Generating Tunable Orbital Angular Momentum Radio Beams With Dual-Circular-Polarization and Dual-Mode Characteristics

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ABSTRACT In this paper, a mode and circular-polarization (CP) simultaneously reconfigurable patch array antenna for orbital angular momentum (OAM) beams generation is presented and experimentally investigated. The array antenna simply consists of a 1:4 power divider and four antenna elements, each of which is fed with two switchable ports and a quadrature phase shift. Besides, the four elements are arranged using an orthogonal configuration. In this manner, switchable CPs are generated for each element, and switchable $\pm 90^\circ$ phase differences are obtained between adjacent elements. By strategically varying the ON/OFF status of the p-i-n diodes loaded as switches, the antenna could operate among left-hand CP (LHCP) with OAM-mode $+1$ or $-1$ and right-hand CP (RHCP) with OAM-mode $+1$ or $-1$. Without additional phase-shifting networks, the design method can be easily extended to large-scale antenna arrays. According to the measured results, an overlapped operational band of 2.39 to 2.64 GHz is obtained among the four states. In addition, both far-field and near-field distributions are performed to verify the design. Owing to its flexibility of OAM mode and polarization reconfigurability as well as symmetrical and simple configuration, the antenna could be a promising application in future OAM-based communications system.

INDEX TERMS Orbital angular momentum, mode reconfigurability, circular-polarization reconfigurability, reconfigurable element.

I. INTRODUCTION

Nowadays, the demand for wireless communications with high capacity and good adaptability is growing rapidly. Due to the limitation of available spectrum resources, orbital angular momentum (OAM) technology is considered as a potential choice in wireless communications, which can remarkably increase the capacity with low crosstalk on the same frequency under certain conditions [1], [2]. As a key component, the antennas with switchable operating states are capable of adapting the sudden change including pattern, polarization, or other performances to enhance their robustness [3]–[5]. With the attractive features mentioned above, the design of OAM reconfigurable antennas has become a topic of concern in recent years.

Up to now, various types of antenna have been used to generate radio beams with OAM vortices, including spiral phase plate (SPP) [6], [7], dielectric resonator antenna (DRA) [8], eigenmode-based antenna [9]–[11], metasurface [12]–[16], and uniform circular array (UCA) [17]–[19]. However, some antennas [6]–[9] can only produce one fixed OAM mode corresponding to a specific structure. In [10]–[14], their physical structures or dimensions must be changed with OAM modes, thus these antennas are not suitable for the adjustable characteristics. The programmable metasurfaces have the potential for flexible OAM-waves generation. An efficient reconfigurable transmissive metasurface [15] is exploited to produce tunable multimode OAM beams. A reflective metasurface loaded with varactor diodes is also applied for realizing mode reconfigurability [16]. However, there exists a large amount of switches and lumped components in these reconfigurable metasurfaces. In addition, it is difficult to integrate their 3D structures within...
the planar circuits. Alternatively, the UCAs facilitate phase control of the elements, which makes them a good candidate for reconfigurable antenna designs [20]–[27]. The antenna arrays [21], [22] enable OAM-mode manipulation with the aid of a reconfigurable feed network (RFN). A mechanically reconfigurable array with single-arm spiral antennas is used to generate broadband circularly polarized vortex waves [23]. By using sequentially rotated feed technique, the antenna [24] with two feed networks can radiate dual CP dual-mode OAM beams, which are controlled by switching the excitation ports. However, most antennas mentioned above suffer from limitations such as complex feed network, slow tuning speed, or single parameter reconfigurability.

In this paper, a dual-mode and dual-circular-polarization compound reconfigurable patch array antenna for generating vortex beams is presented. It is constructed based on a UCA of four multi-functional elements, which offers polarization switching between left-hand CP (LHCP) and right-hand CP (RHCP) as well as provides specific initial phases to simplify the feed structure. By controlling the embedded radio frequency (RF) switches, the initial phases are superimposed with an additional and tunable $+90^\circ$ or $-90^\circ$ phase shift. As a result, the total excitation phases satisfy the phase requirements for achieving both OAM-mode $l = +1$ or $-1$ along with LHCP or RHCP. Also, via theoretical analysis and experimental discussions, good impedance matching and axial ratio (AR) performance are obtained for all chosen states. Moreover, the far- and near-field results for different OAM modes are experimentally verified.

II. ANTENNA DESIGN AND ANALYSIS

A. DESIGN SCHEME

The generation of OAM beams with a UCA requires feeding the antenna elements with equal amplitude but a successive phase delay. In the four-element UCA (denoted by Ant. 1) at Cartesian coordinates $(u, v, w)$, the excitation phases for realizing OAM mode $l = +1$ are adopted as shown in Fig. 1(a). For reconfigurable antenna designs, a conventional way is to feed the elements with tunable phases, which are provided by switchable transmission lines (TLs) of different lengths. However, the use of TLs with electrical lengths of more than $90^\circ$ will complex the feed network layout and cause additional insertion losses. To alleviate this problem, the mirror-image configuration can be adopted to provide a $180^\circ$ phase shift between the left and right two elements. As a result, the lengths of the feedlines can be shortened and the phases of elements in Ant. 2 are symmetric along the diagonals $u = v$ and $u = -v$, as shown in Fig. 1(b). Since the antenna elements can be dual-fed with a quadrature phase difference between the $u$- and $v$-polarized components for CP. Both OAM mode $l = +1$ and LHCP can be obtained by introducing a $v$-polarized component for elements in Ant. 3, as shown in Fig. 1(c). To further realize CP reconfigurability, additional $u$- and $v$-polarized components are introduced for each element, and Ant. 4 is developed. It comprises four elements with switchable dual-fed, as depicted in Fig. 1(d). By appropriately selecting the excitation phases of the $u$- and $v$-polarized components, OAM-mode agility is finally obtained along with CP reconfigurability. The operating states of the antenna array with different feed configurations are summarized in Table 1. In the expression for each excitation component, the subscript plus or minus sign denotes its orientation, while the required excitation phases are given in bracket. It is seen that LHCP or RHCP characteristics along with OAM beam with mode $+1$ or mode $-1$ can be achieved.

*TABLE 1. Feeding schemes for each antenna element under different states.*

| State Element | 1 | 2 | 3 | 4 |
|---------------|---|---|---|---|
| E1            | $u.(0^\circ)+$ | $v.(90^\circ)$ | $u.(0^\circ)+$ | $v.(-90^\circ)$ |
| E2            | $u.(-90^\circ)+$ | $v.(0^\circ)$ | $u.(-90^\circ)+$ | $v.(90^\circ)$ |
| E3            | $u.(0^\circ)+$ | $v.(-90^\circ)$ | $u.(0^\circ)+$ | $v.(-90^\circ)$ |
| E4            | $u.(-90^\circ)+$ | $v.(0^\circ)$ | $u.(-90^\circ)+$ | $v.(90^\circ)$ |
| OAM-mode      | +1 | -1 | +1 | -1 |
| Polarization  | LHCP | LHCP | RHCP | RHCP |
is that for each element, four specific excitation phases are needed in different directions $u^+, u^-, v^+, v^-$. To resolve these challenges, the total antenna array is constructed with an orthogonal arrangement, allowing to form different phases for different elements in one direction. Furthermore, the antenna elements could also be designed tunable feed ports as well as a phase-shifting feedline. Switching the feed ports helps to alter the orientation of antenna currents, and properly selecting the lengths of the corresponding feedlines further results in a switchable phase difference between ports. In this way, the phase requirements for different directions of each element could be satisfied.

**FIGURE 2.** Configuration of the proposed antenna array. (a) Side view. (b) Top view. (c) Zoomed-in view of antenna element (Unit: mm).

**B. ANTENNA CONFIGURATION**

Based on the design idea, the configuration of the proposed array antenna is shown in Fig. 2. The antenna is located at the Cartesian coordinate system $Oxyz$, in which each element is rotated by 45° anticlockwise around $z$-axis so that the total 1:4 power divider can be designed with relatively short lengths. The four elements are mirror arranged with respect to both $x$- and $y$-axes. This 1:4 power divider is composed of two stages of equal-amplitude and in-phase Wilkinson power splitters. A dual-fed antenna element is developed based on the stacked microstrip antenna in our previous work [27]. The ring and circular patches are separately printed on top of the middle and upper substrates. The former is electrically connected and excited by the feeding probes while the latter is coupled-fed by the ring patch. The feed structure of the antenna is modified with four switchable probes, two of which are used each time, as shown in Fig. 2 (c). To realize switching function, 4 pairs of p-i-n diodes are embedded in the feedlines and connected to the feeding probes, which serve as binary switches. Each pair arranged in a back-to-back configuration is controlled by a bias voltage. Moreover, there exists a quarter-wavelength difference between the feedlines connected to the probes along the main and minor diagonals. Hence, the input signal is divided by a 1:2 Wilkinson power divider, then selected by a switchable feedline, and finally delivered to two feed probes with equal amplitude and a quadrature phase difference.

In the bias circuit of p-i-n diodes, the anodes are attached to the individual bias pads while cathodes to the common ground. By switching the probes and corresponding feedlines, dual feed with a counterclockwise $-90° (+90°)$ or $-90°$ phase difference are selected for exciting the element, and thus LHCP or RHCP reconfigurability can be realized. Moreover, thanks to the orthogonal arrangement and switchable dual-feed method, the required phases for both OAM-mode and polarization reconfigurability can be fulfilled without additional reconfigurable feed network.

The performance of antenna array is investigated through simulation. In the simulation using ANSYS HFSS, the equivalent circuit models of the p-i-n diode for ON and OFF status.

**FIGURE 3.** Equivalent circuit models of the p-i-n diode for ON and OFF status.

In Fig. 3, they are modeled as an inductance of $L_s = 0.45 \text{ nH}$ in series with a capacitance of $C_t = 0.18 \text{ pF}$ for OFF status. To explain the working mechanism, the surface current distributions of the antenna array are analyzed. Using state 1 as an example, the simulated results are plotted in Fig. 4. It is found that the current on each antenna element rotates clockwise within a time period $T$, resulting in LHCP. Besides, a 90° successive phase delay is also observed between adjacent elements, which contributes to the generation of OAM waves with mode $l = +1$. The current distributions for the other states can be obtained similarly.

In Fig. 5(a), the simulated reflection coefficients indicate that the antenna array exhibits an overlapped impedance bandwidth with $|S_{11}| \leq -15 \text{ dB}$ of 270 MHz ranging from 2.4 to 2.67 GHz. According to the radiation patterns, the
antenna exhibits good consistency among different operating states, and their main lobe directions are about $\theta = 30^\circ$. The ARs along a circular path on the main lobe are below 3 dB. Specifically, for $\phi = 0^\circ$ at $\theta = 30^\circ$, the overlapped bandwidth with $\text{AR} < 3$ dB is about 660 MHz (2.24–2.9 GHz), as shown in Fig. 5(b).

The near-field phase distributions for the four operating states are plotted in Fig. 6. As can be seen, the phase changes $2\pi$ radians in a clockwise direction along a circular path around the $z$-axis for states 1 and 3, which suggests the generation of OAM beams with mode $+1$. For states 2 and 4, the phase distributions are in correspondence with that of OAM beams with mode $-1$.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. ANTENNA FABRICATION

Based on the design and analysis, an antenna prototype is manufactured, as shown in Fig. 7. The prototype mainly consist of a sandwich-like structure on a three-layered printed circuit board (PCB) and four circular patches on single-layered PCBs. In the sandwich-like structure, the ring patches serving as driven radiators are printed on the upper layer. Their feed lines as well as the total 1:4 power divider of the array are fabricated on the lower layer. The bias circuits including the shoring vias and bias pads are arranged beside the feed lines. In addition, a common ground plane is vertically sandwiched between the upper and lower layers. To prevent
short circuits while feeding energy to the upper ring patches, part of ground plane is demetallized for the feed probes to pass through. The circular substrates with parasitic radiators located at top are supported by plastic holders. To facilitate the switching of bias configurations, a control board realized on a 1mm-thickness FR4 substrate is placed beneath the bias circuit. With the aid of a microcontroller, the appropriate direct current (dc) bias voltages for the reconfigurable states can be produced as listed in Table 2. The generated control signals are delivered to the bias circuit through flexible wires. Assembled with plastic screws, the entire array has overall dimensions of 169 × 169 × 7 mm³.

B. REFLECTION COEFFICIENTS AND AXIAL RATIOS

Measured reflection coefficients of the proposed antenna array are plotted in Fig. 8(a). The operating states are chosen according to those defined in Table 2. It is indicated that the measured bandwidth with $|S_{11}| \leq -15$ dB for four states are 10.4% (2.38-2.64 GHz), 12.7% (2.36-2.68 GHz), 11.2% (2.37-2.65 GHz) and 10.0% (2.39-2.64 GHz), respectively. Therefore, the overlapped impedance bandwidth reaches 10.0% (2.39-2.64 GHz). Moreover, the use of the dual-fed antenna element can offer good AR performance, and the measured AR curves at each state are depicted in Fig. 8(b). It is observed that the ARs values within the range from $\theta = -50^\circ$ to $+50^\circ$ are less than 3-dB except the singularity point of $\theta = 0^\circ$ in both xoz- and yoz-planes at 2.5 GHz.

C. NEAR-FIELD DISTRIBUTIONS

Spiral electric field distributions are typical characteristics of vortex electromagnetic waves, which can be investigated by examining the near-field phase and intensity distributions. The measurement are implemented with a two-dimensional scanning system in the anechoic chamber, as displayed in Fig. 9. The distance between the measured antenna and observed surface is 500 mm, which is about 4.5 $\lambda_0$ at 2.5 GHz. The scanning plane has a range of 800 mm × 800 mm with an increment of 5 mm. $E_x$- and $E_y$- field components are separately recorded. By combining these two field components, the resultant intensity and phase distributions of $E_{cp}$-field are shown in Figs. 10 and 11, respectively.

It is clearly that at all states, there exists intensity nulls in the broadside direction, forming a hollow structure similar to a donut. It also can be seen that the phases of the electric field at states 1 and 3 are distributed along a circular path around the z-axis and change $2\pi$ radians in a clockwise direction, corresponds to OAM mode $l = +1$. In contrast, at states 2 and 4, the phase changes $2\pi$ radians in a counterclock- wise direction, which corresponds to OAM mode $l = -1$. These measured results prove the validity and correctness of the design strategy in the vortex electromagnetic wave generations.

The normalized far-field radiation patterns in the xoz- and yoz-planes at 2.5 GHz are shown in Fig. 12. Due to the symmetry of the structure, the divergence angles at which the maximum co-polarization gain occurs of all states show
TABLE 3. Comparison of OAM mode-reconfigurable antennas.

| Ref. | Center freq. | No. of states | Polarization | OAM modes | Independently controlled of OAM modes and Polarizations | Reconfigurable type (Num. of pin diodes) |
|------|--------------|---------------|--------------|------------|-------------------------------------------------------|----------------------------------------|
| [15] | 7.5 GHz      | 5             | LP           | $l=0, \pm 1, \pm 2$ | NO                                                   | Electrical (800 pin diodes)            |
| [21] | 2.4 GHz      | 2             | LP           | $l=\pm 1$  | NO                                                   | Electrical (4 pin diodes)              |
| [23] | 2.5 GHz      | 7             | LHCP, RHCP   | $l=\pm 1$  | NO                                                   | Mechanical rotation                    |
| [25] | 5.8 GHz      | 2             | LHCP, RHCP   | $l=\pm 1$  | NO                                                   | Electrical (16 pin diodes)             |
| [26] | 5.7 GHz      | 3             | LP           | $l=0, \pm 1$ | NO                                                   | Electrical (32 pin diodes)             |
| Prop.| 2.5 GHz      | 4             | LHCP, RHCP   | $l=\pm 1$  | YES                                                  | Electrical (32 pin diodes)             |

FIGURE 10. Measured near-field intensity distributions of $E_{cp}$ at 2.5 GHz.

FIGURE 11. Measured near-field phase distributions of $E_{cp}$ at 2.5 GHz.

good consistency. It can be found that there is an amplitude null in the propagation direction due to the helical phase profile. Moreover, it is seen that the proposed antenna can produce dual-polarization properties, namely, LHCP and RHCP. It is also found from these figures that the measured cross-polarization discriminations are kept below $-20$ dB.

Finally, Table 3 compares the performance of the proposed reconfigurable OAM antenna with other referenced works.

As indicated, the proposed antenna has superior performance in arbitrarily switching operating states between two circular polarizations while maintaining a relatively simple antenna structure. Moreover, the proposed antenna array supports the element phase reconfiguration. It is expected that this method could be extended to larger elements antenna array to generate higher order OAM waves without extra phase-shifting network.

IV. CONCLUSION

In summary, a dual OAM modes and dual CPs reconfigurable antenna array is designed, fabricated, and measured. The antenna array is constructed based on a UCA of four dual-fed elements, each of which provides a quadrature phase difference between adjacent feed ports. By properly selecting feed probes of each element and arranging the elements orthogonally, the required phases for dual CPs and dual OAM modes can be achieved simultaneously. Measured results indicate that the fabricated antenna prototype achieves four operating states with OAM mode $l = \pm 1$ or $-1$ as well as LHCP or RHCP. These states are switched by tuning the bias voltages of the embedded p-i-n diodes. The antenna operates over the frequency range of 2.39–2.64 GHz and exhibits good AR performance. Besides, far-field patterns are symmetric with null depths of lower than $-20$ dB and cross-polarization discriminations of more than 20 dB. Therefore, this method could be suitable for future OAM-based communication system due to great flexibility of modes and polarizations reconfigurability.
REFERENCES

[1] Y. Yan, G. Xie, M. P. Lavery, H. Huang, N. Ahmed, C. Bao, Y. Ren, Y. Cao, L. Li, Z. Zhao, and A. F. Molisch, “High-capacity millimetre-wave communications with orbital angular momentum multiplexing,” Nature Commun., vol. 5, no. 1, p. 4876, 2014.

[2] W. Zhang, S. Zheng, X. Hui, R. Dong, X. Jin, H. Chi, and X. Zhang, “Mode division multiplexing communication using microwave orbital angular momentum: An experimental study,” IEEE Trans. Wireless Commun., vol. 16, no. 2, pp. 1308–1318, Feb. 2017.

[3] L. Han, Y. Ping, Y. Liu, G. Han, and W. Zhang, “A low-profile pattern reconfigurable MIMO antenna,” IEEE Access, vol. 8, pp. 34500–34506, 2020.

[4] W.-W. Yang, X.-Y. Dong, W.-J. Sun, and J.-X. Chen, “Polarization reconfigurable broadband dielectric resonator antenna with a lattice structure,” IEEE Access, vol. 6, pp. 21121–21219, 2018.

[5] J. Deng, S. Hou, L. Zhao, and L. Guo, “A reconfigurable filtering antenna with integrated bandpass filters for UWB/WLAN applications,” IEEE Trans. Antennas Propag., vol. 66, no. 1, pp. 401–404, Jan. 2018.

[6] X. Hui, S. Zheng, Y. Hu, C. Xu, X. Jin, H. Chi, and X. Zhang, “Ultrawide reflectivity spiral phase plate for generation of millimeter-wave OAM beam,” IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 966–969, 2015.

[7] P. Schemmel, G. Pisano, and B. Maffei, “Modular spiral phase plate design for orbital angular momentum generation at millimetre wavelengths,” Opt. Express, vol. 22, no. 12, pp. 14712–14726, Jun. 2014.

[8] Y. Pan, S. Zheng, J. Zheng, Y. Li, X. Jin, H. Chi, and X. Zhang, “Generation of orbital angular momentum radio waves based on dielectric resonator antenna,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 385–388, 2017.

[9] C. Deng and Z. Feng, “Three methods to generate orbital angular momentum beams in microwaves,” in Proc. Cross Strait Quad-Regional Radio Sci. Wireless Technol. Conf. (CSQRWC), Jul. 2018, pp. 1–2.

[10] F. Shen, J. Mu, K. Guo, and Z. Guo, “Generating circularly polarized vortex electromagnetic waves by the conical conformal patch antenna,” IEEE Trans. Antennas Propag., vol. 67, no. 9, pp. 5763–5771, Sep. 2019.

[11] Z. Zhang, S. Xiao, Y. Li, and B.-Z. Wang, “A circularly polarized multi-mode patch antenna for the generation of multiple orbital angular momentum modes,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 521–524, 2017.

[12] X. Bai, F. Kong, J. Qian, Y. Song, C. He, X. Liang, R. Jin, and W. Zhu, “Polarization-insensitive metasurface lens for efficient generation of convergent OAM beams,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 12, pp. 2696–2700, Dec. 2019.

[13] D. Zelenchuk and V. Fusco, “Split-ring FSS spiral phase plate,” IEEE Antennas Wireless Propag. Lett., vol. 12, pp. 284–287, 2013.

[14] H.-F. Huang and S.-N. Li, “High-efficiency planar reflectarray with small-size for OAM generation at microwave range,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 3, pp. 432–436, Mar. 2019.

[15] X. Bai, “High-efficiency transmissive metasurface for dual-polarized dual-mode OAM generation,” Adv. Opt. Mater., vol. 18, no. 8, Sep. 2020, Art. no. 103334.

[16] K. Guo, Q. Zheng, Z. Yin, and Z. Guo, “Generation of mode-reconfigurable and frequency-adjustable OAM beams using dynamic reflective metasurface,” IEEE Access, vol. 8, pp. 75523–75529, 2020.

[17] S. Mohaghegh Mohammadi, L. K. S. Daldorff, J. E. S. Bergman, R. L. Karlsson, B. Thide, K. Forozesh, T. D. Carozzi, and B. Isham, “Orbital angular momentum in radio—A system study,” IEEE Trans. Antennas Propag., vol. 58, no. 2, pp. 565–572, Feb. 2010.

[18] F. Qin, L. Li, Y. Liu, W. Cheng, and H. Zhang, “A four-mode OAM antenna array with equal divergence angle,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 9, pp. 1941–1945, Sep. 2019.

[19] H. Li, L. Kang, F. Wei, Y.-M. Cai, and Y.-Z. Yin, “A low-profile dual-polarized microstrip antenna array for dual-mode OAM communications,” IEEE Antennas Wireless Propag. Lett., vol. 16, no. 2, pp. 3022–3025, 2017.

[20] C. Deng, K. Zhang, and Z. Feng, “Generating and measuring tunable orbital angular momentum radio beams with digital control method,” IEEE Trans. Antennas Propag., vol. 65, no. 2, pp. 899–902, Feb. 2017.

[21] B. Liu, G. Lin, Y. Cui, and R. Li, “An orbital angular momentum (OAM) mode reconfigurable antenna for channel capacity improvement and digital data encoding,” Sci. Rep., vol. 7, no. 1, p. 9852, Aug. 2017.

[22] Y.-Y. Wang, Y.-X. Du, L. Qin, and B.-S. Li, “An electronically mode reconfigurable orbital angular momentum array antenna,” IEEE Access, vol. 6, pp. 64603–64610, 2018.

[23] L. Li and X. Zhou, “Mechanically reconfigurable single-arm spiral antenna array for generation of broadband circularly polarized orbital angular momentum vortex waves,” Sci. Rep., vol. 8, no. 1, p. 5128, Mar. 2018.

[24] X.-D. Bai, X.-L. Liang, Y.-T. Sun, P.-C. Hu, Y. Yao, K. Wang, J.-P. Geng, and R.-H. Jin, “Experimental array for generating dual circularly-polarized dual-mode OAM radio beams,” Sci. Rep., vol. 7, no. 1, p. 40099, Jan. 2017.

[25] Q. Liu, Z. N. Chen, Y. Liu, F. Li, Y. Chen, and Z. Mo, “Circular polarization and mode reconfigurable wideband orbital angular momentum patch array antenna,” IEEE Trans. Antennas Propag., vol. 66, no. 4, pp. 1796–1804, Apr. 2018.

[26] J. Wu, Z. Zhang, X. Ren, Z. Huang, and X. Wu, “A broadband electronically mode-reconfigurable orbital angular momentum metasurface antenna,” IEEE Antennas Wireless Propag. Lett., vol. 18, no. 7, pp. 1482–1486, Jul. 2019.

[27] L. Kang, H. Li, J. Zhou, and S. Zheng, “An OAM-mode reconfigurable antenna array with polarization agility,” IEEE Access, vol. 8, pp. 40445–40452, 2020.

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