Directional Dipole Dice: Circular-Huygens-Janus Dipole in an Anisotropic Chiral Particle

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Abstract
Directional radiation and scattering play an essential role in light manipulation for various applications in integrated nanophotonics, antenna and metasurface designs, quantum optics, etc. The most elemental system with this property is the class of directional dipoles, including circular dipole, Huygens dipole, and Janus dipole. While each directional dipole has been realized in various optical structures, a mechanism that unifies all three directional dipoles in a single structure at the same frequency is missing. Here, we theoretically and experimentally demonstrate that the synergy of chirality and anisotropy can give rise to all three directional dipoles in one structure at the same frequency under linearly polarized plane wave excitations. This mechanism enables a simple helix particle to serve as a directional dipole dice (DDD), achieving selective manipulation of optical directionality via different “faces” of the particle. We employ three “faces” of the DDD to realize unidirectional excitation of guided waves with the directionality determined by the spin, the power flow, and the reactive power, respectively. This all-in-one realization of three directional dipoles can enable unprecedented control of both near-field and far-field directionality with broad applications in photonic integrated circuits, quantum information processing, and subwavelength-resolution imaging.

Introduction
Controlling the propagation direction of light to achieve directional radiation or scattering is a key objective of light manipulations, with important applications in almost every aspect of photonics and plasmonics [1–9]. Far-field directional radiation can be realized by applying the design principle of high-directivity antennas [10, 11] or engineering the interference of electric and magnetic multipoles to satisfy Kerker conditions as in Huygens antennas [12–16]. Near-field directional routing can be achieved by manipulating the local polarization or symmetries of confined fields, leading to the discovery of directional dipole sources [17–20] and directional meta-sources [21]. There are three types of elemental directional dipoles: circular dipole, Huygens dipole, and Janus dipole. The circular dipole (i.e., circularly polarized electric/magnetic dipole) can excite unidirectionally propagating guided waves via spin-momentum locking [22–27], with fascinating applications in topological photonics and non-Hermitian physics [28–30] as well as in designing novel nanophotonic devices [31–35]. The Huygens dipole can give rise to directional power flow in both the near and far fields [36–40], which can be employed to achieve vanished backscattering, cloaking, perfect refraction, perfect reflection, and near-field optical microscopy [41–45]. The Janus dipole has side-dependent directional properties derived from the reactive power, exhibiting complete near-field coupling or noncoupling to waveguides [46–48].

The directional dipoles are usually realized by using different optical structures because of their different physical mechanisms. The circular dipole, composed of a pair of orthogonal electric/magnetic dipoles $\pm \pi/2$ out of phase, can be realized in plasmonic nanospheres under the excitation of circularly polarized light [41, 22]. The Huygens dipole and Janus dipole, composed of orthogonal electric and magnetic dipoles in phase and $\pm \pi/2$ out of phase, respectively, can be realized by tailoring high-index dielectric nanospheres or nanocylinders supporting electric and magnetic Mie resonances [49, 50]. An interesting question is: Is it possible to realize all three directional dipoles in one structure and at the same frequency? This seems to be an unattainable goal considering that they require different composition dipoles with different relative phases and amplitudes.

Here, we demonstrate a general physical mechanism for the unified realization of all three directional dipoles. We show that the synergy of chirality and anisotropy can give rise to circular dipole, Huygens dipole, and Janus dipole in the same structure and at the same frequency, under the excitation of a linearly polarized plane wave. Such anisotropic chirality can be found in many structures, such as a simple helix particle made of metal. The magnetoelectric coupling of the helix particle enables the excitation of electric and magnetic dipoles at the same frequency, and the anisotropy enables the excitation of different dipoles in different directions. The relative phase differences of the excited electric and magnetic dipoles naturally satisfy the requirements of the directional dipoles. Such a helix chiral particle gives
rise to the three directional dipoles in three orthogonal directions, which enable selective manipulation of optical directionality via different “faces” of the helix, corresponding to a directional dipole dice (DDD). We show that the switch of different directional dipoles can be easily achieved by tuning the propagation and polarization directions of the incident plane wave. Using a mode expansion theory, we uncover that the emergence of the directional dipoles is attributed to the selective excitation of the plasmonic resonance modes supported by the helix. To characterize the unique properties of the DDD, we then employ each directional dipole to achieve unidirectional excitation of guided waves and experimentally demonstrate the phenomena at microwave frequencies.

**Mechanism and realization**

The directional dipoles correspond to a combination of electric and/or magnetic dipoles whose magnitudes and phases satisfy certain conditions. The circular electric and magnetic dipoles can be defined as

\[
D_{\text{cir}}^e = (p \hat{e}_i, \pm ip \hat{e}_j), D_{\text{cir}}^m = (m \hat{e}_i, \pm im \hat{e}_j),
\]

where \(p\) and \(m\) are the magnitudes of the electric and magnetic dipole components, respectively. Here and in what follows, \(\hat{e}_i\) and \(\hat{e}_j\) denote the unit axis vectors in Cartesian coordinate system with \(i, j = x, y, z\) and \(i \neq j\). The directionality of the circular dipoles is given by their spin \(S = \text{Im} [(D_{\text{cir}}^e)^* \times D_{\text{cir}}^m]\). The Huygens dipole can be defined as

\[
D_{\text{Huy}} = (p \hat{e}_i, \pm m \hat{e}_j) \quad \text{with } p = \frac{m}{c},
\]

(2)

Here, \(c\) is the speed of light in vacuum. The directionality of the Huygens dipole is given by the time-averaged power flow (i.e., the real part of the Poynting vector): \(\text{Re}[P] = \frac{1}{2} \text{Re} [E \times H^*]\). The Janus dipole can be defined as

\[
D_{\text{Jan}} = (p \hat{e}_i, \pm m \hat{e}_j) \quad \text{with } p = \frac{m}{j c},
\]

(3)

The directionality of the Janus dipole is given by the reactive power (i.e., the imaginary part of the Poynting vector): \(\text{Im}[P] = \frac{1}{2} \text{Im} [E \times H^*]\). Therefore, we can assign the directions of the spin \(S\), the power flow \(\text{Re}[P]\), and the reactive power \(\text{Im}[P]\) to be the directions of the circular dipole, the Huygens dipole, and the Janus dipole, respectively.

The above directional dipoles can be realized by using passive structures, such as subwavelength particles under the excitation of electromagnetic waves. For an isotropic achiral particle, the induced dipoles can be expressed as

\[
\begin{bmatrix}
\mathbf{p} \\
\mathbf{m}
\end{bmatrix} =
\begin{bmatrix}
\alpha_{ee} & 0 \\
0 & \alpha_{mm}
\end{bmatrix}
\begin{bmatrix}
\mathbf{E} \\
\mathbf{B}
\end{bmatrix},
\]

(4)

where \(\mathbf{E}\) (\(\mathbf{B}\)) is the incident electric (magnetic) field; \(\alpha_{ee}\) (\(\alpha_{mm}\)) is the electric (magnetic) polarizability. For a circularly polarized incident plane wave \(\mathbf{E} = (\hat{e}_x \pm i \hat{e}_y)E_0 e^{ikz}\), this particle can give rise to circular electric dipole \(D_{\text{cir}}^e = (\hat{e}_x, \pm i \hat{e}_y)\alpha_{ee}E_0\) and circular magnetic dipole \(D_{\text{cir}}^m = (\hat{e}_x, \pm i \hat{e}_y)\alpha_{mm}E_0/c\). However, it is impossible to simultaneously achieve the Huygens and Janus dipoles (i.e., Eqs. (2) and (3)), which require different relative phases between the electric and magnetic dipoles.

For an isotropic chiral particle, the induced dipoles can be expressed as

\[
\begin{bmatrix}
\mathbf{p} \\
\mathbf{m}
\end{bmatrix} =
\begin{bmatrix}
\alpha_{ee} & i\alpha_{em} \\
-i\alpha_{em} & \alpha_{mm}
\end{bmatrix}
\begin{bmatrix}
\mathbf{E} \\
\mathbf{B}
\end{bmatrix},
\]

(5)

where \(\alpha_{em}\) denotes the magnetoelectric polarizability derived from the chirality of the particle. Under the excitation of a linearly polarized incident plane wave \(\mathbf{E} = \hat{e}_x E_0 e^{ikz}\), the circular electric dipole can be induced as \(D_{\text{cir}}^e = (\alpha_{ee}\hat{e}_x, \pm i \alpha_{em} \hat{e}_y)E_0\) when \(\alpha_{ee} = \pm \alpha_{em}/c\), and circular magnetic dipole can be induced as \(D_{\text{cir}}^m = (-i \alpha_{em} \hat{e}_x, \alpha_{mm} \hat{e}_y)E_0/c\) when \(\alpha_{em} = \pm \alpha_{mm}/c\). In addition, the Huygens dipole can be induced as \(D_{\text{Huy}} = (\alpha_{ee}\hat{e}_x, \alpha_{mm} \hat{e}_y)E_0\) when \(\alpha_{ee} = \pm \alpha_{mm}/c^2\), and it can also be given by \(D_{\text{Huy}} = (i \hat{e}_y, -\hat{e}_x)\alpha_{em}E_0\) via the magnetoelectric polarizability \(\alpha_{em}\). Finally, the Janus dipole can be induced as \(D_{\text{Jan}} = (\alpha_{ee}\hat{e}_x, \pm \alpha_{mm} \hat{e}_y)E_0\) when \(\alpha_{ee} = \pm i \alpha_{mm}/c^2\). Therefore, all the three directional dipoles can be simultaneously realized in an isotropic chiral particle satisfying the following conditions:

\[
\alpha_{ee} = \pm \frac{i \alpha_{mm}}{c^2} = \pm \frac{\alpha_{em}}{c^2} \quad \text{or} \quad \alpha_{ee} = \pm \frac{\alpha_{mm}}{c^2} = \pm \frac{i \alpha_{em}}{c}.
\]

(6)

The above mechanisms are summarized in Table [I] where the arrows indicate the combinations of polarizabilities that give rise to the desired directional dipoles.
and magnetic dipoles can be expressed as

$$\mathbf{P} = \begin{bmatrix} \alpha_{ee} & \alpha_{em} \\ \alpha_{em} & \alpha_{mm} \end{bmatrix} \begin{bmatrix} \mathbf{E} \\ \mathbf{B} \end{bmatrix},$$

where the polarizability tensors $\alpha_{ee}$, $\alpha_{mm}$ and $\alpha_{em}$ are $3 \times 3$ matrices. The anisotropy provides additional degrees of freedom to realize the circular dipole, Huygens dipole, and Janus dipole in orthogonal directions. We consider, for example, a helix particle with the center axis in the $y$ direction. The magnetoelectric polarizability tensor $\alpha_{em}$ is dominated by the component $\alpha_{yy}$. Under the tilted incidence of a linearly polarized plane wave $\mathbf{E} = (E_y \hat{e}_y + E_z \hat{e}_z) e^{ik_y y + ik_z z}$, the circular electric dipole can be induced in the $\pm y$ direction as $\mathbf{D}_{\text{circ}} = (\alpha_{ee} E_y \hat{e}_x + \alpha_{em} E_z \hat{e}_x)$ when $\text{Arg} (\alpha_{ee}) - \text{Arg} (\alpha_{em}) = \pm \pi/2$. The Huygens dipole can be induced in the $\pm x$ direction as $\mathbf{D}_{\text{Huy}} = (-i\alpha_{em} E_y \hat{e}_y + \alpha_{em} E_z \hat{e}_y)$ when $\text{Arg} (\alpha_{em}) - \text{Arg} (\alpha_{xx}) = \pm \pi/2$. The Janus dipole can be induced in the $\pm z$ direction as $\mathbf{D}_{\text{Jan}} = (\alpha_{em} E_y \hat{e}_x - i\alpha_{em} E_y \hat{e}_y)$ when $\alpha_{xx} = -\alpha_{yy}/c$, or $\mathbf{D}_{\text{Jan}} = (\alpha_{em} E_y \hat{e}_y + \alpha_{xx} B_x \hat{e}_z)$ when $\text{Arg} (\alpha_{xx}) - \text{Arg} (\alpha_{mm}) = \pm \pi/2$. We note that the relative amplitudes of the field components $E_y, E_z$ and $B_z$ in the above expressions can be tuned by varying the incident angle. Therefore, the anisotropic chiral particle can simultaneously realize all the three directional dipoles in orthogonal directions when satisfying the following conditions:

$$\text{Arg} (\alpha_{ee}^{yy}) - \text{Arg} (\alpha_{ee}^{zz}) = \pm \pi/2, \alpha_{ee}^{yy} = \pm \alpha_{yy}/c \quad (8)$$

or

$$\text{Arg} (\alpha_{ee}^{yy}) - \text{Arg} (\alpha_{ee}^{zz}) = \pm \pi/2, \text{Arg} (\alpha_{em}) - \text{Arg} (\alpha_{xx}) = \pm \pi/2, \text{Arg} (\alpha_{ee}) - \text{Arg} (\alpha_{mm}) = \pm \pi/2. \quad (9)$$

Here, we use the metallic helix particle in Fig. 1 to demonstrate the mechanism. The helix has pitch $P = 75$ nm, outer radius $R = 46$ nm, and inner radius $r = 11$ nm (the geometric parameters are defined in the inset of Fig. 2(a)). The center axis of the helix is along the $y$ direction. It is made of gold with relative permittivity characterized by the Drude model $\varepsilon_{Au} = 1 - \omega_p^2 / (\omega^2 + i \omega \gamma)$, where $\omega_p = 1.36 \times 10^{16}$ rad/s and $\gamma = 7.1 \times 10^{13}$ rad/s [52]. Such helices can be fabricated by using low-temperature shadow deposition [53] and have been extensively studied for its intriguing chiroptical properties, such as circular dichroism [54], optical forces [3, 55, 56], polarization conversion [57], and vortex beam generation [58]. We assume that the incident plane wave is linearly polarized with the electric field $\mathbf{E}_{inc} = (-\sin \theta \hat{e}_y + \cos \theta \hat{e}_z) e^{ik_y y - ik_z z}$, where $\theta$ is the incident angle between the wavevector $\mathbf{k}$ and $-y$ direction and we have neglected the time-harmonic factor $e^{-i \omega t}$. We will show that the helix can give rise to three dipole components $p_x, p_z$ and $m_y$ that constitute the three directional dipoles on three “faces” of the DDD. Importantly, the spin $\mathbf{S}$ of the circular dipole, the net power flow Re$[\mathbf{P}]$ of the Huygens dipole, and the reactive power Im$[\mathbf{P}]$ of the Janus dipole point in $-y, +x, -z$ directions, respectively, as shown in Fig. 2.

Under the incidence of the plane wave, currents and charges will be induced in the helix, and their oscillations give rise to resonances of the helix. We conducted full-wave simulation of the helix and computed its scattering cross section for the incident angle $\theta = 90$ degrees, by using a finite-element package COMSOL [59]. The results are shown in Fig. 2(a) as the red symbol line. We notice a resonance appears at the frequency of 108 THz. We then apply multipole expansions and decompose the scattering cross section into contributions of multipoles. As seen, the scattering cross section is dominated by the electric dipole ($C_{sca}^p$) denoted by the red dashed line. The contribution of magnetic dipole ($C_{sca}^m$), denoted by the blue dashed line, is negligible. The sum $C_{sca}^p + C_{sca}^m$ well agrees with the full-wave numerical result, demonstrating the validity of the multipole expansions. The weightings of the electric and

| Directional dipoles realized by an isotropic chiral particle under linearly polarized plane wave excitation |
|-----------------|-----------------|-----------------|
| Circular dipole  | $\alpha_{ee}^{xx} \leftrightarrow i\alpha_{em}^{xx}$ | $\alpha_{ee}^{xx} = \pm \alpha_{em}^{xx}/c$ |
| Huygens dipole   | $-i\alpha_{em}^{xx}$ | $\alpha_{em}^{xx} = \pm \alpha_{mm}^{xx}/c$ |
| Janus dipole     | $-i\alpha_{em}^{xx}$ | $\alpha_{ee}^{xx} = \pm i\alpha_{mm}^{xx}/c^2$ |

Although the above $\mathbf{D}_{\text{circ}}, \mathbf{D}_{\text{Huy}}$, and $\mathbf{D}_{\text{Jan}}$ can be realized simultaneously, their directions overlap. In practical applications, it is desired to have the directional dipoles point in orthogonal directions to enable flexible functionalities. This can be achieved by combining chirality with anisotropy. For an anisotropic chiral particle, the induced electric and magnetic dipoles can be expressed as
magnetic dipoles at the resonance frequency can be tuned by varying the incident angle $\theta$. Figure 2(b) shows the relative amplitudes of $p_x$, $p_z$ and $m_y$ as a function of $\theta$. We notice that $|p_z| / |p_x|$ and $|p_z| / |m_y/c|$ reduce as $\theta$ increases, which is due to a smaller $z$ component of the incident electric field at a larger $\theta$. Interestingly, $|p_z| / |m_y/c| \approx 1$ for a wide range of the incident angle. Figure 2(c) shows the relative phases of $p_x$, $p_z$ and $m_y$ as a function of $\theta$. As seen, Arg ($p_z$) - Arg ($p_x$) = 90 degrees, Arg ($p_z$) - Arg ($m_y$) = 180 degrees, and Arg ($p_z$) - Arg ($m_y$) = 90 degrees over a broad range of $\theta$. In particular, the induced dipoles satisfy $p_z/p_x = i, p_z/(m_y/c) = -1$, and $p_z/(m_y/c) = i$ simultaneously at $\theta = 20$ degrees, corresponding to a circular dipole, a Huygens dipole, and a Janus dipole, respectively. We note that the physical mechanism is robust and can be realized with other geometric parameters or at other frequencies (e.g., microwave frequencies). Another design of the gold helix with a different set of parameters is provided in the Supplemental Information; a realization at microwave frequencies is provided in a later section.

**Mode expansion theory**

The remarkable property of the helix particle can be understood with a mode expansion theory, where we apply three steps to determine its response under external excitations. We first analytically obtain the eigen currents of the helix and use them to construct the Green’s function. Then, we apply the Green’s function to determine the induced currents for a broad range of the incident angle. Figure 2(c) shows the relative phases of $p_x$, $p_z$ and $m_y$ as a function of $\theta$. As seen, Arg ($p_z$) - Arg ($p_x$) = 90 degrees, Arg ($p_z$) - Arg ($m_y$) = 180 degrees, and Arg ($p_z$) - Arg ($m_y$) = 90 degrees over a broad range of $\theta$. In particular, the induced dipoles satisfy $p_z/p_x = i, p_z/(m_y/c) = -1$, and $p_z/(m_y/c) = i$ simultaneously at $\theta = 20$ degrees, corresponding to a circular dipole, a Huygens dipole, and a Janus dipole, respectively. We note that the physical mechanism is robust and can be realized with other geometric parameters or at other frequencies (e.g., microwave frequencies). Another design of the gold helix with a different set of parameters is provided in the Supplemental Information; a realization at microwave frequencies is provided in a later section.

Since the metal helix can be obtained by twisting a nanorod into helical shape, its eigenmodes correspond to the eigenmodes of the nanorod mapped onto the helical path defined by the helix, as long as the helix pitch is large enough so that couplings between helix turns are negligible. The eigenmodes of the nanorod are one-dimensional eigenmodes of the nanorod mapped onto the helical path defined by the helix [60], as long as the helix pitch is large enough so that couplings between helix turns are negligible. The eigenmodes of the nanorod are one-dimensional (1D) standing surface charge waves (i.e., currents) with eigenfrequency $\omega_n$ and propagation constant $\gamma_n$. These eigen currents are approximately uniform on the cross section of the nanorod since the radius of the nanorod $r \ll \lambda$. The expressions of the eigen currents can be obtained semi-analytically, from which we can determine the eigen currents of the helix via a mapping (see Supplemental Information). With the obtained eigen currents $J_n$, the Green’s function of the helix can be constructed as $G(r, r') = \sum_n \frac{A_n(\omega_n - i\omega)^2}{\omega_n} = \sum_n a_n(\omega) J_n(r) J_n^*(r')$ [61], where $A_n$ is the normalization coefficient of the eigen current $J_n$ at eigenfrequency $\omega_n$. The expansion coefficient $a_n(\omega)$ contains holistic resonance characteristics of the helix and is independent of the excitation. It can be numerically determined based on the induced current density

$$J(r) = -i\omega\varepsilon_0 \left(\varepsilon_r - 1\right)^2 \mu \int G(r, r') \cdot E(r') dV_p = \sum_n B_n a_n J_n(r),$$

(10)
FIG. 2. (a) The scattering cross section of the helix particle and the contributions of the electric and magnetic dipoles. (b, c) The relative amplitudes and phases of the dipole components as a function of the incident angle of the linearly polarized plane wave. The dashed line marks the parameters giving three directional dipoles.

where

\[ B_n = -i \omega \epsilon_0^2 (\Delta \epsilon_r)^2 \mu \int J_n^*(r') \cdot E(r') \, dV_p. \]

Here, \( \Delta \epsilon_r = \epsilon_{Au} - 1 \) is the relative permittivity contrast between the helix particle and the background medium (i.e., free space). The integral \( \int J_n^*(r') \cdot E(r') \, dV_p \) is evaluated over the volume of the helix particle \( V_p \). The coefficient \( a_n \) can be determined after one simulation of the induced current, with which we then can analytically calculate the induced dipoles for any excitations as

\[ \mathbf{p} = \frac{i}{\omega} \int \mathbf{J}(r) \, dV_p = \sum_n B_n a_n \mathbf{p}_n \]  

and

\[ \mathbf{m} = \frac{1}{2} \int \mathbf{r} \times \mathbf{J}(r) \, dV_p = \sum_n B_n a_n \mathbf{m}_n, \]
where \( \mathbf{p}_n = \frac{i}{2} \int \mathbf{J}_n(r) dV_r \) and \( \mathbf{m}_n = \frac{i}{2} \int \mathbf{r} \times \mathbf{J}_n(r) dV_r \) are dipoles attributed to the eigen current \( \mathbf{J}_n \). In the following, we focus on the dominant dipole components \( p_x, p_y, p_z \) and \( m_y \) of the helix. Non-axial magnetic dipoles are orders of magnitude smaller than \( m_y \) and thus are negligible. Using Eqs. (11) and (12) and the expressions of \( \mathbf{J}_n \) in the Supplemental Information, the dipole components for odd values of \( n \) can be obtained as

\[
(p_n)_x = \pm \frac{2iN \pi^2 r^2 R}{\omega L} \frac{\left( \sin \left( \frac{\gamma_n L}{2} \right) + \sin \left( \frac{\gamma_n L}{2} \right) \right)}{\left( \gamma_n - 2\pi N/L \right) \gamma_n},
(p_n)_y = \frac{2iN \pi^2 r^2 R}{\omega L} \frac{\left( \sin \left( \frac{\gamma_n L}{2} \right) - \sin \left( \frac{\gamma_n L}{2} \right) \right)}{\left( \gamma_n + 2\pi N/L \right) \gamma_n},
(p_n)_z = 0,
\]

where \( N \) is the number of turns of the helix, \( L = N\sqrt{4\pi^2 R^2 + P^2} \) is arc length of the helix, and the signs ‘+’ and ‘−’ correspond to the left and right handedness, respectively. For even values of \( n \), the dipole components are

\[
(p_n)_x = 0, (p_n)_y = 0, (p_n)_y = \frac{2iN \pi^2 r^2 R}{\omega L} \frac{\left( \sin \left( \frac{\gamma_n L}{2} \right) - \sin \left( \frac{\gamma_n L}{2} \right) \right)}{\left( \gamma_n + 2\pi N/L \right) \gamma_n}.
\]

Equations (13) and (14) indicate that different eigenmodes contribute to different dipole components. The odd-order eigenmodes will generate \( p_x, p_y \) and \( m_y \), while the even-order eigenmodes will only generate \( p_z \). At the eigen frequencies, we have \( \gamma_n L \approx n\pi \). Thus, \( (p_n)_z \) in Eq. (14) vanishes for even values of \( n \) except for \( n = 2N \), i.e., \( p_z \) is mainly contributed by the eigenmode of the order \( n = 2N \). In addition, the odd-order eigenmodes account for the chirality of the helix because it can generate both electric and magnetic dipoles. The odd- and even-order eigenmodes contribute to electric dipoles in orthogonal directions, which account for the anisotropy of the helix. The synergy of chirality and anisotropy via the two types of eigenmodes can give rise to the desired directional dipoles. In addition, the switching of different directional dipoles can be achieved by selectively exciting the eigenmode, i.e., tuning \( B_n \), which depends on the propagation direction and polarization direction of incident field.

We apply the mode expansion theory to analytically determine the induced dipoles in the helix for various incident angles. We find that tilted incidence will predominantly excite the eigenmodes of the orders \( n = 1, 4 \). The charge and current distributions of the two modes are shown in Fig. 3(a), where it is evident that they mainly generate dipole components \( p_x, p_y, p_z \) and \( m_y \). For the \( n = 1 \) eigenmode, the positive and negative charges accumulate at the ends of the helix, giving rise to \( p_x \) and \( p_y \); the current flows in one direction and gives rise to \( m_y \). Figures 3(b) and (c) show the comparisons between the analytical (lines) and numerical results (symbols) of \( p_x, p_y \) and \( m_y \), which show good agreements. For the \( n = 4 \) eigenmode, the positive and negative charges oscillate along the \( z \) direction, generating the dipole component \( p_z \), as illustrated in Fig. 3(a), while the current changes direction periodically in space, leading to vanished magnetic dipole. Figure 3(d) shows the comparison between the analytical (lines) and numerical (symbols) results of \( p_z \), which again exhibits good consistency.

The above electric and magnetic dipole components can fulfill the conditions of the three directional dipoles in Eqs. (1)–(3). This can be understood as follows. First, the emergence of both \( p_x \) and \( m_y \) in the first eigenmode is attributed to the chirality of the helix, and their relative amplitudes can be tailored by the geometry of the helix to satisfy \( |p_x| = |m_y|/c \). In addition, the charge-induced electric dipole \( p_x \) and the current-induced magnetic dipole \( m_y \) have an intrinsic phase difference of \( \pi/2 \). Thus, the first eigenmode can give rise to a Janus dipole \( \mathbf{D}_{Jan} = (p_x \mathbf{e}_x, m_y \mathbf{e}_y) \) with \( p_x / (m_y/c) = i \) irrespective of the incident angle. Second, the different values of \( p_x \) and \( p_z \) are attributed to the anisotropy of the helix. Their relative amplitude can be tuned by the incident angle of the plane wave because the incident fields \( E_y \) and \( E_z \) can excite the first-order and fourth-order eigenmodes, respectively. At an appropriate angle (corresponding to the dashed line in Fig. 2(b)), one can obtain \( |p_x| = |p_z| \). We notice that the first eigenmode is on resonance while the fourth eigenmode is off resonance, which indicates that \( p_x \) of the first-order eigenmode and \( p_z \) of the fourth eigenmode have a phase difference of \( \pi/2 \). Therefore, the first-order and fourth-order eigenmodes can give rise to a circular electric dipole \( \mathbf{D}_{cir} = (p_x \mathbf{e}_x, p_z \mathbf{e}_z) \) with \( p_x / p_z = i \). Third, with the combined effect of the chirality and anisotropy of the helix, the first-order and fourth-order eigenmodes can give rise to the Huygens dipole \( \mathbf{D}_{Huy} = (p_x \mathbf{e}_x, m_y \mathbf{e}_y) \) with \( (p_x / (m_y/c)) \times (p_z / p_x) = p_z / (m_y/c) = -1 \).

The eigenmode analysis can also explain why the phase differences between different dipole components are insensitive to the incident angle \( \theta \), corresponding to the results in Fig. 2(c). As shown in Fig. 3(a), the response of the helix is dominated by the first-order and fourth-order eigenmodes. The first-order eigenmode gives rise to \( p_x, p_y \) and \( m_y \). Thus, their phase differences are intrinsic properties of the eigenmode and do not depend on the excitation properties (including the incident angle). This explains the constant phase difference between \( p_x \) and \( m_y \), corresponding to the black line in Fig. 2(c). In addition, varying the incident angle does not change the relative phase of the excited
first-order and fourth-order eigenmodes. This is because their excitations are attributed to the incident electric field only, which is approximately constant over the deep-subwavelength helix and is independent of the incident angle. Therefore, the phase differences between \( p_z \) of the fourth-order eigenmode and \( p_x, m_y \) of the first-order eigenmode (corresponding to the blue and red lines in Fig. 2(c)) are insensitive to the incident angle.

**Directional excitations of guided wave**

The DDD can be employed to achieve directional scattering and coupling of electromagnetic waves. As a demonstration, we consider the helix located near the surface of a silicon waveguide and under the excitation of an incident plane wave, as shown in Fig. 4(a). The coupling between the helix and the waveguide can be expressed as:

\[
\kappa_{pw} \propto |p \cdot E^* + m \cdot B^*|,
\]

where \( E \) and \( B \) are electric and magnetic fields of the guided mode at the location of the dipoles \( p \) and \( m \). In the presence of the waveguide, the induced electric and magnetic dipoles are generally different from those of an isolated helix due to the reaction field of the waveguide. To achieve high directionality, the directional dipoles can be optimized to satisfy \(|p_x E_x^* + m_y B_y^* + p_z E_z^*| = 0\), i.e., the coupling is vanished for a particular guided mode. Following the terminology in Ref. [18], we call them the optimized directional dipoles to differentiate them from the ideal directional dipoles defined in Eqs. (1)-(3). The optimization can be easily done via tuning the polarization direction of the incident plane wave \( E_{\text{inc}} = (\sin \varphi \hat{e}_x - \sin \theta \cos \varphi \hat{e}_y + \cos \theta \cos \varphi \hat{e}_z)E_0 e^{-ik_0(z \cos \theta y + \sin \theta z)}\), where \( \varphi \) is the polarization angle defined as the projection angle of \( E_{\text{inc}} \) on the \( zy \)-plane, as shown in Fig. 4(a). Thus, we can tune the polarization direction by varying the angle \( \varphi \).

We first demonstrate the directional excitation of guided wave with the circular-dipole face of the DDD. We choose a silicon (relative permittivity \( \varepsilon_{\text{Si}} = 12 \)) waveguide with a rectangular cross section of \( w \times t = 620 \text{ nm} \times 310 \text{ nm} \), which supports a fundamental TE_{11} guided mode at the dipole resonance frequency of the helix (i.e., 108 THz).
The helix is located 80 nm above the waveguide’s upper surface, and its axis is in the $y$-direction to switch on the directionality of electric circular dipole $D_{\text{cir}} = (p_x \hat{e}_x, p_z \hat{e}_z)$. By adjusting the incident angle $\theta$ and the polarization angle $\varphi$, the helix can realize an optimized circular dipole (i.e., elliptical dipole) with $p_z/p_x = -E_z^*/E_x^* = 0.8i$ in the presence of the waveguide, as marked by the dashed line in Fig. 4(b). This dipole can excite guided wave propagating unidirectionally in the silicon waveguide because $\kappa_{pw}(+k_{wg}) > \kappa_{pw}(-k_{wg})$, where $\kappa_{pw}(\pm k_{wg})$ is the coupling coefficient for the guided wave propagating in the $\pm x$ direction. The directionality is clearly observed in the $H_y$ field of the system for $\theta = 22$ degrees and $\varphi = -10$ degrees, as shown in Fig. 4(c). Figure 4(d) shows the distribution of $|H_y|$ inside the waveguide induced by the ideal circular dipole (solid blue line) and the optimized circular dipole (solid yellow line), which has been normalized by the value of $|H_y|$ at $x = -1.5\lambda$ (corresponding to the amplitude of the guided wave propagating in $-x$ direction). We notice that the directionality, defined as $|H_y(+k_{wg})/H_y(-k_{wg})|$, reaches 40 for the optimized circular dipole and 13 for the ideal circular dipole.

To demonstrate the directional excitation of guided wave with the Huygens-dipole face of the DDD, we place the helix near the waveguide surface parallel to $xz$-plane with a distance of 80 nm, as shown in Fig. 5(a), which enables matching between the Huygens dipole $D_{\text{Huy}} = (p_x \hat{e}_x, m_y \hat{e}_y)$ and the fields of the guided wave $(E_z, H_y)$. By tuning the incident angle $\theta$ and polarization angle $\varphi$ to satisfy $|m_y B_y^* + p_z E_z^*| \rightarrow 0$ for the guided wave propagating in $-x$ direction, we obtain the optimized Huygens dipole with $p_z/(m_y/c) = -c B_y^*/E_z^* = -3.6$ at $\theta = 5$ degrees and $\varphi = -5$ degrees, as shown in Fig. 5(b). Figure 5(c) shows the electric field $E_z$ of the guided wave excited by the optimized Huygens dipole, which propagates predominantly in $+x$ direction. In Fig. 5(d), we plot the electric field inside the waveguide excited by the optimized Huygens dipole (solid yellow line), which has a directionality of 24 and is much larger than the directionality of the ideal Huygens dipole (solid blue line).

To demonstrate the directional excitation of guided wave with the Janus-dipole face of the DDD, we place the helix 80 nm above/below the waveguide to turn on the directionality of $D_{\text{Janus}} = (p_x \hat{e}_x, m_y \hat{e}_y)$, as shown in Fig. 6(a). The directionality of the Janus dipole manifests as side-dependent coupling/noncoupling to the waveguide [13], i.e., whether it couples to the waveguide depends on which side of the helix is facing the waveguide. To achieve a high directionality, we optimize the Janus dipole by requiring $|p_x E_z^* + m_y B_y^*| \rightarrow 0$ for the coupling between the helix
and waveguide, which gives $p_x / (m_y / c) = -cB_y^*/E_z^* = 2.5i$ at incident angle $\theta = 75$ degrees and polarization angle $\varphi = 74$ degrees, as shown in Fig. 6(b). Figure 6(c) and (d) show the electric field $E_z$ in the waveguide when the helix locates below and above the waveguide, respectively. As seen, the optimized Janus dipole only couples to the upper waveguide, corresponding to Fig. 6(c). Figure 6(d) shows the electric field amplitude $|E_z|$ inside the waveguide for the two configurations in Fig. 6(c). The solid (dashed) yellow line denotes the result for helix locating near the upper (lower) surface of the waveguide. The directionality in this case is defined as the ratio of the two lines, and it achieves a value of 40. For comparison, we also show the results of the ideal Janus dipole in Fig. 6(d) denoted by solid (dashed) blue lines, which has the directionality of 2.5.

Microwave experiments

We experimentally demonstrate the directional scattering and coupling of the DDD at the microwave regime. A photo of the experimental setup is shown in Fig. 7. The helix is made of copper with the electrical conductivity $\sigma = 5.813 \times 10^7$ S/m. It has minor radius $r = 0.5$ mm, pitch $P = 8$ mm and outer radius $R = 5.5$ mm, and supports the dipole resonance at 2.35 GHz. A horn antenna connected to Port 1 of a Vector Network Analyzer (VNA) provides the plane wave excitation. The antenna is mounted on a stand that allows angular rotations amounting to variations in the propagation and polarization directions of the incident wave (i.e., $\theta$ and $\varphi$). The plane wave excites the appropriate dipoles of the helix, which couple waves into the dielectric waveguide in a directional manner. The dielectric waveguide ($\varepsilon_r = 12$) has a cross-sectional dimension of 30 mm $\times$ 15 mm and a length of 620 mm. Both ends of the dielectric waveguide feature 60 mm-long tapers to optimize coupling into open-ended WR-430 metallic waveguide launchers, which are connected to Ports 2 and 3 of the VNA. This setup enables us to measure the coupling strength by comparing the power sent through Port 1 to the powers received at Ports 2 and 3 respectively. By tuning the direction of incidence, the helix can operate as a circular dipole, a Huygens dipole or a Janus dipole to realize near-field directional waveguiding.

In the circular-dipole experiment, the helix-waveguide configuration follows the settings in the previous section. The helix is placed above the dielectric waveguide with the gap distance of 2 mm, as shown in the inset of Fig. 8(a).
The symbol lines in Fig. 8(a) show the simulated and experimental amplitude directionality as a function of the polarization angle φ when θ = 8 degrees. As seen, the helix can numerically realize an optimized circular dipole with the directionality of 15.2 at (θ, φ) = (8 degrees, −60 degrees). The experimental directionality, given by the ratio of the received amplitude signals at Ports 2 and 3 (|E_{out}^2| / |E_{out}^3| = |S_{21}| / |S_{31}|) exhibits a peak at φ = −65 degrees. The high directionality value of 8.6 indicates the achievement of superior coupling to Port 2, which accounts for 98.68% of the total coupled power as shown in Fig. 8(b). For the Huygens-dipole experiment, we also follow the configuration settings in the previous section and place the helix near the dielectric waveguide with the gap distance of 2 mm as shown in the inset of Fig. 8(c). We again plot the simulated and measured directionality as a function of φ (for θ = 7 degrees) in Fig. 8(c). As seen, the helix can numerically realize an optimized Huygens dipole at (θ, φ) = (7 degrees, 18 degrees), with a simulated directionality of 35. The experimental directionality (|E_{out}^2| / |E_{out}^3| = |S_{21}| / |S_{31}|) reaches a peak value of 8.9 at φ = 20 degrees, where 98.75% of the coupled power is received at Port 2 as shown in Fig. 8(d). For the circular and Huygens dipoles of the DDD, the simulation and experiment results show great agreement, which verifies the robustness of our proposed mechanism.

In a slight deviation from the previous section, in order to overcome a wave blockage phenomenon, we adopt an alternative excitation geometry in demonstrating the side-dependent coupling property of the Janus dipole (see Sup-
FIG. 7. Experiment setup. A horn antenna that excites the helix is mounted on a stand that allows azimuthal and elevation rotations. The dielectric waveguide (DWG) transitions into metallic waveguide (MWG) launchers on both ends.

FIG. 8. (a, b) Simulated and experimental directionality of the circular-dipole face of the helix as a function of the polarization angle $\varphi$, as well as the power percentage of Port 2 and Port 3. (c, d) Simulated and experimental directionality of the Huygens-dipole face of the helix as a function of the polarization angle $\varphi$, as well as the power percentage of Port 2 and Port 3. (e, f) Simulated and experimental directionality of the Janus-dipole face of the helix as a function of the rotation angle $\psi$, as well as the power percentage of the top and bottom waveguides.

Supplemental Information). Figure S(e) shows the placement of the helix midway between the two dielectric waveguides with gap distance 39 mm. In this approach, the incident direction of the plane wave (the wavevector $\mathbf{k}$) is on the $xy$ plane, such that the line of sight from the feed antenna to the helix is unobstructed by the waveguides. The directionality optimization of Janus dipole can be achieved by tuning the incident angle $\theta$ (the angle between $\mathbf{k}$ and $x$) and rotation angle $\psi$ (the angle between the helix axis and $-x$ direction) on the $xy$ plane. We divide the experiment into two parts: (1) the coupling between the helix and upper waveguide, and (2) the coupling between the helix and lower waveguide. Figure S(e) shows the simulated and measured amplitude directionality of the Janus dipole as a function of $\psi$ when $\theta = 40$ degrees, where the directionality is defined as the ratio of the field coupled to the top waveguide (Port 2 + Port 3) and bottom waveguide (Port 4 + Port 5). As seen, the helix can numerically realize an optimized Janus dipole with the directionality of 36 at ($\theta, \psi$) = (40 degrees, 35 degrees). The experimental directionality, given by $(|S_{21}| + |S_{31}|) / (|S_{41}| + |S_{51}|)$, reaches a peak with the value of 6.8 at $\psi = 50$ degrees. At this directionality, over 90% of the power couples to the top waveguide as shown in Fig. S(f). The simulation and experiment results show consistent trend but have a 15-degree shift in the optimal orientation angle, likely due to slight inaccuracies in the measurement setup.
Conclusion
In conclusion, we theoretically and experimentally demonstrate that a single anisotropic chiral particle can serve as a DDD to give the circular dipole, Huygens dipole, and Janus dipole under the excitation of a linearly polarized plane wave at the same frequency. We apply the three directional dipoles to realize directional coupling of light to a dielectric waveguide in the infrared regime. The phenomena are experimentally verified in the microwave regime using a copper helix placed near dielectric waveguides. The emergence of the directional dipoles in the helix particle can be well understood based on a mode expansion theory. It is found that the chirality gives rise to the Janus dipole via the odd-order eigenmodes of the helix; the anisotropy gives rise to the circular dipole via both the odd-order and even-order eigenmodes; the anisotropy and chirality together generate the Huygens dipole via the odd-order and even-order eigenmodes. The analytical theory enables straightforward designing of optimal directional sources for arbitrary waveguides. The proposed DDD can enable unprecedented control of near-field and far-field directionality with broad applications in photonic integrated circuits, quantum information processing, and metasurface design.

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Supplemental Information
Eigenmodes of the helix. The eigenmodes of the metal helix can be determined by mapping the eigenmodes of the corresponding nanorod, which can be semi-analytically determined as follows. The eigenmodes of the nanorod are Fabry-Perot standing waves of currents with eigenfrequencies $\omega_n$ satisfying

$$\omega_n \sqrt{\mu_0 \varepsilon_0 n_{\text{eff}}(\omega)L + \phi(\omega)} = n\pi,$$

where $L = N\sqrt{4\pi^2 R^2 + P^2}$ is the arc length of the $N$–turn helix, $n$ is the order of the eigenmodes, $n_{\text{eff}}(\omega)$ is the effective refractive index of propagating surface plasmon, and $\phi(\omega)$ is the reflection phase at the ends of the helix. The values of $n_{\text{eff}}(\omega)$ and $\phi(\omega)$ are approximately constant for a fixed $r$ over a range of frequencies, and they can be numerically determined via solving for the TM$_0$ guided mode of the nanorod. Equation (16) allows us to analytically calculate the eigenfrequency $\omega_n$ and the propagating constant $\gamma_n(\omega) = \omega_n \sqrt{\mu_0 \varepsilon_0 n_{\text{eff}}(\omega)}$ of the current wave. Figure 9 shows $\omega_n$ of the nanorod for the first eigenmode $n = 1$ and $\gamma_n$ of the nanorod for the eigenmodes of orders $n = 1, 2, 3, 4$. The cross symbols denote the analytical results obtained using Eq. (16), which agree well with the numerical results obtained using COMSOL (denoted by the circle symbols). The currents on the nanorod can

![Figure 9](image-url)

**FIG. 9.** (a) Charge distribution for the Fabry-Perot standing wave of order $n$ in the helix and the nanorod. (b) Comparison between analytical results (cross) and numerical results (circle) of the eigen frequency for different lengths of the nanorod. (c) Comparison of the propagation constants of the eigenmodes obtained by the analytical method (cross) and numerical method (circle).
FIG. 10. Alternative design of the gold helix as the DDD. (a) Scattering cross sections of the helix particle and the contributions of the electric and magnetic dipoles. (b) The relative amplitudes and phases of the dipole components as a function of the incident angle of the linearly polarized plane wave. The dashed line marks the parameters giving three directional dipoles.

be approximately expressed as \( \cos(\gamma_n l) \) for odd orders and \( \sin(\gamma_n l) \) for even orders with \( l \in [-L/2, L/2] \). The eigen currents of the helix can be obtained by mapping these currents of the nanorod as

\[
J_n = \begin{cases} 
\cos(\gamma_n l) \mathbf{t}, & n = 1, 3, 5, \ldots \\
\sin(\gamma_n l) \mathbf{t}, & n = 2, 4, 6, \ldots 
\end{cases}
\]

with \( \mathbf{t} = (\pm(2\pi NR/L) \cos(2\pi NL/L + N\pi), \frac{NP}{L}, 2\pi NR/L \sin(2\pi NL/L + N\pi)) \) being the tangent direction vector of the helix path.

**Alternative design of helix.** The physical mechanism of realizing the directional dipoles in an anisotropic chiral particle is robust, and the phenomena can be demonstrated in different designs of the helix working at different frequencies. In addition to the design in the main text, another design of the helix is shown in Fig. 10(a), where the pitch is \( P = 90 \text{ nm} \), the outer radius is \( R = 40 \text{ nm} \), and the inner radius is \( r = 15 \text{ nm} \). This helix works at the dipole resonant frequency of 147 THz, and it can give rise to the three types of directional dipole when the incident angle is 15 degrees, as shown in Fig. 10(b).

**Dielectric waveguide to metallic waveguide transition.** The dielectric waveguide (\( \mu_r = 1, \varepsilon_r = 12 \)) used in this experiment with cross-sectional dimension of 30 mm × 15 mm and a total length of 620 mm was fabricated by CNC technology. In opposition to what is obtainable in a metallic waveguide, the fields are not totally confined to the
FIG. 11. Dielectric waveguide to metallic waveguide transition. The inset shows the simulation and experiment model (DWG – Dielectric waveguide with dimensions $a = 15$ mm, $b = 30$ mm, $l_t = 60$ mm, $L = 500$ mm, MWG – Metallic waveguide). Extracted simulation and experiment results show minimal reflection and excellent transmission from the input port (Port 1) to the output port (Port 2).

guiding structure in a dielectric waveguide. Transitioning between these two types of waveguides thus presents an interesting challenge. Many transition methods have been proposed over the years [64, 65]. In this experiment, we adopt the end tapering method to ensure optimum transition from the dielectric waveguide to the standard WR430 metallic waveguide launchers, which are connected to the vector network analyzer. The two ends of the dielectric waveguide thus have a 60 mm-long taper.

An HFSS simulation setup to confirm the efficient transition is shown in the inset of Fig. 11. We excite Port 1 and measure the received power at Port 2 ($S_{21}$) as well as the reflected power back into Port 1, comprising the reflection from the metallic waveguide launcher (at Port 1) and the reflection from the end of the dielectric waveguide (at Port 2) back into Port 1 ($S_{11}$). We also experimentally extract the reflection and transmission parameters when the two ends of the dielectric waveguide are terminated with WR430 metallic waveguide launchers. The WR430 waveguides launchers have a coaxial-to-waveguide adaptor, through which the waveguides are connected to a Vector Network Analyzer (VNA). Port 1 is excited while Port 2 serves as the receiver. The simulated and measured results as presented in Fig. 11 show minimal reflection and good transmission at 2.35 GHz. The results show efficient coupling of the waves from the dielectric waveguide to the metallic waveguides.

**System analysis.** We consider the experimental setup shown in Fig. 7 as a 3-port network representable by

$$
\begin{bmatrix}
V_{1\text{out}} \\
V_{2\text{out}} \\
V_{3\text{out}}
\end{bmatrix} =
\begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23} \\
S_{31} & S_{32} & S_{33}
\end{bmatrix}
\begin{bmatrix}
V_{1\text{in}} \\
V_{2\text{in}} \\
V_{3\text{in}}
\end{bmatrix}
$$

(18)

where the voltages $V_{i\text{in}}$ and $V_{i\text{out}}$ correspond to field of the incident and received waves respectively and $i = 1, 2, 3$ corresponds to respective VNA port. Since only Port 1 is excited, then $V_{2\text{in}} = V_{3\text{in}} = 0$. If $V_{1\text{in}}$ is assumed to be 1 V, then the output voltages at ports 2 and 3 can be calculated

$$
V_{2\text{out}} = S_{21} \times V_{1\text{in}} = S_{21},
$$

$$
V_{3\text{out}} = S_{31} \times V_{1\text{in}} = S_{31}.
$$

(19)

Examining the ratio of the field magnitudes at both ends of the dielectric waveguide which gets coupled into the metallic waveguide hence serves as a useful indicator to observe directive wave guiding towards either side of the dielectric waveguide. A background measurement is taken whereby $[S]_{\text{bgd}}$ is measured when the helix is absent from the experimental setup. This measurement picks up faint spurious signals directly coupled from the source antenna (Port 1) to the waveguide launchers (Ports 2 and 3) or scattered by other objects within the measurement chamber. Thereafter, performing a background calibration $[S] = [S]_{\text{helix}} - [S]_{\text{no helix}}$ minimizes these background contributions to the measurement.
The rotated Janus dipole. To enable efficient excitation of the Janus dipole, we employ a slightly different configuration in the microwave experiment, where the Janus dipole is rotated in the \(xy\) plane, as shown in Fig. 12a. The helix is sandwiched by two waveguides with the gap distance of 19.5 mm. The incidence is a linearly polarized plane wave in the form of \(E_{\text{inc}} = (\sin \theta_x - \cos \theta_y)E_0 e^{i(k_0 \cos \theta + ik_0 \sin \theta_y)}\), where \(\theta\) is the incident angle between the wavevector \(k\) (on the \(xy\) plane) and the \(+x\) axis. The optimized Janus dipole can be achieved via tuning the rotation angle \(\psi\) of the helix axis with respect to the \(-x\) axis on the \(xy\) plane, i.e., tuning the match between the dipoles \((m_x\) and \(p_y)\) and the waveguide mode \((B_x\) and \(E_y\)) so that \(m_x B_x^* + p_y E_y^* \to 0\), which gives \(p_y/(m_x/c) = -cB_x^*/E_y = -1.8i\), at incident angle \(\theta = 40\) degrees and rotation angle \(\psi = 35\) degrees, as shown in Fig. 12b.

**FIG. 12.** (a) Schematic of the helix-dual-waveguide coupling configuration for demonstrating the directionality of the rotated Janus dipole. (b) The relative amplitude and phase of the dipoles \(p_y\) and \(m_x\) as a function of the rotation angle \(\psi\). The incident angle \(\theta\) is set to be 40 degrees.
[49] P. Woźniak, P. Banzer, and G. Leuchs, Selective Switching of Individual Multipole Resonances in Single Dielectric Nanoparticles, Laser Photonics Rev. 9, 234 (2015).

[50] M. F. Picardi, C. P. McPolin, J. J. Kingsley-Smith, X. Zhang, S. Xiao, F. J. Rodríguez-Fortuño, and A. V. Zayats, Integrated Janus Dipole Source for Selective Coupling to Silicon Waveguide Networks, Appl. Phys. Rev. 9, 021410 (2022).

[51] M. Kerker, D.-S. Wang, and C. L. Giles, Electromagnetic Scattering by Magnetic Spheres, J. Opt. Soc. Am. 73, 765 (1983).

[52] R. L. Olmon, B. Slovick, T. W. Johnson, D. Shelton, S.-H. Oh, G. D. Boreman, and M. B. Raschke, Optical Dielectric Function of Gold, Phys. Rev. B 86, 235147 (2012).

[53] A. G. Mark, J. G. Gibbs, T.-C. Lee, and P. Fischer, Hybrid Nanocolloids with Programmed Three-dimensional Shape and Material Composition, Nat. Mater. 12, 802 (2013).

[54] J. Gibbs, A. Mark, S. Eslami, and P. Fischer, Plasmonic Nanohelix Metamaterials with Tailorable Giant Circular Dichroism, Appl. Phys. Lett. 103, 213101 (2013).

[55] X.-L. Zhang, S. B. Wang, Z. Lin, H.-B. Sun, and C. T. Chan, Optical Force on Toroidal Nanostructures: Toroidal Dipole Versus Renormalized Electric Dipole, Phys. Rev. A 92, 043804 (2015).

[56] K. J. Wo, J. Peng, M. K. Prasad, Y. Shi, J. Li, and S. Wang, Optical Forces in Coupled Chiral Particles, Phys. Rev. A 102, 043526 (2020).

[57] J. K. Gansel, M. Thiel, M. S. Rill, M. Decker, V. Saile, G. von Freymann, S. Linden, and M. Wegener, Gold Helix Photonic Metamaterial as Broadband Circular Polarizer, Science 325, 1513 (2009).

[58] C. Fang, C. Wu, Z. Gong, S. Zhao, A. Sun, Z. Wei, and H. Li, Broadband and High-efficiency Vortex Beam Generator Based on a Hybrid Helix Array, Opt. Lett. 43, 1538 (2018).

[59] www.comsol.com;

[60] K. Höflich, T. Feichtner, E. Hansjürgen, C. Haverkamp, H. Kollmann, C. Lienau, and M. Silies, Resonant Behavior of a Single Plasmonic Helix, Optica 6, 1098 (2019).

[61] L. Novotny and B. Hecht, Principles of Nano-optics (Cambridge University Press, New York, 2012).

[62] S. Wang and C. T. Chan, Strong Optical Force Acting on a Dipolar Particle over a Multilayer Substrate, Opt. Express 24, 2235 (2016).

[63] L. Novotny, Effective Wavelength Scaling for Optical Antennas, Phys. Rev. Lett. 98, 266802 (2007).

[64] T. Trinh, J. Malherbe, and R. Mittra, A Metal-to-dielectric Waveguide Transition with Application to Millimeter-wave Integrated Circuits, in 1980 IEEE MTT-S International Microwave Symposium Digest (IEEE, 1980) pp. 205–207.

[65] S. Dudorov, Rectangular Dielectric Waveguide and Its Optimal Transition to a Metal Waveguide, Ph.D. thesis, Helsinki University of Technology (2002).