Coupling-inspired metasurfaces for polarization-correlation customizable absorption

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Abstract
Polarization-correlation customizable metasurface absorbers based on circular dichroism (CD) meta-atoms were proposed in this paper, of which the polarization-correlation can be altered by controlling the coupling effect between the CD meta-atoms with the same chirality. CD meta-atoms implemented via introducing resistance film into chiral resonators were firstly proposed. Wideband, high-efficiency left-handed/right-handed CD meta-atoms were demonstrated, respectively, for which the left-handed/right-handed circularly polarized (LCP/RCP) incident wave was strongly absorbed but the RCP/LCP incident wave was reflected into LCP/RCP wave with high efficiency. The metasurface absorber consisting of CD-meta-atom pairs were put forward for polarization-correlation customizable absorption. The coupling between two CD meta-atoms was investigated by theoretical and simulation analysis, which can be manipulated by controlling the orientation angles of the CD meta-atoms. As a proof-of-concept, a polarization-insensitive absorber utilizing a C4 2 × 2 CD-meta-atom pair was designed, simulated and measured. Attributed to the strong coupling between the four CD meta-atoms, both LCP and RCP wave were strongly absorbed in a wide frequency range from 8 GHz to 20 GHz. This paves a new way for designing wideband metasurfaces with polarization-correlation customizable performance.

1. Introduction
Metamaterials are materials with artificial structures which can achieve properties that may not be found in nature. They are attractive not only for their exotic electromagnetic properties, but also their promise for applications in various fields. A particular branch—the metamaterial absorber (MMA)—has been paid a great attention increasingly due to its potential application in stealth technology, energy harvester, sensing and so on [1–6]. The performance of MMAs is related to the constituent materials as well as the structure and dimensions of their unit cells, offer nearly perfect absorption, deeply sub-wavelength thickness, and tenability. Since Landy et al firstly reported the concept of the perfect MMA, which consists of two resonators coupled to the electric and magnetic fields separately to absorb the incident waves [7], realizations of the high performance and multi-functional MMAs for various applications are always the important goals pursued by researchers [8, 9]. Up to now, various MMAs, which are either multiple band [10–12], polarization-insensitive [13, 14] or broadband [15–17], have been successfully realized to absorb EM waves across the whole spectrum from microwave to visible region [18–21]. Chen proposed the interference theory to explain the physical mechanism of MMAs, an extremely broadband absorber based on destructive interference mechanism was then demonstrated [22, 23]. The MMA composed of
three-layered split ring resonators (SRRs) structure realized a successive anti-reflection in a wide frequency range, originated from the destructive interference of two reflection waves from the two surfaces. A multi-band MMA consisting of a delicate arrangement of donut-shape resonators with different sizes was proposed in reference [24]. Additionally, tunable MMAs, of which the absorptivity can be switched or tuned by an external stimulus, are another research hotspot [25–31]. An active MMA based on lumped elements was demonstrated in a wide frequency region [28]. A switchable metamaterial reflector/absorber at microwave frequencies was realized by embedding diodes [29]. A polarization-insensitive tunable MMA with varactor diodes embedded between metamaterial units was designed, for which the absorption frequency can be controlled continuously [30].

Recently, chiral metamaterials have been attracted great interest since they cannot only manipulate linearly polarized (LP) waves but also circularly polarized (CP) waves. Chiral metamaterials usually have different responses for left-handed CP (LCP) and right-handed CP (RCP) waves. It has been shown that the circular-polarization spin-selective absorptions can be achieved using the chiral metamaterials [32–38]. Li et al proposed an ultra-thin chiral MMA based on the L-shaped folded metallic wires, which can only absorb the LCP wave with the absorbance of 93.2% [39]. Tang et al proposed a chiral-selective plasmonic absorber based on U-shaped-resonators, for which the absorption peaks for LCP and RCP wave occurred at different resonance wavelengths resulting in significant circular dichroism (CD). However, the absorption is less than 90% [40].

Moreover, the absorption bandwidth is often highly limited due to the resonant nature of metamaterial units, which may impede its application in practice. In this paper, a wideband CD metasurface was achieved via introducing resistance film into circular polarization conversion resonator. Spin-selective absorption and polarization conversion reflection were realized in a wide frequency regime respectively for CP incident waves with opposite helicities. Wide-band polarization-correlation customizable absorbers implemented by CD meta-atom pairs, composed of CD meta-atoms with different orientation angles, were demonstrated. The polarization-correlation of absorption can be manipulated by controlling the coupling effect between the consisted CD meta-atoms, which was demonstrated by theoretical analysis of the two-CD-meta-atom pair. Particularly, a wide-band polarization-insensitive absorber realized using a C4 CD-meta-atom pair was validated. Our approach promises potential applications in the design of customizable absorber as well as polarization-controlled multi-functional devices.

2. Circular dichroism meta-atoms

Assuming a beam of CP wave is incident onto a metasurface in xoy-plane, and the Cartesian Jones reflection matrix is $R_{\text{lin}} = \begin{bmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{bmatrix}$, the circular Jones reflection matrix $R_{\text{circ}}$ can be derived by employing the coordinate transformation matrix $\Lambda = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ i & -i \end{bmatrix}$, that is

$$R_{\text{circ}} = \begin{bmatrix} R_{RR} & R_{RL} \\ R_{LR} & R_{LL} \end{bmatrix} = \Lambda^{-1} R_{\text{lin}} \Lambda = \frac{1}{2} \begin{bmatrix} (R_{xx} + R_{yy}) + i (R_{xy} - R_{yx}) & (R_{xx} - R_{yy}) - i (R_{xy} + R_{yx}) \\ (R_{yx} + R_{xy}) - i (R_{xx} - R_{yy}) & (R_{xx} + R_{yy}) + i (R_{xy} - R_{yx}) \end{bmatrix}, \quad (1)$$

where $[1 \ 1]^T$ and $[1 \ -i]^T$, the column vectors in the coordinate transformation matrix $\Lambda$, are the eigenmode vectors for the RCP and LCP incidence waves, respectively. $R_{RR(LL)}$ and $R_{LR(RL)}$ are co- and cross-polarization reflection coefficients under incidence of RCP (LCP) waves. To keep consistent with the transmissions, the viewing direction is fixed along the incidence direction while defining the spin of the reflected CP wave. $R_{yy(xx)}$ and $R_{y(x)x}$ are co- and cross-polarization reflection coefficients under incidence of $y$- ($x$-) polarized waves. Equation (1) indicates that, for the passive, non-magnetic and reciprocal metasurfaces with $R_{yy} = R_{yx}$, the co-polarization reflection coefficients $R_{RL}$ and $R_{RR}$ are identical under the CP wave incidence. However, the cross-polarization reflection coefficients $R_{RL}$ and $R_{LR}$ can vary greatly. Thus CD can be achieved. From the equation (1), we can readily elicit the required linear reflection matrix to meet the complete cross-polarization reflection of CP incident wave with one spin and total absorption of CP incident wave with the other spin. For instance, if the incident LCP wave is totally absorbed and incident RCP wave is highly reflected into the LCP wave, i.e. $r_{RR} = r_{LL} = r_{RL} = 0$ & $r_{LR} = 1$, the required linear reflection matrix can be derived as follows,

$$R_{\text{lin}} = \frac{e^{i\gamma}}{2} \begin{bmatrix} 1 & i \\ i & -1 \end{bmatrix}, \quad (2)$$

where $\gamma$ is an arbitrary phase shift. To solve the eigenvalue problem of above linear reflection matrix $R_{\text{lin}}$, we can derive the eigenvalue $\kappa = 0$ with the eigenvector $(1, -i)^T$. This indicates that no wave is reflected under...
LCP wave incidence. The structural symmetry of the metasurfaces required for the CD was studied using symmetry analysis method. Both considering the mirror symmetry and rotational symmetry, the necessary condition to achieve CD is the simultaneous breaking of the $n$-fold rotational ($n > 2$) and mirror symmetries. Accordingly, chiral resonators without $n$-fold rotational ($n > 2$) symmetry can realize the CD. Wide-band, high-efficiency CD meta-atoms were designed by loading resistive film into planar chiral resonators, as shown in figure 1. The planar chiral resonators are composed of a metallic double-split ring, metal back-sheet and the foam dielectric spacer. As for the metallic double-split ring, the out diameter $r = 3.35$ mm and the line width $w = 0.16$ mm. The two splits at the metallic ring have different gap widths $s = 2$ mm and $s_1 = 2.8$ mm, and form a 90° angle around the resonator center. As for the planar chiral resonators, both the incident LCP and RCP waves will be highly converted into the cross-polarized wave (Supplementary Figure 1) (https://stacks.iop.org/NJP/23/093034/mmedia). As the resistive film was loaded at one opening of the planar chiral resonators, the CD meta-atoms were implemented. The width of the resistive film $w_1 = 0.66$ mm, and the square resistance is 75 $\Omega$. The repetition period of the meta-atoms $a = 7.6$ mm, and the 5 mm-thick polymethacrylimide (PMI) foam ($\varepsilon_r = 1.01$, tan $\delta = 0.001$) is employed as the dielectric spacer. The 3D views of the designed left-handed and right-handed CD meta-atoms were shown in figures 1(a) and (d), for which the front views were illustrated in inset of figures 1(c) and (f), respectively. The commercial software CST Microwave Studio was employed to simulate the CD meta-atoms. The boundary conditions in $x$- and $y$-directions were set to be unit cell. In $z$-direction, the boundary conditions were set to be open add space, and a Floquet port is used. The amplitudes of the simulated reflection coefficients and absorptions of the left-handed CD meta-atom under CP wave normal incidence were illustrated in figure 1(b). It is observed that the incident LCP wave was strongly absorbed over a wide frequency range from 8 GHz to 15 GHz, and the incident RCP wave was highly converted into LCP wave with the amplitude of the circular cross-polarization reflection coefficient greater than 0.9 in the frequency region 8–15 GHz. The CD spectrum, i.e. $CD = A_L - A_R$, of the left-handed CD meta-atom was illustrated in figure 1(c). It is evident that the CD of the left-handed CD meta-atom is greater than 0.8 in the frequency range from 7 GHz to 14 GHz. From the simulated results of the right-handed CD meta-atom depicted in figure 1(e), the incident RCP wave was strongly absorbed and the incident LCP wave was highly converted into RCP wave over a wide frequency range from 8 GHz to 16 GHz. From figure 1(f), the CD spectrum of the right-handed CD meta-atom is less than −0.8 in the same frequency region 8–15 GHz. To analyze the working mechanism of the CD meta-atoms, the surface current distributions under LCP and RCP wave normal illumination at the resonance frequency 12 GHz were simulated and presented in figure 2. The black arrow lines indicate the surface current directions. The color denotes the surface current intensity. The simulation results indicate that strong chiral resonances dominate the CD under CP wave illumination. One can find that the surface currents mainly distribute on the left parts of the metallic ring under LCP wave incidence (see in figures 2(a) and (c)) and on right parts of the metallic ring for RCP wave incidence.
incident waves as shown in figures 2(b) and (d), which are strong associated with dipolar responses contributing to the effective permittivity \( \varepsilon(\omega) \). The loaded resistive films are capable of conducting electricity just like metal. Thus the surface current distributions on both left-handed and right-handed CD meta-atoms were analogous under illumination of CP wave with the same helicity, which should be similar to that on the metallic SRRs. As a result, for the left-handed CD meta-atom the incident power of the LCP wave can be absorbed by the lossy resistive film while right-handed CD meta-atom shows high-efficiency absorption for the RCP wave due to the lossy resistive film located in the right part of the meta-atom. Under RCP (LCP) wave incidence onto the left-handed (right-handed) meta-atoms, strong current accumulate at the right (left) parts, which works as a dipolar response. This leads to high-efficiency circular polarization conversion reflection.

3. Polarization-correlation-customizable absorption mediated by coupling effect

It has been indicated that the designed left-handed and right-handed CD meta-atoms can only absorb the LCP and RCP incident waves, respectively. To overcome this limit and further provide a flexible absorption manipulation associated with the polarization state, the CD pair including multiple meta-atoms is designed as the element of polarization-correlation-customizable metasurfaces. In order to facilitate the analysis, the two left-handed CD meta-atom pair is considered here, as shown in figure 3(a). The two left-handed CD meta-atoms, of which the orientation angles are 0° and 90°, respectively, were arranged along x-direction. The orientation angle of the CD meta-atom on the left is \( \alpha \). And the orientation angle difference between the two CD meta-atoms is \( \delta \), which is described in figure 3(b). The distance between the two meta-atom centres is exactly equal to the repetition period of the meta-atoms \( a \). It should be noted that the right-handed CD meta-atoms also can be used to design the polarization-correlation-customizable metasurfaces, and the conclusion is consistent with the case of the left-handed CD meta-atoms.

The reflection and absorption properties of the two-meta-atom pair under CP wave normal incidence have been simulated and are shown in figures 3(c) and (d). It can be found that, besides the case of the LCP wave incidence, the incident RCP wave can be also absorbed by the two-meta-atom pair. The absorption of RCP wave is greater than 80% over a wide frequency range from 6.3 GHz to 13 GHz, greater than 60% in frequency region 13 GHz–17.5 GHz, and greater than 90% in frequency region 18 GHz–21 GHz. This is completely different from the single left-handed CD meta-atom as shown in figure 1, where the incident RCP wave is efficiently converted into the LCP wave. This performance can be attributed to the coupling effect between the two CD meta-atoms. To intuitively understand the coupling effect of the two-meta-atom pair, the surface current distributions at 12 GHz under the LCP and RCP wave incidence were simulated, as shown in figure 4. One observes that rotating the left-handed meta-atom has little effect on the surface current distribution. The surface current distributions in the two meta-atoms are identical under the LCP wave incidence, which indicate a symmetric mode. As a result, the high-efficiency absorption can be kept all the same under the LCP wave incidence as expected, as shown in figure 4(a). However, the surface current directions in the pair are opposite because of the coupling effect between the two CD meta-atoms under the RCP wave incidence, which reveal an anti-symmetric mode as shown in figure 4(b). This makes sure that the surface current of one meta-atom mainly distributes around the loss resistive film, and thus the incident
power can be absorbed. This implies that the absorption efficiency under the RCP wave incidence can be tailored by changing the position relationship between the strong surface current distribution and the resistive film location.

To check the tunable performance of the two left-handed CD meta-atom pair, the absorption spectra and circular polarization conversion reflection spectra with different $\delta$ and $\alpha$ have been simulated. The results are given in figure 5. It was evident from figure 5(a) that the absorption of the LCP incident wave can be approximately considered to be insensitive to the orientation angle difference $\delta$. However, the
absorption under the RCP wave incidence are sensitive to the orientation angle difference \( \delta \), which can be greatly enhanced as the orientation angle difference \( \delta \) is in the two ranges of \( 60^\circ–120^\circ \) and \( 240^\circ–300^\circ \), as shown in figure 5(b). And the cross-polarization reflection under RCP wave illumination is dramatically increased as the orientation angle difference \( \delta \) is in the three ranges of \( 0^\circ–30^\circ \), \( 150^\circ–210^\circ \) and \( 330^\circ–360^\circ \). Thus the CD of the two left-handed CD meta-atom pair can be controlled via changing their orientation angle difference. Besides, the coupling between two CD meta-atoms under RCP wave incidence was also closely related to the frequency. Moreover, considering the influence of the orientation angle for the left-handed CD meta-atom on the left, the angle difference between the two CD meta-atoms was fixed to be \( -90^\circ \). The simulations illustrated in figures 5(c)–(h) indicated that both the absorption and polarization conversion reflection of the LCP wave are insensitive to the orientation angle \( \alpha \), but the absorption and polarization conversion reflection under RCP wave incidence are associated on the orientation angle \( \alpha \). Accordingly, polarization-correlation customizable absorber can be implemented via altering the coupling between two meta-atoms in the CD meta-atom pair, which was realized by controlling the orientation angle \( \alpha \) and orientation angle difference \( \delta \). When the number of the CD meta-atom pairs increases, the coupling will become complicated and the absorption will become more desirable.

We now analyzed the absorption properties in the view of the LP wave incidence. The electric field of the LP incident wave can be expressed as

\[
E_i = \frac{\sqrt{2}}{2} (1 \pm 1) \cdot \left( \frac{E_{iL}}{E_{iR}} \right),
\]

where \( E_{iL} \) is the electric field expression of the decomposed LCP wave, and \( E_{iR} \) for the decomposed RCP wave. The incident wave is \( x \)-polarized as the sign is ‘+’, and \( y \)-polarized for the sign ‘−’.

Assuming the absorption of the LCP incidence wave is \( A_L \), and the absorption under RCP wave incidence is \( A_R \). The absorptions of the incident \( y \)- and \( x \)-polarized waves can be expressed as

\[
A_y = \frac{A_L + A_R}{2} - \frac{R_{LL(RR)} \cdot (R_{LR} + R_{RL}) + R_{LR(RR)} \cdot (R_{LR} + R_{RL})}{2},
\]

\[
A_x = \frac{A_L + A_R}{2} - \frac{R_{LL(RR)} \cdot (R_{LR} + R_{RL}) + R_{LR(RR)} \cdot (R_{LR} + R_{RL})}{2},
\]

where ‘−’ is conjugate of the complex circular polarization reflection coefficient. The circular co-polarization reflection coefficients under LCP and RCP wave incidence are identical.

The reflections and absorptions of the two left-handed meta-atom pair under normal incidence of the \( y \)- and \( x \)-polarized waves were simulated and illustrated in figures 3(e) and (f). As for the single left-handed CD meta-atom, the absorptions were approximately equal to 50% for both \( y \)- and \( x \)-polarized waves, and
the amplitudes of the co- and cross-polarization reflection coefficients were all nearly equal to 0.5. Nevertheless, the two left-handed meta-atom pair shows a high-efficiency absorption performance for both y- and x-polarized waves. For example, the absorption of y-polarized wave is greater than 85% over a wide frequency range from 6.5 GHz to 22.5 GHz, and greater than 65% in the same frequency regime for the x-polarized incident wave. It is found that the absorption level for the x-polarized incident wave is slight less than the case of the y-polarized incident wave. This mainly results from the weak coupling effect of the two-meta-atom pair.

To gain high absorption for both y- and x-polarized incident waves, a pair consisting of a $2 \times 2$ left-handed CD meta-atoms has been designed, as shown in figure 6(a). The four left-handed CD meta-atoms were numbered form 1 to 4. The orientation angle of the first left-handed CD meta-atom is $\alpha$. The orientation angle differences between adjacent meta-atoms, indicated by $\delta$, were identical. The coupling between the consisted CD meta-atoms contributed greatly to the absorption of the designed $2 \times 2$ CD-meta-atom pair. And the coupling differs significantly for different arrangements of the four meta-atoms or different polarization of the incident wave. Thus a polarization-correlation-customizable absorber can be realized. In particular, wide-band, high-efficiency and polarization-insensitive absorber were achieved as shown in figure 6(a). It is a $C_4$ isomer of the $2 \times 2$ CD-meta-atom pair. The orientation angles of the first left-handed CD meta-atom is $\alpha = 0^\circ$, and the angle differences between adjacent meta-atoms are all equal to $\alpha = 90^\circ$. Figure 6(b) depicted the amplitudes of the simulated reflection coefficients and the absorptions under normal incidence of y- and x-polarized wave. As expected, the absorption efficiency is improved with respect to the case of the two-meta-atom pair in figure 3. The absorption under y- and x-polarized wave incidence is greater than 0.9 from 7 GHz to 22.5 GHz. The cross-polarization reflections are nearly zero in the whole frequency spectrum due to the $C_4$ symmetry of the $2 \times 2$ meta-atom pair. Figure 6(c) shows the photograph of the fabricated prototype, in which the inset depicts a zoom in of four unit cells. The metallic structure was firstly fabricated on a 0.1 mm-thick FR4 dielectric substrate using print circuit board technique. The resistive film was then printed at the openings using silk printing method. The final prototype was achieved via holding the 0.1 mm-thick FR4 dielectric, 5 mm-thick foam dielectric substrate and the metallic back-sheet together with film adhesive. The fabricated prototype was measured in an anechoic chamber. The measuring system is based on the Agilent N5224A vector network analyzer with wideband horn antennas. In the experiment setup, the fabricated prototype is placed on a foam tower and is fixed uprightly into a foam base. Two horn antennas are closed together and symmetrically located with a distance of 1.5 m away from the center of the prototype, and formed a $4^\circ$ angle relative to the prototype. The co- and cross-polarization reflections under y- and x-polarized wave normal incidence, i.e. $r_{yy}$, $r_{yx}$, $r_{xx}$, and $r_{xy}$, were measured directly. Then the absorptions were calculated by $A_y = 1 - |r_{yy}|^2 - |r_{yx}|^2$ and $A_x = 1 - |r_{xx}|^2 - |r_{xy}|^2$. The measured results under y- and x-polarized wave normal incidence were illustrated in figure 6(d). By comprising with the results in figure 6(b), one can find that the measured results are in a good agreement with the simulation. Both the simulations and measured results indicated that the designed absorber was polarization-insensitive. That is to say, both LCP and RCP waves can be completely absorbed by this $C_4$ CD-meta-atom pair. The CD vanished as the four different left-handed CD meta-atoms are arranged together. The polarization-insensitive absorption comes from the couplings between CD meta-atoms. When the number of the CD meta-atom pairs increases, the coupling will become complicated and the absorption will become more desginable. To verify this, the $3 \times 3$ CD meta-atom pairs were designed and simulated in Supplementary Figure 2.

To analyze the absorbing mechanism of the $C_4$ $2 \times 2$ meta-atom pair, the surface current distributions and power loss densities at the frequencies 12 GHz, which are corresponding to the absorption peak, were simulated (see in figure 7). From the simulated surface current distributions, under y-polarized wave normal incidence, the surface currents on the two adjacent CD meta-atoms in vertical direction are opposite along x-direction. Considering the surface current distributions along y-direction on the two adjacent CD meta-atoms in horizontal direction, the surface current on the right part of the left meta-atoms is opposite to that on the left part of the right meta-atoms, but the surface current on the left part of the left meta-atoms has the same direction with that on the right part of the right meta-atoms. This resulted in the strong absorption of the y-polarized incident wave. The power loss density shows the strongest absorptions are located at the left and right parts of the $2 \times 2$ meta-atom pair. For x-polarized incident wave, anti-parallel surface currents on the right part of the left CD meta-atoms and on the left part of the right CD meta-atoms are observed. Considering the surface current distributions on the adjacent CD meta-atoms in vertical direction, the surface currents along x-direction on adjacent arms are in-phase and each is strongly associated a dipolar response which contributes to the effective $\varepsilon(\omega)$, eventually attenuating the power of wave to be very low. It is clearly that most of the power loss takes place in the left and right parts of the comprising CD meta-atoms. Thus it can be deduced that the high-efficiency absorption under
Figure 6. Design, simulations and experimental verifications of the C4 2 × 2 meta-atom pair. (a) The front view of the C4 2 × 2 meta-atom pair, (b) simulated reflections and absorptions under normal incidence of y- and x-polarized wave, (c) photograph of the fabricated prototype, (d) measured absorptions under y- and x-polarized wave normal incidence.

Figure 7. Surface current distributions and power loss densities under normal incidence of y- and x-polarized waves at 12 GHz. (a) Surface current distributions. (b) Power loss densities.

x-polarized wave incidence was attributed to the couplings between adjacent CD meta-atoms in vertical direction.

4. Conclusion

In summary, the CD meta-atom pair was proposed to realize polarization-correlation customizable metasurface. The CD resonator is made of the metal-dielectric/metal chiral structure loaded with resistive films. Results indicate that the CD metasurfaces consisting of single left-handed or right-handed
meta-atoms can only absorb the corresponding polarized CP waves. However, the CD meta-atom pair formed by combining two or four meta-atoms with the same chirality shows completely absorption performance. Besides the original absorption property can be kept, the other polarized CP wave can be also absorbed and the absorption efficiency can be tailored by changing the arrangement of the meta-atoms. As a result, our proposed metasurface shows a polarization-correlation customizable absorption feature. Such performance is contributed to the coupling effect between the meta-atom. Finally, a polarization-insensitive metasurface absorber was designed and fabricated based on a four-meta-atom pair. Both the simulated and measured results indicate that the LCP and RCP waves can be absorbed with the absorption greater than 90% over a wide frequency range from 6.5 to 22.5 GHz. The metasurface absorbers based on CD meta-atom pairs can be used in stealth technique, antenna isolation, electromagnetic shielding, etc.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The authors declare no conflicts of interest.

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