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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 strongest 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,

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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 TM_{21} vortex mode superimposed to an RHCP vortex-free TM_{11} mode, the following expressions have been derived [17]:

$$\begin{aligned}\phi &= \delta - \frac{\pi}{2}\\ \sin\theta &= C\tan\alpha\end{aligned}\tag{1}$$

where C is a constant depending on the geometrical and electric parameters of the two radiating elements [17] and α and δ 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 α while its azimuth depends only on δ. In particular, for $\delta = 0$, the singularity is on the negative y-axis and it can be moved away from the origin by increasing α. For a fixed value of α, instead, by increasing δ 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:

$$\begin{aligned}\phi &= -\delta + \frac{\pi}{2}\\ \sin\theta &= C\tan\alpha\end{aligned}\tag{2}$$

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 δ, 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 δ 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 δ, 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 δ.

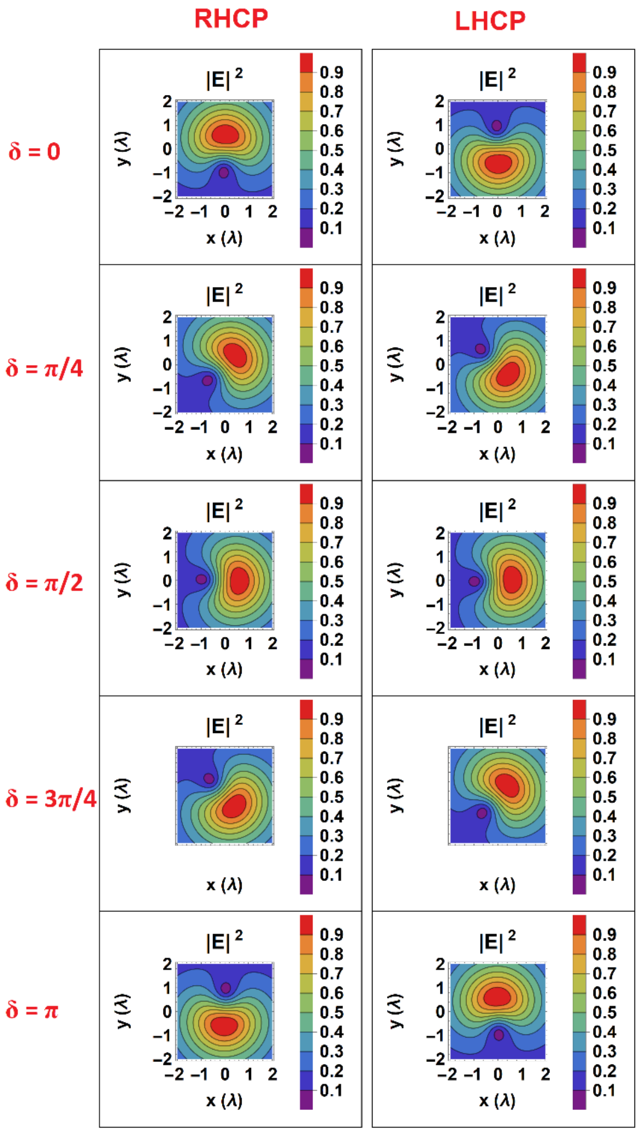

FIGURE 1. Analytically calculated total electric energy density ($|E|^2$) distributions at a distance λ_0 from a patch radiating the superposition of a TM_{11} and a TM_{21} mode for different values of δ (here $\alpha = \pi/4$) and different polarization handedness.

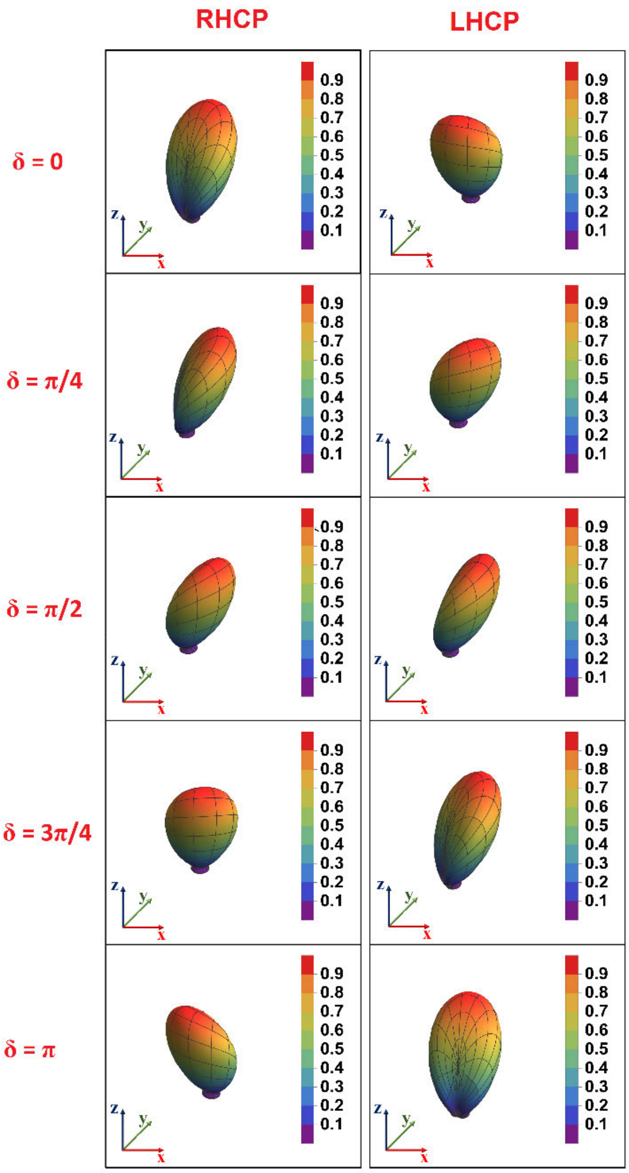

FIGURE 2. Analytically calculated normalized directivity patterns for the superposition of a TM_{11} and a TM_{21} mode for different values of δ (here $\alpha = \pi/4$) and different polarization handedness.

Please note that, as discussed in [17], by acting on α (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

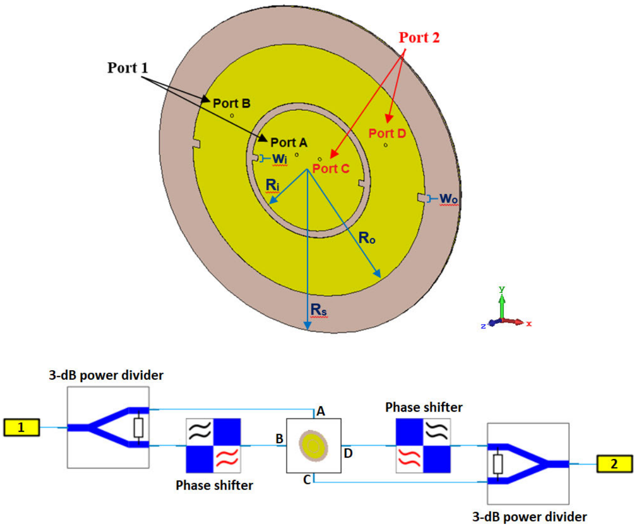

FIGURE 3. Perspective view of the proposed multi-antenna system and schematic representation of the feeding mechanism. Dimensions: $R_o = 38.4$ mm, $R_i = 18.5$ mm, $R_s = 50$ mm, $w_o = 2.33$ mm, $w_i = 1.83$ mm. Coaxial feed positions A = (−3.8 mm; 4.2 mm), B = (−25.4 mm; 12.4 mm), C = (3.8 mm; 4.2 mm), D = (25.4 mm; 12.4 mm). Substrate material: Roger Duroid^{TM} RT5870 (thickness 0.787 mm).

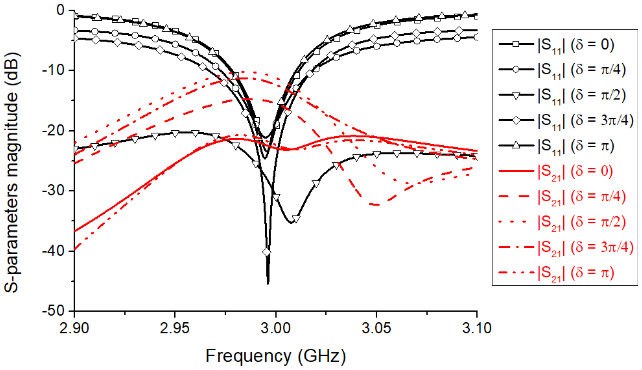

FIGURE 4. Simulated magnitude of the scattering parameters at the input ports of the radiating elements shown in Fig. 3.

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.

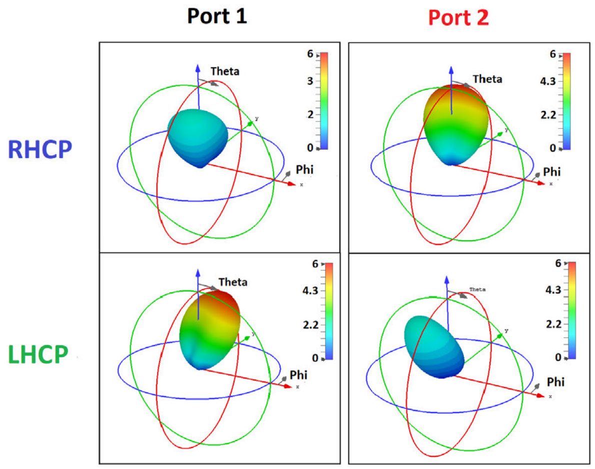

FIGURE 5. Co-polar and cross-polar 3D directivity patterns of Port 1 (LHCP composite vortex generation) and Port 2 (RHCP composite vortex generation). Here $\delta = 0$ and $\alpha = \pi/4$.

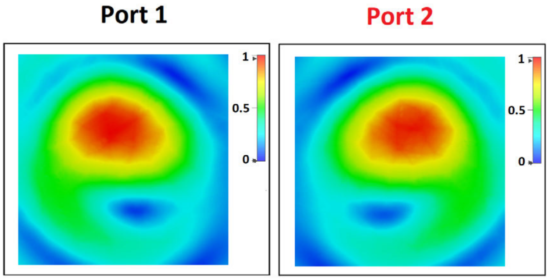

FIGURE 6. Total electric energy density ($|E|^2$) distributions at a distance $\lambda_0/2$ from the patch when exciting Port 1 (LHCP composite vortex generation) or Port 2 (RHCP composite vortex generation). Here $\delta = 0$ and $\alpha = \pi/4$.

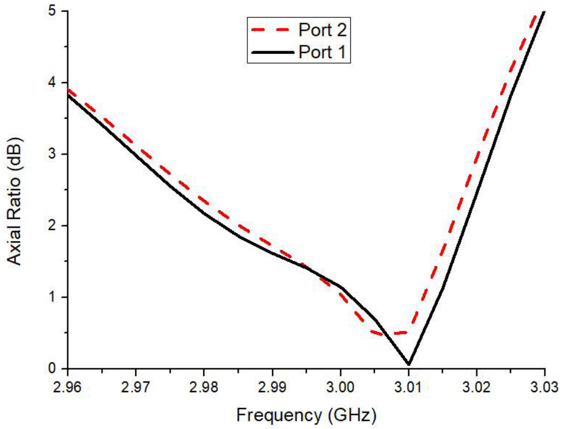

FIGURE 7. Axial Ratio in the main beam direction for Port 1 (LHCP composite vortex generation) and Port 2 (RHCP composite vortex generation). Here $\delta = 0$ and $\alpha = \pi/4$.

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

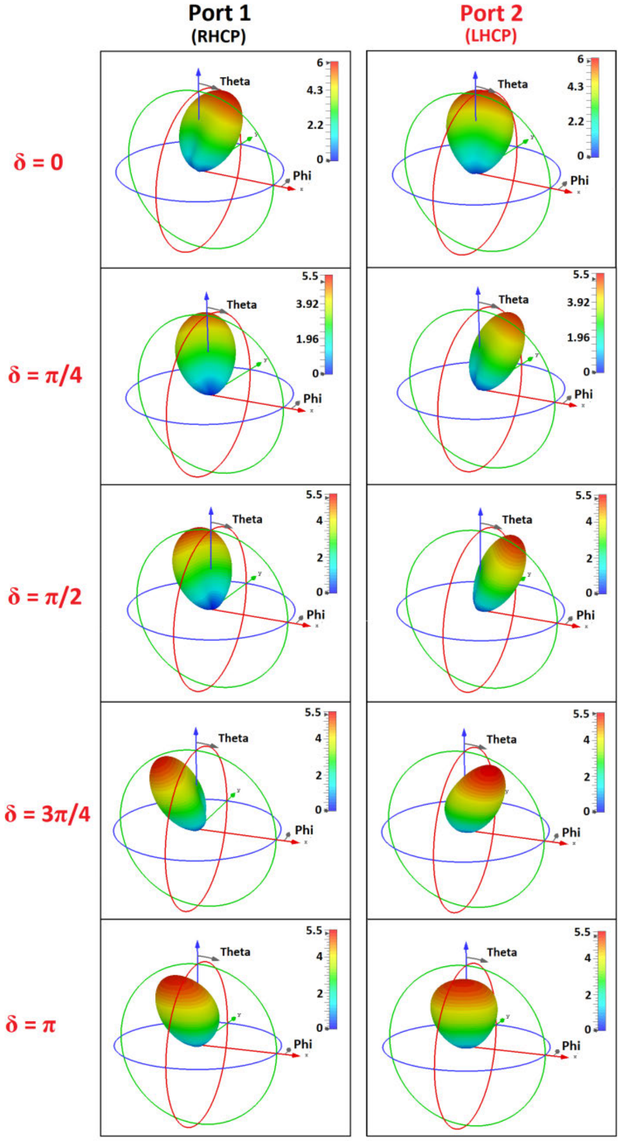

FIGURE 8. **Numerically calculated directivity patterns of Port 1 (LHCP composite vortex generation) and Port 2 (RHCP composite vortex generation) for different values of δ (here $\alpha = \pi/4$). In all the cases, the simulated total efficiency was above 0.7.**

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, $|S_{11}|$ and $|S_{21}|$ are both below -10 dB around the operative frequency of 3 GHz. The same results can be obtained also for $|S_{22}|$ and $|S_{12}|$, not reported here for sake of brevity.

TABLE 1. **Diversity performance at the center operating frequency.**

δ	$\|S_{21}\|$ (dB)	Pointing direction (θ°, φ°)			DG	ECC
		Port 1	Port 2	Δφ		
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^{-3}
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 ($\delta = 0$) 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 $\delta = 0$, 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

TABLE 2. Comparison with others pattern/polarization diversity two-element antennas.

Ref.	Pol. states	Pattern shapes	Pattern reconf.	Freq. behavior	Geometric structure
[7]	Dual-Linear	Conical vs. omni.	×	Single-band	3D
[8]	LH	Broadside vs. Omni.	×	Single-band	3D
[9]	Dual-Linear	Dual-directive	×	Dual-band	Planar
[10]	Dual-Linear	Broadside/ conical	×	Wide-band	Quasi-2D
[11]	Dual-Linear	Broadside/ Omni.	×	Single-band	Planar
[12]	LH/RH	Conical	×	Single-band	Planar
[13]	Dual-Linear	Broadside/ conical	×	Wide-band	Quasi-2D
[14]	Dual-Linear	Broadside/ conical	×	Single-band	Quasi-2D
This work	LH/RH	Dual-directive	✓	Single-band	Planar

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.

REFERENCES

[1] W. C. Y. Lee, *Mobile Communication Design Fundamentals*. Hoboken, NJ, USA: Wiley, 1993.

[2] C. Kilgus, "Shaped-conical radiation pattern performance of the backfire quadrifilar helix," *IEEE Trans. Antennas Propag.*, vol. AP-23, no. 3, pp. 392–397, May 1975.

[3] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.

[4] C. A. Balanis, *Antenna Theory: Analysis and Design*, Hoboken, NJ, USA: Wiley, 2016.

[5] S. N. Diggavi, N. Al-Dhahir, A. Stamoulis, and A. R. Calderbank, "Great expectations: The value of spatial diversity in wireless networks," *Proc. IEEE*, vol. 92, no. 2, pp. 219–270, Feb. 2004.

[6] Z. Xu and C. Deng, "High-isolated MIMO antenna design based on pattern diversity for 5G mobile terminals," *IEEE Antennas Wireless Propag. Lett.*, vol. 19, no. 3, pp. 467–471, Mar. 2020.

[7] X. Wang, Z. Feng, and K.-M. Luk, "Pattern and polarization diversity antenna with high isolation for portable wireless devices," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 209–211, 2009.

[8] C. Deng, Y. Li, Z. Zhang, and Z. Feng, "A circularly polarized pattern diversity antenna for hemispherical coverage," *IEEE Trans. Antennas Propag.*, vol. 62, no. 10, pp. 5365–5369, Oct. 2014.

[9] D. Sipal, M. P. Abegaonkar, and S. K. Koul, "Highly isolated compact planar dual-band antenna with polarization/pattern diversity characteristics for MIMO terminals," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 4, pp. 762–766, Apr. 2019.

[10] W. K. Toh, Z. N. Chen, X. Qing, and T. See, "A planar UWB diversity antenna," *IEEE Trans. Antennas Propag.*, vol. 57, no. 11, pp. 3467–3473, Nov. 2009.

[11] K. Wei, Z. Zhang, W. Chen, and Z. Feng, "A novel hybrid-fed patch antenna with pattern diversity," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 562–565, 2010.

[12] X. Bai, X. Liang, M. Li, B. Zhou, J. Geng, and R. Jin, "Dual-circularly polarized conical-beam microstrip antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 482–485, 2015.

[13] L. Cui, W. Wu, and D.-G. Fang, "Wideband circular patch antenna for pattern diversity application," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 1298–1301, 2015.

[14] L. Sun, G.-X. Zhang, B.-H. Sun, W.-D. Tang, and J.-P. Yuan, "A single patch antenna with broadside and conical radiation patterns for 3G/4G pattern diversity," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 433–436, 2016.

[15] M. Barbuto, F. Trotta, F. Bilotti, and A. Toscano, "Circular polarized patch antenna generating orbital angular momentum," *Prog. Electromagn. Res.*, vol. 148, pp. 23–30, Jun. 2014.

[16] M. Veysi, C. Guclu, F. Capolino, and Y. Rahmat-Samii, "Revisiting orbital angular momentum beams: Fundamentals, reflectarray generation, and novel antenna applications," *IEEE Antennas Propag. Mag.*, vol. 60, no. 2, pp. 68–81, Apr. 2018.

[17] M. Barbuto, M.-A. Miri, A. Alù, F. Bilotti, and A. Toscano, "Exploiting the topological robustness of composite vortices in radiation systems," *Prog. Electromagn. Res.*, vol. 162, pp. 39–50, May 2018.

[18] M. Barbuto, M.-A. Miri, A. Alù, F. Bilotti, and A. Toscano, "A topological design tool for the synthesis of antenna radiation patterns," *IEEE Trans. Antennas Propag.*, vol. 68, no. 3, pp. 1851–1859, Mar. 2020.

[19] P. Burghignoli, W. Fuscaldo, F. Mancini, D. Comite, P. Baccarelli, and A. Galli, "Twisted beams with variable OAM order and consistent beam angle via single uniform circular arrays," *IEEE Access*, vol. 8, pp. 163006–163014, 2020.

[20] A. F. Morabito, L. Di Donato, and T. Isernia, "Orbital angular momentum antennas: Understanding actual possibilities through the aperture antennas theory," *IEEE Antennas Propag. Mag.*, vol. 60, no. 2, pp. 59–67, Apr. 2018.

[21] M. Barbuto, A. Bassotti, A. Alu, F. Bilotti, and A. Toscano, "On the topological robustness of vortex modes at microwave frequencies," *Radioengineering*, vol. 27, no. 3, pp. 499–504, Sep. 2019.

[22] Dassault System. *CST Studio Suite*. Accessed: Mar. 25, 2021. [Online]. Available: https://www.3ds.com/products-services/simulia/products/cst-studio-suite/

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ANDREA ALÙ (Fellow, IEEE) received the Laurea, M.S., and Ph.D., degrees from Roma Tre University, Rome, Italy, in 2001, 2003, and 2007, respectively.

From 2002 to 2008, he has been periodically with the University of Pennsylvania (UPenn), Philadelphia, PA, USA, where he has also developed significant parts of his Ph.D. and postgraduate research. After spending one year as a Postdoctoral Research Fellow with UPenn, in 2009, he joined the Faculty of The University of Texas at Austin, Austin, TX, USA, where he was the Temple Foundation Endowed Professor, until 2018. He is currently an Adjunct Professor, the Senior Research Scientist, and a member of the Wireless Networking and Communications Group with The University of Texas at Austin. He is currently the Founding Director of the Photonics Initiative with the Advanced Science Research Center, Graduate Center of the City University of New York (CUNY), New York, NY, USA. He is also the Einstein Professor of physics with the CUNY Graduate Center, New York, and a Professor of electrical engineering with the City College of New York, New York. He has coauthored an edited book *Optical Antennas*, over 400 journal articles, and over 30 book chapters, with over 20000 citations to date. His current research interests include metamaterials and plasmonics, electromangetics, optics, and nanophotonics, acoustics, scattering, nanocircuits, and nanostructures, miniaturized antennas and nanoantennas, and RF antennas and circuits.

Dr. Alù is a Full Member of the International Union of Radio-Science (URSI) and a fellow of the Optical Society of America (OSA), the International Society for Optics and Photonics (SPIE), and the American Physical Society. He has received several research awards, including the URSI Commission B, in 2004, 2007, and 2010, the Young Scientist Awards from URSI General Assembly, in 2005, the AFOSR and the DTRA Young Investigator Awards, in 2010 and 2011, the NSF CAREER Award in 2010, the URSI Issac Koga Gold Medal, in 2011, the SPIE Early Career Investigator Award, in 2012, the Franco Strazzabosco Award for Young Engineers, in 2013, the IUPAP Young Scientist Prize in Optics, in 2013, the OSA Adolph Lomb Medal, in 2013, the IEEE Microwave Theory and Techniques (MTT) Outstanding Young Engineer Award, in 2014, the NSF Alan T. Waterman Award, in 2015, the ICO Prize in Optics, in 2016, the Inaugural MDPI Materials Young Investigator Award, in 2016, the Kavli Foundation Early Career Lectureship in Materials Science, in 2016, the Inaugural ACS Photonics Young Investigator Award Lectureship, in 2016, the Edith and Peter O'Donnell Award in Engineering, in 2016, the Vannevar Bush Faculty Fellowship from the Department of Defense, in 2019, and the IEEE Kiyo Tomiyasu Award, in 2019. His students, Y. Zhao in 2011 and J. Soric in 2012, have also received several awards, including student paper awards from the IEEE Antennas and Propagation Symposia. He was the Technical Program Chair of the IEEE Antennas and Propagation (AP)-S Symposium, in 2016, and the International Metamaterials Conference, in 2014 and 2015. He has been a Simons Investigator in physics, since 2016, has been selected twice as the finalist of the Blavatnik Award for Young Scientists, in 2016, 2017, 2018, and 2019. He has organized and chaired various special sessions in international symposia and conferences. He is currently on the Editorial Boards of *Physical Review B*, the *New Journal of Physics*, *Advanced Optical Materials*, *MDPI Materials*, *EPJ Applied Metamaterials*, and *ISTE Metamaterials*. He served as an Associate Editor for the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, *Scientific Reports*, Metamaterials, *Advanced Electromagnetics*, and *Optics Express*. He has Guest Edited Special Issues for the IEEEJOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, the IEEE ANTENNAS AND WIRELESS PROPAGATION Letters, *Nanophotonics*, the *Journal of Optics*, the *Journal of the Optical Society of America B*, *Photonics and Nanostructures: Fundamentals and Applications*, *Optics Communications*, *Metamaterials*, and *Sensors* on a variety of topics involving metamaterials, plasmonics, optics, and electromagnetic theory. He has been a Highly Cited Researcher from Web of Science, since 2017. He has been serving as an OSA Traveling Lecturer since 2010, the IEEE AP-S Distinguished Lecturer since 2014, and as the IEEE joint AP-S and MTT-S Chapter for Central Texas.

FILIBERTO BILOTTI (Fellow, IEEE) received the Laurea and Ph.D. degrees in electronic engineering from Roma Tre University, Rome, Italy, in 1998 and 2002, respectively.

Since 2002, he has been with the Faculty of Engineering, from 2002 to 2012, and then, the Department of Engineering, Roma Tre University, since 2013, where he has been serving as a Full Professor of Electromagnetic Field Theory, since 2014, and the Director of the Antennas and Metamaterials Research Laboratory, since 2012. His main research interests include analysis and design of microwave antennas and arrays, analytical modeling of artificial electromagnetic materials, metamaterials, and metasurfaces, including their applications at both microwave and optical frequencies. In the last ten years, his main research interests have been focused on the analysis and design of cloaking metasurfaces for antenna systems, on the modeling and applications of (space and) time-varying metasurfaces, on the topological-based design of antennas supporting structured field, on the modeling, design, and implementation of non-linear and reconfigurable metasurfaces, on the concept of meta-gratings and related applications in optics and at microwaves, on the modeling and applications of optical metasurfaces. The research activities developed in the last 20 years, from 1999 to 2019, has resulted in more than 500 articles in international journals, conference proceedings, book chapters, and three patents.

Prof. Bilotti has been serving for the scientific community, by playing leading roles in the management of scientific societies, such as the editorial board of international journals and the organization of conferences and courses. In particular, he was a Founding Member of the Virtual Institute for Artificial Electromagnetic Materials and Metamaterials (Metamorphose VI), in 2007. He was elected as a member of the Board of Directors of the Virtual Institute for Artificial Electromagnetic Materials and Metamaterials (Metamorphose VI) for two terms, from 2007 to 2013, and the President for two terms, from 2013 to 2019. He has been serving for the Metamorphose VI as the Vice President and the Executive Director, since 2019. He was a recipient of a number of awards and recognitions, including the elevation to the IEEE fellow grade for contributions to metamaterials for electromagnetic and antenna applications in 2017, an Outstanding Associate Editor of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION in 2016, the NATO SET Panel Excellence Award in 2016, the Finmeccanica Group Innovation Prize in 2014, the Finmeccanica Corporate Innovation Prize in 2014, the IET Best Poster Paper Award (Metamaterials 2013 and Metamaterials 2011), and the Raj Mittra Travel Grant Senior Researcher Award in 2007. In 2007, he hosted the inaugural edition of the *International Congress on Advanced Electromagnetic Materials in Microwave and Optics–Metamaterials Congress*. He served as the Chair for the Steering Committee of the International Congress on Advanced Electromagnetic Materials in Microwave and Optics–Metamaterials Congress for eight editions, from 2008 to 2014, and 2019. He was elected as the General Chair of the Metamaterials Congress, from 2015 to 2018. He was also the General Chair of the Second International Workshop on Metamaterials-by-Design Theory, Methods, and Applications to Communications and Sensing, in 2016. He has been serving as the Chair or a member of the technical program, steering, and organizing committee of the main national and international conferences in the field of applied electromagnetics. He served as an Associate Editor for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, from 2013 to 2017, and the journal *Metamaterials*, from 2007 to 2013 and as a member of the Editorial Board of the *International Journal on RF and Microwave Computer-Aided Engineering*, from 2009 to 2015, *Nature Scientific Reports*, from 2013 to 2016, and *EPJ Applied Metamaterials*, since 2013. He was also the Guest Editor of five Special Issues in international journals.

ALESSANDRO TOSCANO (Senior Member, IEEE) was born in Capua, in 1964. He received the degree in electronic engineering from the Sapienza University of Rome, in 1988, and the Ph.D. degree, in 1993.

Since 2011, he has been a Full Professor of Electromagnetic Fields with the Department of Engineering, Roma Tre University. He carries out an intense academic and scientific activity, both nationally and internationally. From April 2013 to January 2018, he was a member of Roma Tre University Academic Senate. From October 2016 to October 2018, he was a member of the National Commission which enables National Scientific Qualifications to Full and an Associate Professors in the tender sector 09/F1–Electromagnetic fields. Since 23rd January 2018, he has been a Vice-Rector for Innovation and Technology Transfer. He actively participated in founding the international association on metamaterials of the Virtual Institute for Advanced Electromagnetic Materials (Metamorphose, VI). He coordinates and participates in several research projects and contracts funded by national and international public and private research institutions and industries. He is the author of more than 100 publications in international journals indexed ISI or Scopus of these on a worldwide scale, three are in the first 0.1 percentile, five in the first 1 percentile, and 25 in the first 5 percentile in terms of number of quotations and journal quality. His scientific research has as ultimate objective the conceiving, designing, and manufacturing of innovative electromagnetic components with a high technological content that show enhanced performance compared to those obtained with traditional technologies and that respond to the need for environment and human health protection. His research activities are focused on three fields: metamaterials and unconventional materials, in collaboration with Prof. A. Alù's Group, The University of Texas at Austin, USA, research and development of electromagnetic cloaking devices and their applications (First place winner of the Leonardo Group Innovation Award for the research project entitled: 'Metamaterials and electromagnetic invisibility') and the research and manufacturing of innovative antenna systems and miniaturized components (first place winner of the Leonardo Group Innovation Award for the research project entitled: ''Use of metamaterials for miniaturization of components''–MiniMETRIS).

Dr. Toscano commitment in organizing scientific events, he also carries out an intense editorial activity as a member of the review committees of major international journals and conferences in the field of applied electromagnetics. He has held numerous invited lectures at universities, public and private research institutions, national and international companies on the subject of artificial electromagnetic materials, metamaterials, and their applications.

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