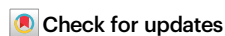


# Freeform optical flow based on meta-conveyors for compact, programmable in situ nanomanipulation

Received: 16 November 2025

Accepted: 28 April 2026

Published online: 09 May 2026

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Programming light flow offers significant potential for diverse applications. However, conventional spatial light modulators are bulky, have large pixels, and slow switching. Miniaturized metasurface strategies offer flexibility but are limited to radial or azimuthal phase gradients, hindering free shaping of light flow in ultracompact footprints. Here, we present a meta-conveyor technique (MCT) using metasurfaces to encode user-defined optical flow, demonstrating programmable stable transport of nanoparticles (NPs) with arbitrary open-path round-trip movement and on-demand stopping. Theoretical analysis reveals efficient phase gradient switching from hybrid propagation and geometric phases, enabling tunable lateral optical forces via input and output polarization control. We validate universality with a maze-solving meta-conveyor that drives NPs from entrance to exit while avoiding dead ends. The MCT provides a compact, passive platform for programmable on-chip manipulation, opening avenues for heterogeneously integrated clinical devices in minimally invasive and extreme environments.

Arbitrary shaping of structured light fields using engineered materials has significantly advanced both fundamental research and practical applications in light-matter interactions<sup>1,2</sup>. Since the early 21st century, mature techniques such as liquid-crystal spatial light modulators (SLMs) and digital micromirror devices have enabled flexible light-field modulation in laboratories, yielding numerous exciting accomplishments in laser micro-processing<sup>3</sup>, optical manipulation<sup>4</sup>, microscopic imaging<sup>5</sup>, and illumination engineering<sup>6</sup>. Among these, optical manipulation, a non-contact, high-precision technique for trapping and transporting microscopic objects via light momentum transfer<sup>7</sup>, has particularly benefited fields such as biology and medicine, enabling high-precision drug delivery within complex fluidic

environments like blood vessels<sup>8,9</sup>. Although spatial movement with optical tweezers (OTs) can be achieved using a mechanical translation stage that maintains a fixed trapping spot, such global movement often disturbs the surrounding environment. Moreover, the tunable intensity-gradient forces are subject to a critical speed-power-heat trade-off. Increasing the manipulation speed necessitates higher laser power, which inevitably introduces detrimental thermal effects and laser noise that compromise trapping precision. To overcome these limitations, realizing high-precision in situ applications in stationary and undisturbed environments requires generating user-defined optical flows in a sophisticated manner to exert stable and independent optical forces (OFs) on targets. Notably, by employing pre-

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engineered phase profiles, the lateral optical force (LOF)—which is mediated by light flow and depends on both intensity and phase gradients—can be designed to induce directional nano-object migration<sup>10–14</sup>. Programmable OTs, for instance, often employ dynamic computer-generated holograms loaded on SLMs. However, the pixelated structure of SLMs, typically with limited microscale pixels, introduces optical noise and speckle, compromising trapping stability. Moreover, real-time manipulation necessitates constant refreshment of holographic patterns, leading to system complexity, large footprints, and poor portability. These constraints ultimately restrict their practical use in integration-sensitive fields such as biomedicine.

In contrast, metasurfaces offer an ultrathin platform to address these challenges by imposing abrupt phase gradients at sub-wavelength interfaces to sculpt light<sup>15,16</sup>, naturally giving rise to phase-gradient optical forces (PGOFs) and are promising for applications demanding high precision, robustness, and integrability. Over the past decade, the meta-atom phase response, typically determined by parametric functions such as hyperbolic<sup>17</sup> or spiral phases<sup>18</sup> (or their mixtures<sup>19</sup>), has been used to form structured light flows. However, these approaches are fundamentally limited in scope for metasurface-based trapping or spanning applications<sup>20–26</sup>. They generally produce only a uniform radial phase gradient—derived from hyperbolic or conical profiles for focusing—or an azimuthal phase gradient from the linear spiral phase profiles contained in standard vortex beams for orbital rotation. Recent efforts have aimed to overcome this by engineering far-field patterns with arbitrary profiles, as demonstrated in generalized optical vortices<sup>27,28</sup> and caustic loops<sup>29</sup> featuring spatially and azimuthally varying phase gradients—referred to here as non-uniform phase modulation—to control intensity distributions and generate tailored patterns. Nevertheless, these studies remain confined to closed-loop trajectories and are still far from practical applications. There is thus a pressing need to break free from these constraints and realize highly complex, freeform, open-path optical flows that are compact and tunable, surpassing bulky SLM-based systems for heterogeneous integration.

In this work, we propose an ultracompact and programmable metasurface that achieves fully functional in situ optical transport, enabling forward, halted, and backward motion of nanoparticles without any constraints. This is accomplished simply by switching the combination of input and output circular polarization states, a technique we term the “meta-conveyor”. Unlike holographic OTs that require sample movement or frequent phase-mask refreshing, our approach uses a single and ultrathin static interface to realize complex round-trip transport paths and allows pausing at desired intermediate

points. As a proof of concept, we experimentally demonstrate in situ nanoparticle transport with obstacle avoidance via rapid polarization selection, where the metasurface-tailored optical flow drives particles along pre-defined wavy trajectories. This capability to generate switchable PGOFs originates from the analysis of meta-atoms’ anisotropy, which combines judiciously designed propagation and geometric phases, thereby exceeding the multiplexing capacity of conventional two-channel circular-polarization-multiplexed metasurfaces<sup>30–34</sup>. Furthermore, to showcase the high complexity achievable with the meta-conveyor, we encoded the solution into a phase-gradient flow path based on a virtual maze, demonstrating a novel optical maze-solver robust to any extreme environment. This metasurface-based freestyle nanomanipulation technology can be extended to applications such as arbitrary lithographic patterning<sup>35</sup>, colloidal self-assembly<sup>36</sup> and may be heterogeneously integrated with other portable devices to translate laboratory OT system into practical use.

## Results

### Concept of fully functional meta-conveyor

Figure 1a presents a schematic illustration of multimodal NP transport achieved via a multifunctional metasurface. Under CP illumination at the working wavelength, the metasurface shapes the incident beam and can generate three independent channels that are denoted as channels 1–3, depending on different combinations of input and output CPs. Each channel produces a distinct force characterized by a transverse PG, enabling precise nanomanipulation of NP: propelling them forward, backward, or trapping them in place, mimicking an optical conveyor belt. Figure 1b–d elucidate the operational mechanism of the meta-conveyor. Here, we define  $\hat{\epsilon}_{x,y}$  as the electric vector basis. In Fig. 1b–d, the handedness of the incident and output CP states is indicated by arrows labeling the outer and inner circles, colored as blue and red, respectively. Specifically, Fig. 1b, d depict the cross-CP channels, whereas Fig. 1c illustrates the co-CP channel. Therefore, under right-circularly polarized (RCP) incidence and left-circularly polarized (LCP) analyzer, the NP experiences a PGOF ( $F_{PG}$ ) that propels it forward along the predefined trajectory, while simultaneously being confined transversely by the intensity gradient force ( $F_{IG}$ ), ensuring stable movement along the path. Therefore, to achieve precise control within the transverse  $x$ - $y$  plane, our system utilizes the conservative  $F_{IG}$  for lateral confinement and the non-conservative  $F_{PG}$  for on-track driving along the trajectory.

When the CP configuration is switched to the case where the input polarization and output channel are identical, as shown in Fig. 1c, the PGOF vanishes. The NP is thus solely subjected to  $F_{IG}$  and becomes

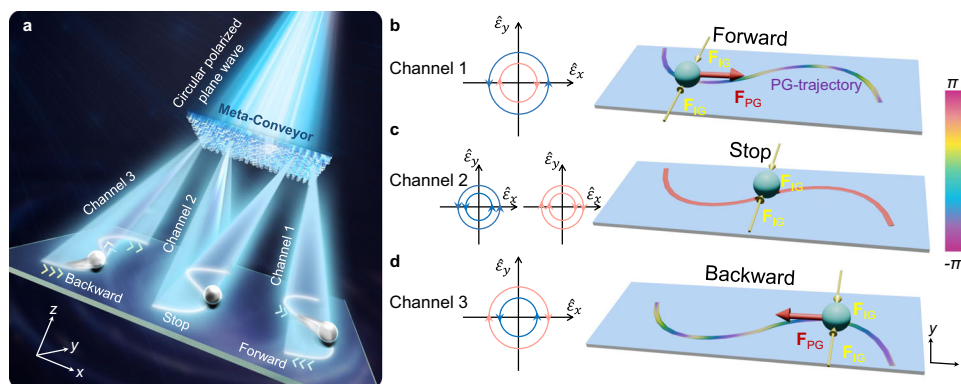


**Fig. 1 | Schematic diagram of the fully functional meta-conveyor for providing multimodal transverse PGOF. a** The metasurface modulates orthogonal CP plane waves to create three distinct phase-gradient patterns under different combinations of incident polarization state and analyzed channel, enabling NP transport

along a wavy trajectory in forward, halted, and backward directions. The corresponding PGOF exerted on the NP for different channels is illustrated in (b–d). The NP remains stably trapped within the trajectory due to the intensity-gradient OF exerted near the edges.

trapped in place. Conversely, as depicted in Fig. 1d, when the CP combination is switched to LCP incidence and RCP output, the direction of  $F_{PG}$  is reversed. Consequently, the NP experiences a reversed PGOF pointing in the backward direction along the trajectory. By rapidly toggling among these incident CP-dependent channels, the full conveyor-like functionality can be achieved, allowing NPs to be transported, halted at arbitrary positions, or to have the direction of PGOF reversed on demand, offering flexible and dynamic control over NP manipulation. For the bidirectional conveyance demonstrated here, these three motion states—forward, stop, and backward—constitute a logically complete set for fully functional operation.

### Optical conveyance based on metasurface

Based on the above framework, we proceed to investigate the underlying mechanisms responsible for the OFs exerted by the metasurface-generated light on the NP. In general, the time-averaged OF acting on the NP under monochromatic light illumination can be described within the framework of the dipole approximation<sup>37–39</sup>:

$$\mathbf{F}(\mathbf{r}) = \frac{1}{4} \alpha' \nabla u^2(\mathbf{r}) + \frac{1}{2} \alpha'' u^2(\mathbf{r}) \sum_{j=1}^3 a_j^2(\mathbf{r}) \nabla \Phi_j(\mathbf{r}) \quad (1)$$

where  $\mathbf{r} = (x, y, z)$  and  $\alpha = \alpha' + i\alpha''$  denotes the complex polarizability of the dipole, and  $\mathbf{E}(\mathbf{r}) = u(\mathbf{r}) \hat{\mathbf{e}}(\mathbf{r}) e^{i\Phi(\mathbf{r})} e^{-i\omega t}$  represents the complex electric field, with  $u(\mathbf{r})$  being the field magnitude,  $\hat{\mathbf{e}}(\mathbf{r}) = \sum_{j=1}^3 a_j^2(\mathbf{r}) e^{i\Phi_j(\mathbf{r})} \hat{\mathbf{e}}_j$  being the polarization, and  $\Phi_j(\mathbf{r})$  being the phase profile of the  $j^{\text{th}}$  component. Here, the component of the polarization along the direction of  $\hat{\mathbf{e}}_j$  is denoted as  $a_j(\mathbf{r})$ , with the phase along this direction given by  $\Phi_j(\mathbf{r})$ . The normalization condition requires that  $\sum_{j=1}^3 a_j^2(\mathbf{r}) = 1$ . In our study, the light propagates along the  $z$ -direction, exerting a force on the NP that pushes it against the substrate. Simultaneously, the light field possesses a transverse phase distribution, denoted as  $\phi(x, y)$ , and Eq. (1) can be reduced to:

$$\mathbf{F}(x, y) = \frac{1}{4} \alpha' \nabla u^2(x, y) + \frac{1}{2} \alpha'' u^2(\mathbf{r}) \sum_{j=1}^3 a_j^2(x, y) \nabla \Phi_j(x, y) \quad (2)$$

Here, we only focus on the transverse OFs exerted on the NP in the  $x$ - $y$  plane. The first and second terms in Eqs. (1) or (2) are known separately as intensity-gradient-induced force  $\mathbf{F}_{IG}$  and phase-gradient-induced force  $\mathbf{F}_{PG}$ <sup>39–41</sup>. In general, conservative OF enables NP trapping or confinement, while non-conservative forces provide additional DoFs for NP manipulation, including transport in forward<sup>42,43</sup>, backward<sup>44,45</sup>, and lateral directions<sup>46,47</sup>. Consequently, by engineering a transverse PGOF through light-field modulation via a metasurface, simultaneous trapping and transport of NPs along arbitrary trajectories can be achieved simply by controlling the input and output CP states of the metasurface.

The output field generated by the metasurface exhibits a high intensity gradient within the encoded path, while the effective PG varies exclusively along the direction perpendicular to the intensity gradient, enabling precise manipulation of the particles. To achieve this, the electric field before and after passing through the metasurface can be given by  $\mathbf{E}^{\text{out}}(x, y) = \mathbf{J}(x, y) \mathbf{E}^{\text{in}}(x, y)$  with Jones matrix  $\mathbf{J}(x, y)$ . Since the metasurface here only modulates the transverse field, the input field  $\mathbf{E}^{\text{in}}$  is related solely to  $\hat{\mathbf{e}}(\mathbf{r})$  in  $x$ - $y$  plane. We consider the metasurface to be lossless, which implies that its Jones matrix is symmetric and unitary. By employing CP bases  $\hat{\mathbf{e}}_R$  and  $\hat{\mathbf{e}}_L$  into this scheme, the above relation can be decomposed in terms of its eigenvectors and the

eigenvalue matrix  $\mathbf{M}(x, y)$  as<sup>33</sup>:

$$\mathbf{E}^{\text{out}}(x, y) = \mathbf{R}(-\theta) \mathbf{M}(x, y) \mathbf{R}(\theta) \begin{pmatrix} 1 \\ \mp i \end{pmatrix} \quad (3)$$

with:

$$\mathbf{M}(x, y) = \begin{pmatrix} T_o e^{i\varphi_o(x, y)} & 0 \\ 0 & T_e e^{i\varphi_e(x, y)} \end{pmatrix} \quad (4)$$

where  $T_{o,e}$  and  $\varphi_{o,e}$  represent the transmittance and phase profiles carried by the ordinary and extraordinary polarizations, respectively, imparted by an array of anisotropic meta-atoms.  $\mathbf{R}(\theta)$  is the in-plane rotation matrix by the meta-atom's orientation angle  $\theta$ . The matrix  $\mathbf{M}(x, y)$  represents the diagonalized form of the local Jones matrix  $\mathbf{J}(x, y)$  expressed in the basis of the meta-atom's principal axes. Mathematically, this diagonalization decouples the system's response into two orthogonal polarization channels, indicating that no cross-coupling occurs between the ordinary and extraordinary components when the field is described in the local coordinate system of the metasurface. Physically,  $\mathbf{M}(x, y)$  characterizes each meta-atom as a linear birefringent waveplate with spatially variant properties, where the eigenvalues  $T_{o,e} e^{i\varphi_{o,e}(x, y)}$  encapsulate the propagation phase accumulated by light along the two principal axes of the anisotropic meta-atoms, which can be independently controlled by tailoring the geometric dimensions. Meanwhile, the rotation matrix  $\mathbf{R}(\theta)$  introduces the geometric phase through the spatial variation of the orientation angle  $\theta$ . Assuming power conservation for maximizing CP conversion efficiency, we have  $T_o = T_e$ . By defining a reference  $\varphi_r = (\varphi_o + \varphi_e)/2$  and phase difference  $\delta = (\varphi_o - \varphi_e)/2$ , which quantifies the meta-atom's anisotropy, the final output optical field can be expressed as:

$$\mathbf{E}^{\text{out}}(x, y) = T_o [e^{i\varphi_r(x, y)} \cos \delta (\hat{\mathbf{e}}_x \pm \hat{\mathbf{e}}_y) + i e^{i\varphi_r(x, y) \mp i2\theta} \sin \delta (\hat{\mathbf{e}}_x \mp \hat{\mathbf{e}}_y)] \quad (5)$$

Detailed derivations can be found in Supplementary Note 1. For the multiplexing of both RCP and LCP, the anisotropic phase difference should be  $\delta_1 = \pi/2$ ,  $\delta_2 = 0$  for two sets of phase libraries within the metasurface, respectively, which means nanopillars satisfy  $\delta_1 = \pi/2$  and  $\delta_2 = 0$  in an interleaved configuration<sup>48,49</sup>. Consequently, three independent PGOFs follow the relations:  $\mathbf{F}_1 \propto \nabla \varphi_o^1$ ,  $\mathbf{F}_2 \propto \nabla \varphi_e^1$ ,  $\mathbf{F}_3 \propto \nabla \varphi_o^2$  to achieve bidirectional transport and on-demand stationary positioning capabilities.

This constitutes one of the main conclusions of this article, as it establishes the principle for controlling the direction of PGOF and provides a foundation for metasurface design. Crucially, the three phase profiles are mutually independent, allowing  $\mathbf{F}_1$  and  $\mathbf{F}_2$  to be unequal. Unlike conventional holographic OTs, the tunable PGOF here is jointly governed by both the propagation and geometric phases of the metasurface. This necessitates a pixel-level design that adheres to the above phase relations. Furthermore, since communication between channels relies solely on output co-CP or cross-CP channels, the crosstalk between channels can be negligible. This property holds even under slight elliptical polarization, ensuring that no PG cancellation occurs that could trap particles at certain points along the trajectory. Additionally, the magnitude of the PG directly influences the OF, thereby allowing the forward and backward transport speeds of the optical conveyor to be tailored as desired.

### Implementation of the meta-conveyor technique

We designed an encodable, triple-channel metasurface consisting of a single layer of amorphous silicon (a-Si) nanopillars on a fused silica substrate (the a-Si refractive index is given in Supplementary Note 2). As shown in Fig. 2a, these rectangular nanopillars have a fixed height ( $H$ ) of 800 nm and are arranged in a square lattice with period 600 nm ( $\Lambda_x = \Lambda_y = 600$  nm); their in-plane dimensions (length  $L$  and width  $W$ )

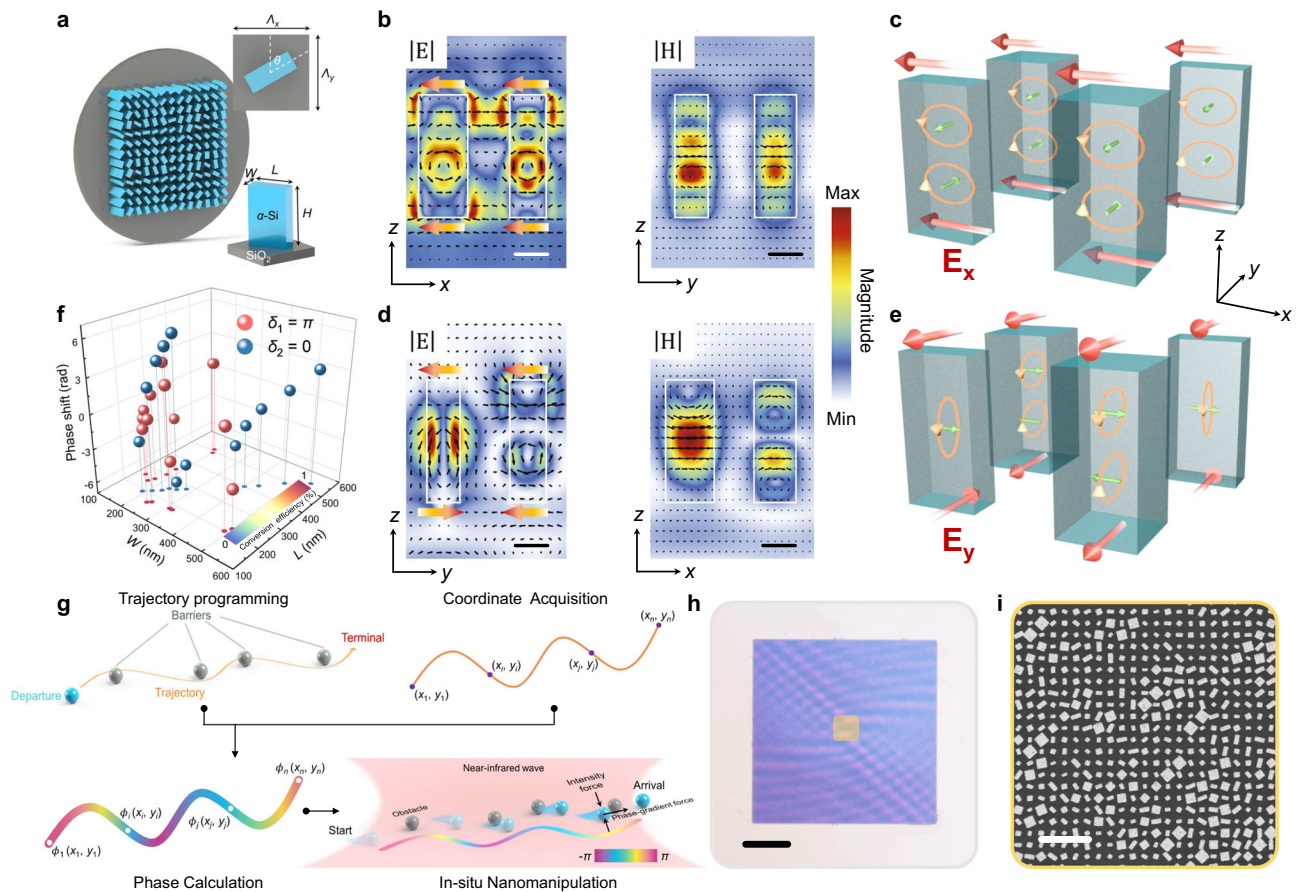


**Fig. 2 | Implementation of meta-conveyor.** **a** Schematic illustrations of a nanopillar-based meta-atom, showing its top and side views. **b, d** Distributions of total electric and magnetic fields within the nanopillars under  $x$ - and  $y$ -polarized illumination, respectively. Black arrows denote the vector profiles of the induced vector fields, while white dashed contours mark the boundaries of the nanopillars. Vertically staggered magnetic dipole moments configured in anti-parallel anti-ferromagnetic modes are excited and confined inside the meta-atoms. Scalebar:

250 nm. Corresponding schematic diagrams in **(c, e)** illustrate simplified models of the anti-ferromagnetic resonance mode, where green arrows depict magnetic dipoles and orange arrows represent electric currents. **f** Geometric parameters of the nanopillars corresponding to reference phase  $\phi_r$  under two distinct phase delays  $\delta$ . **g** Encoding workflow for arbitrary PG trajectories, exemplified by a wavy pattern. **h, i** Optical micrograph of the fabricated metasurface and a magnified SEM of its central region. Scale bar: 200  $\mu\text{m}$  (left) and 3  $\mu\text{m}$  (right).

are varied to produce the required phase shifts at the operation wavelength of  $\lambda = 1064$  nm.

As mentioned above, for transmissive metasurfaces, achieving both high cross-polarized and co-polarized components under CP illumination requires that the orthogonal electric field components simultaneously exhibit high transmission efficiency with a phase difference of  $\pi/2$  and 0, respectively. Here, we note that “anti-ferromagnetic” resonances with staggered induced magnetic dipole modes can be excited in rectangular dielectric nanopillars<sup>50</sup>. To investigate this effect, we arranged nanopillars satisfying  $\delta_1 = \pi/2$  and  $\delta_2 = 0$  in an interleaved configuration and simulated the total electromagnetic field for two representative sets of geometric parameters ( $L, W$ ) with (320, 180) and (260, 260), as shown in Fig. 2b–e. For the  $\hat{e}_x$  component, the induced fields arise from two looped displacement currents within the meta-atoms, corresponding to so-called anti-ferromagnetic modes with antiparallel magnetic dipoles (AMD)<sup>50</sup>. The even number of AMDs ensures that the electric field vectors at the input and output interfaces remain aligned (Fig. 2b), indicating that the  $\hat{e}_x$  component is preserved after transmission. Figure 2c illustrates these currents as orange round arrows along the  $z$ -axis, depicting two AMDs with alternating clockwise and counterclockwise orientations. Under  $\hat{e}_y$  component incidence, the distinct phase responses between anisotropic and isotropic meta-atoms stem from the interplay between geometric symmetry and the number of excited AMD modes. The broken symmetry in the anisotropic structure selectively permits only

a single AMD mode. In contrast, the higher symmetry of the isotropic meta-atom supports a degenerate pair of AMD modes under  $\hat{e}_y$  excitation. This critical difference in mode multiplicity directly dictates the overall mode configuration. The single AMD mode in the anisotropic structure exhibits an odd number of equivalent current loops, and it reverses the electric field vector of the transmitted light relative to the incident plane wave, which is inherently associated with a  $\delta = \pi/2$  phase delay. Conversely, the superposition of the two AMD modes in the isotropic meta-atom results in a composite mode of an even number of current loops. This symmetric near-field distribution preserves the electric field direction and yields no net phase delay. Thus, the deliberate symmetrical engineering of the meta-atoms provides a powerful and deterministic pathway for controlling the phase of light by leveraging the distinct number of confined AMDs (Fig. 2e). Consequently, the polarization of the transmitted light is orthogonal to that of the incident light in the former case, while it remains identical to that of the incident light in the latter. The resulting co- and cross-polarized channels under CP incidence are illustrated in Supplementary Note 3. Based on this principle, we systematically scanned the entire parameter space to collect transmittance and phase shift, with the aim of selecting suitable nanopillars for constructing a meta-atom library. The results of this parameter sweep are presented in Supplementary Note 4. In accordance with the discussion in the previous section, the realization of arbitrary PGOF is related to the reference phase shift  $\phi_r$  and  $\theta$ . Therefore, we selected a series of parameters to construct a

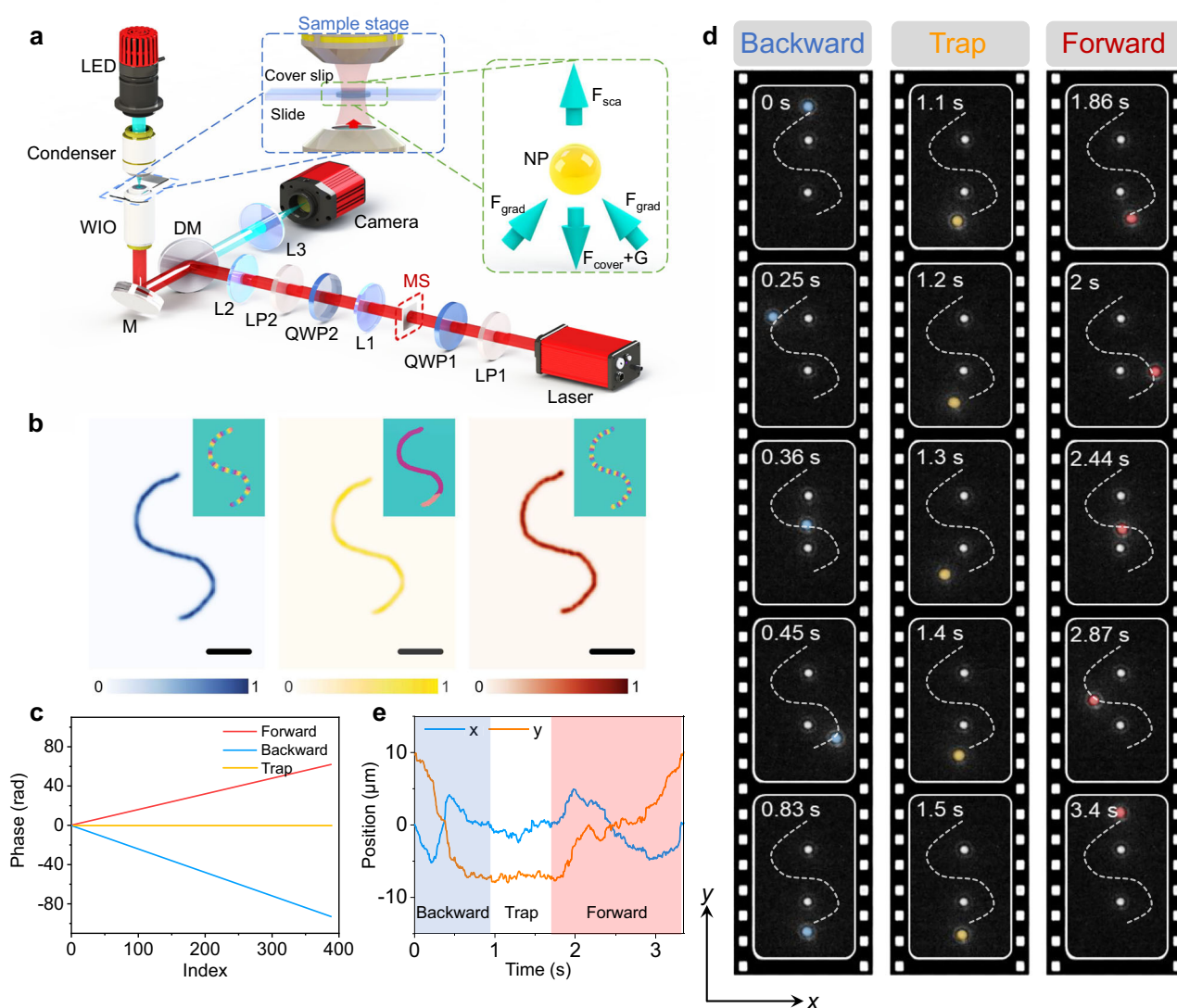


**Fig. 3 | Experimental characterization of the meta-conveyor and demonstration of NP transport.** **a** Optical setup for metasurface characterization and nanomanipulation demonstration. **b** Measured transverse intensity distributions of the light fields and their corresponding PG profiles. Scale bar: 4  $\mu m$ . **c** Phase magnitude

as a function of pixel index along the trajectory. **d** Time-snapshots from the in situ NP nanomanipulation process. Two NPs in the field of view serve as stationary references throughout the process. **e** Time-dependent displacement of the NP, indicating three distinct regimes: backward, trapping, and forward motion.

phase library comprising  $\phi_r^1$  and  $\phi_r^2$ . These are presented as functions of the nanopillar dimensions ( $L$  and  $W$ ), along with the corresponding CP conversion efficiency magnitudes, in Fig. 2f. The associated  $M_{xx,yy}^1$  and  $M_{xx,yy}^2$  derived from Eq. (3) including their amplitudes and arguments in the Cartesian polarization basis, are provided in Supplementary Note 5.

We further engineered a wavy PG trajectory—which could be particularly useful for collision-free nanomanipulation of a single NP through an array of obstacles—by populating each pixel with a selected phase value from the library in Fig. 2f. The trajectory programming process is illustrated in Fig. 2g. To demonstrate the ability to arbitrarily design the trajectory shape, we use a stylus, which allows us to define the trajectory with a high degree of freedom. The pixel coordinates ( $x_i, y_i$ ) of this path were acquired and recorded as a function of array indices (with the starting index set to zero). The optical phase value ( $\phi_i$ ) at each coordinate point was then assigned via a linear function, establishing the phase relationship  $\phi_i(x_i, y_i)$  across the 2D coordinates. A positive PG along the path pushes the NP in the forward (increasing index) direction, whereas a negative

gradient pushes it backward. Consequently, the vector path defined by the dataset ( $x_i, y_i, \phi_i$ ) associates the direction of NP motion with the magnitude and sign of the optical PG. This approach enables arbitrary control over NP movement—including direction, path length, and shape—simply by encoding versatile paths onto the multifunctional metasurface (see Methods). We propose that, under a controlled incident CP state and a selected analysis channel, a gold NP (marked in blue) can function as a programmable, light-driven nanorobot with obstacle-avoidance capability in complex environments, enabled by continuous phase modulation across the metasurface. Details of this procedure and the metasurface configuration route are provided in Supplementary Note S6, where a comprehensive design flowchart for the meta-conveyor is presented. The fabrication procedure, detailed in the Methods section, adhered to standard micro-nano manufacturing techniques. Figure 2h shows the image of the fabricated sample. A top-down scanning electron microscopy (SEM) image of a representative central region of the sample is shown in Fig. 2i, confirming the precise arrangement and uniformity of the nanopillars.

## Experimental realization of in situ nanomanipulation

The nanomanipulation setup based on the metasurface is illustrated in Fig. 3a, with details provided in the Methods section. The inset of Fig. 3a schematizes the chamber for optical manipulation: gold NPs ( $n_{\text{gold}} = 0.26 + 6.97i$ ) are suspended in water ( $n_s = 1.33$ ) between a glass coverslip and slide, 140  $\mu\text{m}$  apart. In equilibrium at the longitudinal  $z$ -direction, we balance the scattering force ( $F_{\text{sca}}$ ), the intensity-gradient force ( $F_{\text{IG}}$ ), the effective weight  $G$  (gravity minus buoyancy), and the repulsive force from the coverslip ( $F_{\text{cover}}$ ). The shaped optical patterns show nearly identical intensity profiles across the three channels (Fig. 3b) but feature distinct phase distributions in the  $x$ - $y$  plane (inset of Fig. 3b, c). These tailored phase profiles result in unidirectional PGs that drive OFs responsible for forward motion, backward motion, and stable trapping. In our experiment, when the input beam is LCP and the cross-CP channel is analyzed (corresponding to channel 1 with a positive PG), the NP (marked in blue) moves forward along the encoded path. Switching to the co-CP channel yields a null PG, thereby halting the particle at its current position (i.e., trapping). Reversing the CP combination of channel 1 gives channel 3, which generates an opposite PG along the path with RCP input and the corresponding cross-CP channel, driving the NP (marked in red) back to its original location.

The measured trajectories of the NP are shown in Fig. 3e, which plots the NP's  $x$ - $y$  position over time for each channel configuration. Note that the magnitude of the phase gradient in channel 1 and channel 3 may differ, allowing the same nanoparticle to be driven forward and backward at possibly different velocities. These results confirm that selecting different channels allows precise and reversible control over particle transport along arbitrary encoded paths, enabling program-mable optical manipulation with sub-micrometer precision. Supplementary Movie 1 demonstrates the complete control process, including forward, halted, and reverse NP movement. Note that we prioritized quasi-collimated illumination rather than a Gaussian beam to ensure functional fidelity. Since the metasurface acts as a phase-modulating interface where the output field is determined by the product of the incident field and the metasurface's transmission function with polarization conversion efficiency, a planar incident wavefront ensures that the output phase gradient is governed solely by the pre-programmed metasurface phase. It is also worth noting that the phase imparted by each meta-atom is a relative quantity; the metasurface shapes the global wavefront through local, individual phase shifts. Consequently, small deviations from the designed phase values in a few regions do not fundamentally violate the conveyor effect, as the collective interference of all meta-atoms still reconstructs a functional light field. The main penalty of such minor fabrication errors is a reduction in polarization conversion efficiency, increased speckle or lower focal-plane intensity, which can be compensated by moderately increasing the input laser power. Only widespread or severe imperfections would critically degrade the performance.

Beyond the experimental demonstration with gold NPs, we further conducted a systematic numerical analysis to evaluate the generality of our approach. As detailed in Supplementary Note 7 and Fig. S6a, the PGOFs acting on NPs with various complex refractive indices were calculated via the Maxwell stress tensor (MST). The results show that for NPs with low absorption at the laser wavelength of 1064 nm, the PGOF increases significantly with the real part of the refractive index, indicating that our meta-conveyor is universal and equally suitable for efficient manipulation of NPs made of other materials. The OF acting on a 200 nm diameter gold NP and the corresponding velocity under different phase-gradient magnitudes and laser powers are presented in Fig. S6b, c. Furthermore, we also compare the OF under monochromatic plane wave illumination calculated using the electric dipole approximation employed in our experiment with that obtained from including electric and magnetic multipoles up to the 10th order. As detailed in Fig. S6d, the comparison confirms that

the multipolar contribution has a negligible impact on the force magnitude for the NPs.

We also provide an extended demonstration of manipulating polystyrene (PS) spheres. The experimental results, showing the position as a function of time for PS beads of different diameters, are presented in Supplementary Note 8. For PS beads with diameters comparable to the Au NPs, the motion exhibits stronger fluctuations due to the weaker PGOF arising from their low absorption, making the transport more susceptible to Brownian disturbances. In contrast, larger PS beads show clearly observable start-stop manipulation, confirming that our meta-conveyor is effective for low-absorption dielectric particles when the OF sufficiently overcomes thermal fluctuations.

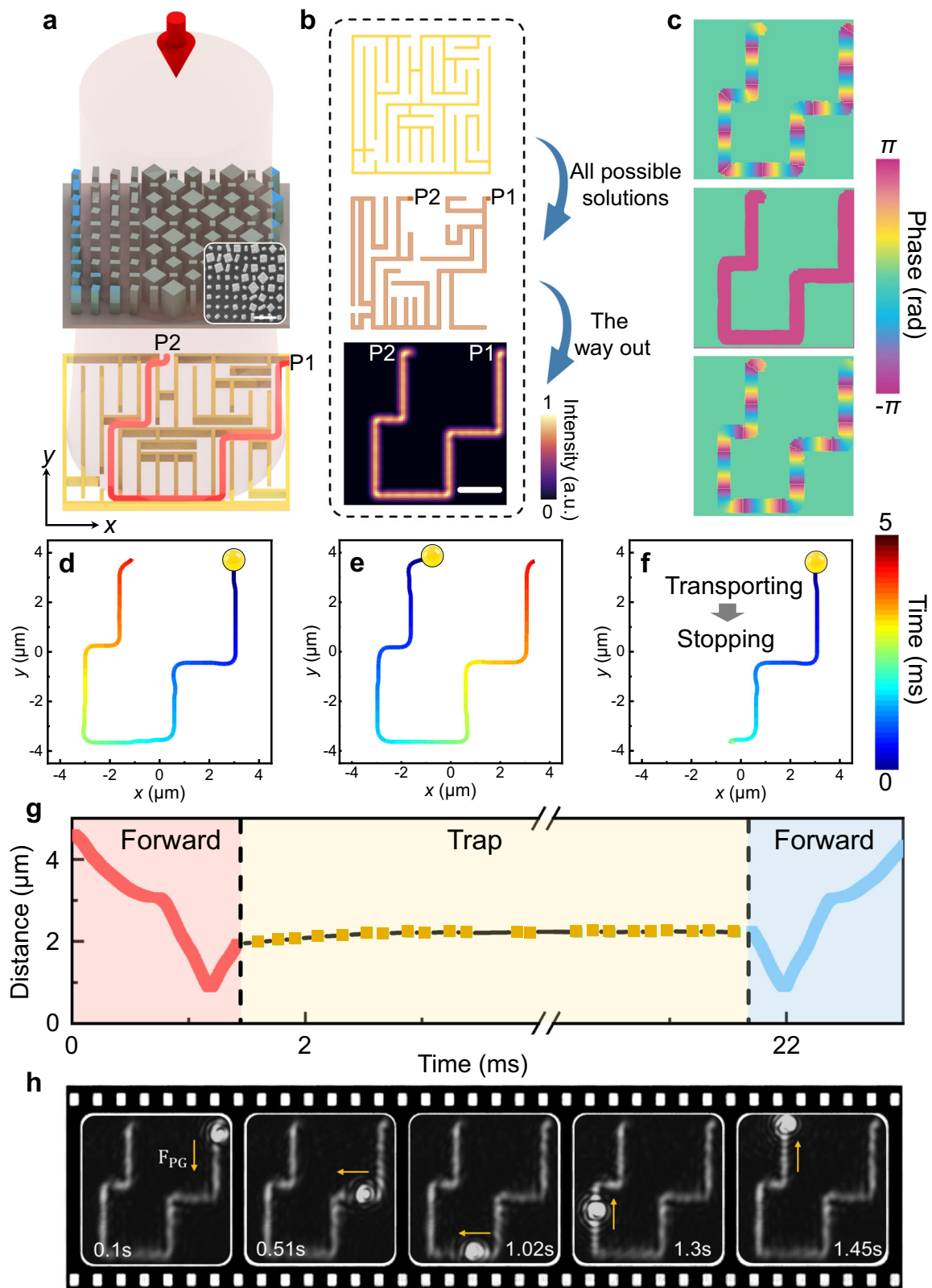
To further control the velocity or behavior of particle movement, more than three channels, each carrying distinct phase gradients, are required. This approach can be implemented in bilayer metasurfaces. Given the inherent trade-off between enhanced DoFs and efficiency in such metasurfaces, the recently developed free-standing bilayer architecture emerges as a particularly promising platform for meta-conveyor techniques. It enables high-efficiency multidimensional wavefront control, thereby facilitating both efficient OF generation and complex trajectory encoding.

## Meta-conveyor-assisted maze solving applications

To highlight the broad potential application of proposed meta-conveyors, particularly in complex environments that require polarization-controlled and reversible particle transport, we demonstrate their functionality using a conceptually designed maze as an example. As shown in Fig. 4a, a suitable polarization-selective channel is chosen through aforementioned design approach, resulting in red colored optical “way out” features projected onto the yellow virtual maze. These features include two ports, P1 and P2, which function as potential entry or exit points. The inset shows the SEM image of the meta-conveyor in this case. Specifically, Fig. 4b illustrates the encoding methodology: an image of the maze is first captured (top of Fig. 4b), where any continuous path referred to as an “optical conveyor”, connecting P1 and P2 without intersecting the walls represents a valid solution (middle of Fig. 4b). Using a custom-written program, the correct paths (bottom of Fig. 4b) are identified and encoded into the metasurface.

We demonstrate that our metasurface conveyors can generate switchable phase-gradient optical flow with a uniform intensity profile along the predefined path in situ, as shown in Fig. 4c. These reconfigurable optical paths allow bidirectional transport between the two ports (separately shown in the top and bottom). Additionally, by encoding an identical phase profile, a uniform phase distribution can immobilize particles at any point along the path, as illustrated in middle of Fig. 4c.

Building on this concept, we calculate the particle's spatial trajectory over time in the  $x$ - $y$  plane, as shown in Fig. 4d–f, where the colorbar denotes temporal progression. As shown in Fig. 4d, e, the particles are successfully guided from P1 to P2 and vice versa, demonstrating bidirectional transport governed by phase modulation (see Supplementary Movie 2 and 3 for the movement of NP over time). Furthermore, our design allows dynamic termination of transport at arbitrary locations within the maze, rather than restricting endpoints to P1 or P2. Figure 4f illustrates a case where the particle halts within the maze after switching from channel 1 to channel 2 mid-transport. Correspondingly, we plot the distance from the center position (0, 0) as a function of time for this scenario, as depicted in Fig. 4g. The particle moves forward from P1 for approximately 1.5 ms before being stopped via channel switching, and around 20 ms later, another phase modulation enables reversal via channel 3. These results demonstrate that our proof-of-concept allows the metasurface to define starting and stopping locations and



transport directions flexibly, even when navigating highly complex geometries with real physical obstacles. Figure 4h presents experimental verification of NP transport from the entrance (P1) to the exit (P2) in a single pass, showing excellent agreement with our simulation results. The observed experimental time delay is attributed to Brownian motion in the ambient environment, which introduces stochastic noise that prevents nanoparticles from reaching the

theoretically predicted transport velocity observed in simulated conditions. The results underscore the generality of our technique in generating optimal transport pathways through entirely programmable means, offering strong potential for integration into confined or extreme environments inaccessible to conventional bulky optics, such as real-time in-vivo manipulation in endoscopic or biomedical contexts. Moreover, the technique holds promise for extension to 3D

**Fig. 4 | Meta-conveyor for programmable NP transport within a virtual micro-maze.** **a** Schematic scheme of meta-conveyor-based virtual maze-solver. The inset shows the SEM image of the meta-conveyor in this case. Scale bar, 2  $\mu\text{m}$ . **b** From top to bottom: a manually designed micro-maze with two ports (P1 and P2, marked in red) serving as potential entrances or exits (top); possible maze solutions, illustrating that any continuous optical path connecting P1 to P2 without crossing walls constitutes a valid solution (middle); and the intensity distribution of the correct routing path selected via a custom algorithm and encoded onto the metasurface (bottom). **c** Simulated bidirectional PGs and constant phase enabling polarization-

controlled transport from P1 to P2 (top), stop (middle) and P2 to P1 (bottom). Calculated spatial trajectories of NPs over time during transport from P1 to P2 (**d**) and vice versa (**e**), with color indicating temporal evolution. **f** Controlled mid-path transport termination achieved through dynamic polarization switching, demonstrating halting and reversal capability within the maze. **g** Corresponding displacement relative to the center (0,0) as a function of time, showing forward motion, trapping, and reversal under sequential phase modulation. **h** Experimental demonstration of one-trip NP movement across time slots.

NP trapping and forward-directed controlled transport along curvilinear light fields<sup>51,52</sup>.

## Conclusion and discussion

In conclusion, we have demonstrated a miniaturized and fully functional meta-conveyor capable of multimodal in-situ particle transport along custom-designed wavy paths. By interleaving meta-atoms with distinct optical responses, we harness birefringent propagation phases together with geometric phases to generate multimodal phase-gradient optical forces, enabling tunable nanoparticle navigation controlled solely by polarization switching. We experimentally confirm robust and continuous motion along arbitrary trajectories, including obstacle avoidance and maze solving, without altering the optical setup or reloading computer-generated holograms. Notably, our freeform phase-gradient encoding method is inherently scalable. Longer transport paths or larger working areas require only a redesigned phase gradient and a larger metasurface with more meta-atom pixels. For parallel multi-channel manipulation, independent phase profiles can be superimposed with distinct deflection phases to generate a composite phase distribution<sup>26</sup>. As long as the metasurface provides sufficient pixel sampling over a larger footprint, no fundamental performance degradation occurs.

To further realize a variable-speed or switchable-trajectory meta-conveyor, one could load more versatile phase profiles to generate phase-gradient forces of varying magnitudes along arbitrary paths. The required expansion of independent phase-encoding channels can be achieved either by employing a meta-conveyor module that eliminates the need for bulky polarization filtering—for instance, by using bilayer<sup>53–56</sup> or active metasurfaces<sup>57–60</sup>—or by utilizing adjoint optimization-based design to decouple additional phase profiles from non-orthogonal polarization states<sup>61</sup>. This metasurface-based platform provides a universal route for heterogeneous integration with optical fibers and photonic chips, supporting multifunctional applications such as simultaneous endoscopy and manipulation. Beyond this, it offers a foundation for exploring diverse metasurface-mediated optical forces, opening new opportunities for multidisciplinary applications in biophotonics<sup>62,63</sup>, lab-on-a-chip systems<sup>64</sup>, and quantum technologies<sup>65</sup>.

Compared with traditional SLM-based holographic OTs, which offer near-infinite DoFs through real-time hologram refreshing, these systems are fundamentally limited by the slow response of liquid crystals—typically only tens of hertz—and suffer from inherent drawbacks such as speckle noise and phase instability induced by mechanical vibrations. By contrast, although meta-conveyor is restricted to discrete, predefined trajectories, it achieves switching speeds determined solely by external polarization control elements, reaching millisecond or even microsecond scales. Their compact, passive architecture inherently eliminates the optical noise and stability issues associated with active components, rendering them particularly appealing for applications that demand high stability, low optical noise, and high integration density. For instance, in microfluidic-integrated lab-on-a-chip devices, long-term, repetitive, and reliable transport of cells or drug particles is required—such as shuttling samples between distinct culture chambers. In such cases, frequent alterations to the optical landscape are unnecessary, making

the metasurface platform ideally suited for these tasks (see Supplementary Note 9 and Fig. S8a for a schematic diagram of the optofluidic meta-conveyor architecture).

To further advance toward practical clinical utility, the proposed meta-conveyor can be heterogeneously integrated onto the distal facets of optical fiber-based endoscopes<sup>66</sup> using either substrate-spacer bonding<sup>67</sup> or 3D direct laser writing techniques<sup>68</sup>. In the former approach, the metasurface is prefabricated on a quartz substrate that serves as a calibrated spacer and then bonded to the fiber tip using UV-curable adhesive. This metafiber-based architecture is illustrated schematically in Supplementary Fig. S8b. The latter technique enables the direct printing of complex nanostructures onto functionalized fiber facets, offering high flexibility for the development of customized surgical probes. By superimposing a Fresnel-zone-plate phase profile onto the freeform phase gradients, the meta-conveyor achieves wide field-of-view self-focusing<sup>69,70</sup>, allowing for the direct manipulation of drugs or nanoparticles without the need for external objective lenses. When integrated with existing fiber-based endoscopic imaging capabilities, this platform can simultaneously perform real-time endoscopy and in situ nanomanipulation, enabling a new paradigm for minimally invasive nanosurgery.

## Methods

### Numerical simulation

We designed arrays of a-Si nanopillars to achieve specified phase shifts at  $\lambda = 1064 \text{ nm}$ . To determine the optimal pillar geometries, we performed finite-difference time-domain (FDTD) simulations of periodic square arrays of nanopillars. At normal incidence, we applied periodic boundary conditions in the lateral directions and perfectly matched layers (PMLs) above and below the pillar to simulate an infinite array under plane-wave illumination. A plane wave with a wavelength of 1064 nm was employed to discern the transmission coefficients and phase shifts along the  $x$ - and  $y$ -axes, corresponding to the two principal axes of the nanopillars. For NP dynamics, we employed a hybrid simulation framework combining FDTD and Langevin dynamics to study the motion of NPs under the influence of structured optical fields. OFs were first computed for each particle using the MST. These forces were then incorporated into the two-dimensional Langevin equations to update particle velocities and positions, enabling us to capture their stochastic trajectories within the optical landscape.

### Sample fabrication

The silica substrate was subjected to ultrasonic cleaning in acetone, ethanol, and deionized water. Subsequently, an 800 nm a-Si film was deposited on the cleaned silica wafer using a Plasma-Enhanced Chemical Vapor Deposition system (Oxford PlasmaPro 100 PECVD). Following this, a roughly 200 nm-thick layer of conductive positive-tone electron-beam resist (ZEP520A, Zeon) was spin-coated onto the silicon surface. The desired metasurface patterns were then written into the CSAR-6200 resist by means of an Electron Beam Lithography technique (Elionix ELS-F125-G8). After exposure, the sample was developed in a photoresist developer to transfer the patterns into a chromium (Cr) mask. The next step involved depositing a patterned chromium layer onto the sample using Electron Beam Evaporation, thereby forming a Cr mask on the thin film for subsequent etching. The etching

process was carried out in an Inductively Coupled Plasma Reactive Ion Etching system (ICP-RIE) with a mixture of O<sub>2</sub> and CHF<sub>3</sub> gases. To finalize the metasurface fabrication, the residual Cr mask was stripped off using a ceric ammonium nitrate solution.

### Experimental setup

A continuous-wave 1064 nm laser (MIL-SU-1064, Changchun New Industries Optoelectronics Tech. Co., Ltd., up to 2 W) was first passed through a linear polarizer (LP1) and a quarter-wave plate (QWP1) to generate the desired input circular polarization (CP) state. The metasurface (MS) plane was re-imaged onto the back aperture of the objective lens using a 4*f* optical system. Another linear polarizer (LP2), followed by a quarter-wave plate (QWP2), was employed to analyze and select the specific channel of the light transmitted through the metasurface. To enable rapid switching among the three channels, two full-wave liquid crystal variable retarders (Thorlabs, LCC1513-C) were used as QWP1 and QWP2, respectively. The intensity and phase distributions of the shaped laser beam were recorded by a beam profiler (Edmund) and a wavefront sensor (Thorlabs, WFS20-5C), respectively. The optical setup for measuring the conversion efficiency of the overall meta-structures over a wide band is described in Supplementary Note 10, along with the simulated and experimental results.

For nanoparticle (NP) manipulation, the beam was directed toward the sample on a microscope stage. A dichroic mirror (DM) reflected the infrared beam upward through a water-immersion objective (Olympus UPLSAPO60XW, NA = 1.2, Fig. 3a), focusing it onto the fluidic cell. Simultaneously, a top-mounted LED was used to illuminate the sample through a dark-field condenser (Nikon MBL12000).

### Freeform beam shaping algorithm

The design of an arbitrary phase-gradient optical line trap at the focal plane is based on an algorithm that coherently superimposes an array of diffraction-limited focal spots with predesigned phase profiles. Thus, the complex incident field  $U(x, y)$  was modeled as a weighted summation of plane-wave components associated with the target focal positions:

$$U(x, y) = \sum_{n=1}^N A \exp\left[\frac{2\pi}{\lambda f} (xy_n + yx_n)i + \phi_n i\right] \quad (6)$$

where the number and coordinates of the spots ( $x_n, y_n$ ), the objective focal length  $f$ , and the laser wavelength  $\lambda$  jointly determined the spatial frequency terms, while  $\phi_n$  denoted the applied phase modulation and  $A$  adjusted the overall intensity distribution. By properly selecting these parameters, the synthesized optical field produced a uniform, S-shaped trapping profile. The calculated complex field was converted into a pure phase distribution through a checkerboard encoding method, which then was used to decide the orientation and size of the nanopillars within the metasurface.

### Data availability

The datasets generated and analyzed during this study are available from the corresponding author upon request. Source data for Figs. 2f, 3c, 3e and 4g are provided with this paper. Source data are provided with this paper.

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## Acknowledgements

T.L. dedicates this paper to the memory of his late Kitty Wan Wan, who was his faithful companion throughout his studies. The authors thank Prof. Shuming Wang (NJU) for discussions in January 2026 and Dr. Katsuya Tanaka (FSU, Jena) for insightful exchanges in August 2025. T.L., X.L., C.T.C. appreciate the support from RGC Hong Kong (AoE/P-502/20) and the State Key Laboratory of Optical Quantum Materials. F.N. acknowledges the support of the Alexander von Humboldt Foundation and the National Science Foundation of China (No. 12404361). Y.Z. acknowledges the support of the Temple Foundation Endowed Professorship No. 2.

## Author contributions

T.L. and F.N. conceived the idea. T.L. carried out all the design and simulations. T.L., X.L. and J.N. developed the theoretical framework and conducted the analysis. Z.G. carried out the sample fabrication and V.B. supervised the fabrication and characterization processes. F.N. performed experimental measurements. The manuscript and Supplementary Information were written by T.L., X.L., F.N., Y.Z. and C.T.C., with input from all authors. F.N. and C.T.C. supervised the entire project.

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary information** The online version contains supplementary material available at <https://doi.org/10.1038/s41467-026-73024-0>.

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**Peer review information** *Nature Communications* thanks Haoran Ren, Ji Chen, and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. A peer review file is available.

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