Nanoscale emitters, scatterers and their assemblies have been recently considered for quantum optical technologies, metasurface designs enabling flat lenses and hologrammes, and scalable photonic circuitry, where the requirements on miniaturization and efficient coupling to photonic modes are strict [1–3]. Scatters can be realised as strongly resonant plasmonic or high-index dielectric nanoparticles supporting electric and/or magnetic dipolar resonances, while emitters can be quantum dots or atoms. Near field interference and related directional excitation of fields from circularly polarized electric and magnetic dipoles [4–13] have proven to have fascinating applications in quantum optics [14–16] and in novel experimental photonic devices such as nanorouters, polarimeters, and non-reciprocal optical components [17–25]. These effects rely on the photonic quantum spin-Hall effect exploiting the phenomenon of spin-momentum locking in evanescent and guided waves [26–31]: in essence, the spin of the dipole can be matched to the inherent spin of confined fields to be directionally excited. Electromagnetic spin accounts for the rotation of the electric \( \mathbf{E} \) and magnetic \( \mathbf{H} \) field vectors, however it does not account for the relative amplitude and phases between electric and magnetic components. By engineering superpositions of electric and magnetic dipoles and their interference [32–35] we can exploit these relations to achieve near-field directionality beyond spin-momentum locking. An example of a well-known dipolar source which exploits these relations to achieve far-field directionality is the Huygens’ antenna. This source combines two orthogonal linearly polarized electric \( \mathbf{p} \) and magnetic \( \mathbf{m} \) dipoles satisfying Kerker’s condition [36, 37]:

\[
p = \frac{m}{c},
\]

with \( c \) being the speed of light. Its radiation diagram is highly directional and has zero back-scattering, due to the interference of magnetic and electric dipole radiation. These antennas are attracting great attention due to the feasibility of implementing them using high-index dielectric nanoparticles [38–41], with applications in null back-scattering metasurfaces, and all-dielectric mirrors [42–48].

Here we show that Huygens’ sources can be generalized to achieve near-field directionality, and that there exists a dipolar source complementary to a Huygens’ dipole, which we term Janus dipole, with a different relation between the phases of electric and magnetic dipoles, which is not directional in the far-field, but has unique near-field properties allowing side-dependent coupling to guided modes. Together, Huygens’, Janus, circular electric and magnetic dipoles (as well as the infinite spectrum of their linear combinations) provide a general closed solution to dipolar far- and near-field directionality that takes into account the topology of the vector structure of free space and guided electromagnetic fields. These dipolar sources can be experimentally realised as plasmonic, dielectric and hybrid nanoparticles.

We consider three elemental dipole sources for near-field directionality: circularly polarized dipoles have spinning electric or magnetic dipole moments, while Huygens’ and Janus sources combine orthogonal electric and magnetic dipoles that are in phase or 90° out of phase to each other, respectively. Each can be introduced from their close relation to well known electromagnetic quantities (Fig. 1). Firstly, Huygens’ sources are often explained in terms of the time-averaged Poynting vector \( \propto \text{Re} \left[ \mathbf{E}^* \times \mathbf{H} \right] \). This vector represents intensity and direction of the electromagnetic power flow. It arises whenever electric and magnetic field are in phase and orthogonal to each other. It follows that, when electric and magnetic dipoles are orthogonal and in phase—a Huygens’ source—they produce fields associated with a net power flow in a given direction. This gives rise to directionality in the far-field [42–48], but we can exploit the same idea in the near-field of a waveguide (Fig. 1). Secondly, circularly polarized dipole directionality can be explained by means of the spin angular momentum [49] \( \propto \text{Im} \left[ \mathbf{E}^* \times \mathbf{E} \right] + \text{Im} \left[ \mathbf{H}^* \times \mathbf{H} \right] \), which accounts for the rotation of the vectors \( \mathbf{E} \) and \( \mathbf{H} \). Owing to the existence of out-of-phase longitudinal components of the
fields in guided modes, this spin can be transverse to the propagation direction. Circularly polarized dipoles – two orthogonal electric or magnetic dipole moments, \(90^\circ\) out of phase– exploit this well-known transverse spin-momentum locking [6, 28–31], exciting the guided mode in one direction only. Finally, we can consider a third quantity \(\propto \text{Im}\{E^* \times H\}\). This expression resembles spin angular momentum, but it mixes electric and magnetic components. It arises when \(E\) and \(H\) are orthogonal but \(90^\circ\) out of phase. This phase shift results in harmonic oscillations of the instantaneous power flow, with a zero time-averaged net flow. This is the imaginary part of the complex Poynting vector, and is known as reactive power. It points in the direction of evanescent gradient: away from or towards the nearby waveguide, depending on the mode. We thus propose the Janus source, using orthogonal electric and magnetic dipoles with a \(90^\circ\) phase shift to match or oppose this vector, accounting for its two ‘faces’: one face couples into the mode, while the other is non-coupling. The three vector quantities, each associated with one of the sources, form a triad at each point near a waveguide [31] (Fig. 1).

As a simple example, Fig. 2 shows the fields generated by (a) a circular dipole, (b) a Huygens’ antenna, and (c,d) a Janus dipole for its two orientations, all placed over a dielectric slab waveguide. We used a planar slab as an example, but the directionality of the dipoles is universal and completely independent of the waveguide’s nature. The first two sources lead to directional evanescent wave excitation of guided modes. While this is known for circular dipoles [4–13, 29, 31], Huygens’ antennas have been extensively studied for their strong directional radiation diagram, but their near-field directionality had not been explored. The direction of excitation of these sources can be switched by flipping the sign of one of their two dipole components, which can be experimentally achieved tuning polarization and wavelength of the light illuminating
the nanoparticle, with respect to its electric and magnetic resonances.

The Janus dipole has an intriguing property: by opposing or matching the direction of reactive power, perpendicular to the waveguide, it either shows (c) a complete absence of coupling, not exciting waveguide modes at all or (d) excitation of the guided mode in both directions. This is determined by which ‘side’ of the dipole is facing the waveguide. Inverting the sign of one component in the Janus dipole will change the side facing the waveguide, like when flipping a coin, and this will switch the coupling on and off [Figs. 2(c,d)]. Alternatively, the dipole’s behaviour depends on which side of the waveguide it is placed. Each of these three elemental sources possesses the same symmetries as the vector it is associated with, sharing its behaviour under parity (P) and time-reversal (T) symmetry transformations [50], as summarized in Fig. 1(b).

A quantitative explanation of the three sources can be obtained from Fermi’s golden rule [6–9, 14, 15, 31]. This rule dictates that the coupling efficiency between an electric \( p \) and magnetic \( m \) dipole source and a waveguide mode is proportional to \( |p \cdot \mathbf{E}^* + m \cdot \mu \mathbf{H}^*|^2 \), where \( \mathbf{E} \) and \( \mathbf{H} \) are the electric and magnetic fields, respectively, of the mode calculated at the location of the dipoles, and \( \mu \) is the permeability of the medium. In Fig. 2, the dipoles are interacting with a \( p \)-polarized waveguide mode, so the only non-zero field components are the transverse electric and magnetic fields \( E_x \) and \( H_y \), and the longitudinal field \( E_z \). The circular dipole exploits spin-momentum locking [6, 28–31] to achieve \( p \cdot \mathbf{E}^* = p_x E_x^* + p_z E_z^* = 0 \) for the mode propagating to the left or right, thereby showing unidirectional excitation in the opposite direction. Analogously, circular magnetic dipoles directionally excite \( s \)-polarized modes when \( m \cdot \mu \mathbf{H}^* = 0 \).

To describe the nature of the other two sources, however, we must also take into account the relative phase and amplitude between \( \mathbf{E} \) and \( \mathbf{H} \). Their relation can be exploited such that the electric and magnetic coupling terms interfere destructively between each other \( p \cdot \mathbf{E}^* + m \cdot \mu \mathbf{H}^* = 0 \). In other words, the mode excited by the electric dipole \( p \) in a given direction is exactly cancelled out by the one excited by the magnetic dipole \( m \) after their superposition. The Huygens’ source exploits the fixed relative amplitude and phase that exists between the transverse field components \( E_x \) and \( H_y \), which depends on the propagation direction of the mode, as dictated by the Poynting vector. This relation is a well-known property of plane waves which extends directly into evanescent and guided waves.

The Janus dipole exploits the locked amplitude and phase relation that exists between \( H_y \) and the longitudinal electric field \( E_z \). The unique feature of the Janus dipole, which distinguishes it from the other two, is that the modes excited by the electric \( p_x \) and magnetic \( m_y \) dipoles simultaneously interfere destructively for both propagation directions. This is possible because the ratio between \( E_x \) and \( H_y \) is dictated by the reactive power flow vector, and is independent of the mode’s left or right propagation direction (time-reversal). This is universally true, at any location, on any waveguide, as follows from the even time-reversal (T) symmetry of the reactive power flow (see Fig. 1(b)). Thus, a Janus dipole can be designed to achieve polarization and position-dependent “non-coupling” in every scenario where longitudinal fields are present, such as inside nanowires and photonic crystal waveguides, not being limited to external evanescent coupling as illustrated here. This is a remarkable topological property of near-field polarization in addition to transverse spin [28]. Both the circular and Janus dipole rely on the longitudinal component of the field, while the Huygens’ source does not. This explains why circular and Janus dipoles are not directional in the far field [4, 13], as plane waves have no longitudinal field.

![FIG. 3. Amplitude of the electric field generated by (a) a circular dipole, (b) a Huygens’ antenna and (c) a Janus dipole embedded in the centre of a metal-air-metal waveguide, with \( \varepsilon = -1.5 + 0.02i \) and \( \mu = 1 \). The distance between the two waveguides is 0.7λ. These fields have been simulated using Comsol Multiphysics.](image-url)
Mathematically, this simple equation defines a geometrical dipole into a given mode: $$\mathbf{q}_p \cdot \mathbf{F}_p = \left( p_z, \frac{m_y}{c}, p_z \right) \cdot \left( \pm \frac{i \alpha_m}{k}, 1, -\frac{\pm k_m}{k} \right) = 0.$$ 

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of the guided mode’s fields $\mathbf{E}$ and $\mathbf{H}$, neglecting their mutual amplitude and phase relations. By considering the complete vector structure of electromagnetic fields, we provide a unified theory describing all possible dipole sources exhibiting far- and near-field directionality with planar structures; these considerations can be applied to arbitrary geometries once the modes supported by the waveguide are known. The implementation of these new sources using resonant plasmonic or dielectric nanoparticles and their integration in photonic circuitry will provide a step change in the already broad range of near-field directionality applications, currently based on circular dipoles exclusively. We expect novel ideas to emerge in quantum optics, photonic nano-routing, photonic logical circuits, optical forces and torques of particles in near-field environments, inverse and reciprocal scenarios for polarization synthesis, integrated polarimeters, and other unforeseen devices throughout the whole electromagnetic spectrum.

ACKNOWLEDGEMENTS

This work was supported by European Research Council Starting Grant ERC-2016-STG-714151-PSINFONI and EPSRC (UK). A.Z. acknowledges support from the Royal Society and the Wolfson Foundation. All data supporting this research is provided in full in the main text and Supplementary Materials.

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