, as discussed in [17], by acting on $\alpha$ (excitation amplitude of the two modes) the amplitude patterns, as well as, the shape of the radiation patterns can be slightly manipulated and could provide a further degree of freedom for the overall system. Moreover, the aforementioned properties are not limited to the composite vortex under investigation, but could be also applied to higher-order modes of patch antennas [18].

III. FULL-WAVE NUMERICAL VALIDATION

The previous analysis, extended from [17], is based on the cavity model for patch antennas and on the superposition of different radiating modes. As discussed in [17], [18], at a given frequency, a standard patch antenna can effectively radiate a single mode only, which can be selected by properly designing the patch dimension. In order to superimpose, at the same frequency, two different radiating modes, one of the most effective and compact solution is to concentrically place, on a common grounded substrate, an inner circular patch and an outer annular ring. In this way, the dimensions of the two radiating elements can be independently adjusted to support the desired modes (i.e., a TM$_{11}$ mode and a TM$_{21}$ mode in our analysis). Starting from this configuration, the circular polarization operation is achieved by etching two peripheral slits on both the radiating elements. Then, two coaxial feeds can be used for exciting the selected modes and, depending on their positions with respect to the slit axis, RHCP or LHCP composite vortices can be generated [17]. However, as discussed in the previous section, here we

FIGURE 2. Analytically calculated normalized directivity patterns for the superposition of a TM$_{11}$ and a TM$_{21}$ mode for different values of $\delta$ (here $\alpha = \pi/4$) and different polarization handedness.
aim at generating, at the same frequency and simultaneously, two composite vortices with opposite handedness. Therefore, for each radiating element, two coaxial cables should be used. In this way, both RHCP and LHCP TM$_{11}$ and TM$_{21}$ modes can be excited. The proposed structure, satisfying all these design requirements and operating around 3 GHz, and corresponding feeding configuration are shown in Fig. 3.

Please note that Port A and Port B can be simultaneously excited for radiating an LHCP structured field with a phase singularity point whose position can be determined by equation (2). On the contrary, Port C and Port D allow radiating an RHCP structured field according to eq. (1). However, the previous analysis requires the exact overlap of the excited modes while, in our case, the coaxial cables exciting the orthogonal composite vortices cannot be superimposed. Therefore, an angular shift between the two components is expected.

In order to evaluate the effectiveness of the proposed structure, we have performed a set of circuital and full-wave numerical simulations by exploiting the software package CST Studio Suite [22]. In particular, the four coaxial feeds simulated in the full-wave numerical simulator CST Microwave Studio have been combined, through the
FIGURE 8. Numerically calculated directivity patterns of Port 1 (LHCP composite vortex generation) and Port 2 (RHCP composite vortex generation) for different values of δ (here α = π/4). In all the cases, the simulated total efficiency was above 0.7.

schematic design tool CST Design Studio, in the two exciting ports (Port 1 and Port 2) through the use of a 3-dB power divider. Moreover, for allowing the dynamic reconfiguration of the radiation patterns, an ideal phase shifter has been inserted in one branch of each excitation port. The magnitudes of the scattering parameters are reported in Fig. 4, when Port 1 (Port 2) is excited and Port 2 (Port 1) is closed on a matched load. These results confirm that, despite the two composite vortices share the same radiating structure, they can be excited with good impedance matching and low mutual coupling. In fact, for all the considered excitation conditions, |S11| and |S22| are both below −10 dB around the operative frequency of 3 GHz. The same results can be obtained also for |S21| and |S12|, not reported here for sake of brevity.

TABLE 1. Diversity performance at the center operating frequency.

| δ  | |S11| (dB) | Pointing direction (θ°, ϕ°) | DG | ECC |
|----|----|---|----|----|---|
| 0  | -22.9 | (25°, 72°) | (25°, 108°) | 36° | 9.96 | 8.6 × 10⁻³ |
| π/4 | -15.5 | (26°, 128°) | (26°, 48°) | 80° | 9.39 | 1.2 × 10⁻¹ |
| π/2 | -11.2 | (26°, 142°) | (26°, 35°) | 107° | 9.11 | 1.7 × 10⁻¹ |
| 3π/4 | -12.3 | (26°, 190°) | (26°, -15°) | 155° | 9.99 | 1.2 × 10⁻¹ |
| π  | -22.3 | (25°, 252°) | (25°, -75°) | 33° | 9.96 | 7.1 × 10⁻³ |

Then, we have analyzed the radiation properties of the overall radiating structure, when Port 1 or Port 2 is excited with a zero phase shift (δ = 0) between the corresponding coaxial feeds. The 3D radiation patterns of the co- and cross-polarized components, reported in Fig. 5, show that the composite vortex with the desired polarization state can be radiated, with a low cross-polarization level, depending on the excitation port. The two radiation patterns point toward different directions, which are consistent with the position of the amplitude nulls in the total electric energy density distributions reported in Fig. 6. The good polarization purity is also confirmed by the axial ratio (AR) in the main beam direction, shown in Fig. 7, which is below 3 dB in the matching bandwidth of the two ports.

In order to confirm the reconfigurable properties analytically predicted in Section II, we have instead evaluated the 3D radiation patterns of the two excitation conditions for different values of δ. These results, reported in Fig. 8, confirm that the two orthogonal CP components of the radiated field can be pointed toward different directions, as expected by our analysis based on the phase singularity points. Moreover, being δ the excitation phase between the two modes, it can be simply controlled for reconfiguring the radiation pattern of both orthogonal components and, thus, for maximizing system performance in real-time. Please note that, for sake of brevity, we have reported information about the polarization purity (AR and cross-polarization levels) only for the case δ = 0, but the full-wave numerical simulations have provided very similar results for all the considered phase shift values and, thus, for all the pointing angles.

To specify the benefit of the proposed structure when exploited in a MIMO antenna system, the envelope correlation coefficient (ECC) for a Gaussian distribution and the diversity gain (DG) between the two operating modes have been also evaluated by using the templates provided by the software [22]. The results, summarized in Table 1, confirm the strong orthogonality between the two radiation modes in all the considered scenarios. In fact, despite the increase of the mutual-coupling for some of the considered phase shift values, the worst correlation conditions in terms of scattering parameters are balanced by better properties in terms of radiation pattern diversity (increasing angular distance between the main beam directions).

Finally, the unique properties of the proposed structure is confirmed by the comparison, reported in Table 2, with other pattern/polarization diversity two-element antennas proposed...
in the literature. In fact, to the best of the authors’ knowledge, the proposed solution is the only one that allows radiating two CP components in two different directions. In addition, by implementing a feeding network with tunable phase shifters, it would also allow to dynamically control the pointing directions of the two components.

We remark here that our analysis focuses on demonstrating the main properties enabled by the superposition of composite vortices with opposite handedness and presents only a sample of all the possible configurations. In fact, further degrees of freedom could be added by either acting on the excitation amplitude of the two modes or using independent phase shifts for RHCP and LHCP components.

**IV. CONCLUSION**

Composite vortices at microwave frequencies have been recently exploited as a tool for shaping the radiation pattern of patch antennas. In this paper, we have further investigated the possibilities offered by this approach and designed a compact dual-circularly polarized patch antenna. The proposed structure can radiate the two orthogonal components in different directions and with low mutual coupling and, thus, could find applications in antenna diversity or MIMO systems. Moreover, although it consists of only two concentric elements, it is able to reconfigure the radiation pattern in real-time for maximizing system performance.

Numerical full-wave simulations have validated the effectiveness of the proposed structure in terms of scattering parameters, radiation patterns, and diversity performance.

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