Interferometry can completely redirect light, providing the potential for strong and controllable optical forces. However, small particles do not naturally act like interferometric beamsplitters and the optical scattering from them is not generally thought to allow efficient interference. Instead, optical trapping is typically achieved via deflection of the incident field. Here, we show that a suitably structured incident field can achieve beamsplitter-like interactions with scattering particles. The resulting trap offers order-of-magnitude higher stiffness than the usual Gaussian trap in one axis, even when constrained to phase-only structuring. We demonstrate trapping of 3.5–10.0 μm silica spheres, achieving a stiffness up to 27.5 ± 4.1 times higher than was possible using Gaussian traps as well as a two-orders-of-magnitude higher measured signal-to-noise ratio. These results are highly relevant to many applications, including cellular manipulation, fluid dynamics, micro-robotics and tests of fundamental physics.

Optical forces are exerted when a particle changes the propagation direction of light. In optical tweezers this typically involves deflection of the light in proportion to the particle displacement, with minimal changes in its spatial structure (Fig. 1a). Similarly, a beamsplitter combining two fields will also experience an optical force (Fig. 1b). In this case, the force arises because a relative phase shift between the incident fields redires power between the outputs. Because the phase changes with beamsplitter displacement, interferometry can be used to trap stably. Here, in contrast to deflection-based trapping, the interference redires light between two discrete propagation directions. Displacements as small as \( \lambda/(4n_m) \) are capable of completely re-routing the light, where \( \lambda \) is the wavelength and \( n_m \) is the refractive index of the medium. This far greater sensitivity can, in principle, allow a trap stiffness exceeding that achieved in any previous experiment \(^5\) by over an order of magnitude. However, the beamsplitters that are traditionally used to interfere fields are poorly suited to optical micromanipulation experiments. Such experiments instead rely almost exclusively on scattering particles.

Recent works have shown that precise knowledge of scattering together with wavefront shaping allows particles to act as near-arbitrary optical elements, such as a mirror or lens \(^6\). In a similar way, we use non-trivial spatial structure in Mie scattering to convert particles into effective beamsplitters, which separate a phase-structured input field into distinct output fringes (Fig. 1c). Rather than deflecting the fringes, particle displacements act to redirect optical power between them. This enables a new form of beamsplitter-like optical trapping, which we refer to as ‘enhanced trapping via structured scattering’ (ENTRAPS).

To understand the forces achieved with ENTRAPS, it is useful to first review the force on an interferometer beamsplitter. When the incident fields have equal power \( P/2 \) and phase difference \( \phi \), the power imbalance \( \Delta P \) between the two output ports is \( \Delta P = P \cos \phi \). This results in an optical force

\[
F = \frac{P n_m \cos \phi \sin \theta}{c}
\]

where \( c \) is the speed of light and \( \theta \) is the incident angle on the beamsplitter. Lateral movement of the beamsplitter by a distance \( x \) causes a relative phase shift \( \Delta \phi = 4 m \pi n_m (x/\lambda) \sin \theta \) between the input fields, and changes the force on the beamsplitter. If the initial phase is set to \( \phi = \pi/2 \) and the light is normally incident (\( \theta = \pi/2 \)), this achieves a stable trap of the form \( F = -\Delta x \), with trap stiffness \( \kappa = (4 \pi n_m^2 P)/c \lambda \). As discussed in Supplementary Section 1, without recourse to non-propagating fields or quantum states of light that exhibit non-classical photon correlations, this represents a fundamental upper limit on the achievable stiffness of any optical trap.

ENTRAPS achieves strong trapping through similar principles, but instead uses a scattering microparticle to interfere the fields. The particle can have any geometry, although here we restrict our discussion to homogeneous dielectric spheres for which the scattered light is described with Mie theory. It is well known that Mie scattering preferentially occurs into fringes at distinct scattering angles. However, the intensity of these fringes is usually much lower than the forward-scattering. Furthermore, neighbouring fringes are \( \pi \) rad out of phase and destructively interfere if the incident illumination is homogeneous over a broad angular range, as is the case for a Gaussian trap. This further suppresses the fringe intensities (Fig. 1a, middle). As a consequence, Mie scattering fringes can usually be ignored in optical traps. However, we show here that they can be controllably populated using structured illumination (Fig. 1c, middle). As such, the incident phase controls interference in Mie scattering fringes in a manner similar to the output of a beamsplitter. In ENTRAPS, the fringes are populated with fields that have near-orthogonal phase, such that a small phase shift can lead to constructive or destructive interference and redirect light between interference lobes on either side of the particle. This provides a beamsplitter-like trapping force (Fig. 1c, bottom).

One might expect that full control of both the amplitude and phase is required to achieve ENTRAPS. However, the phase alone determines whether interference is constructive or destructive, while the amplitude profile determines the efficiency of the interference. As such, ENTRAPS can be achieved using phase-only control of the incident light. Henceforth in this Letter, we focus on these phase-only implementations. Although the restriction to phase-only control can be expected to limit the achievable stiffness, it makes the protocol easily accessible to the widely used holographic optical tweezers and, as we show here, still allows order-of-magnitude enhancements.
To identify appropriately structured incident optical fields for phase-only ENTRAPS and predict the performance of the protocol, we numerically optimized the phase profile of the incident field to maximize the trap stiffness (Methods and Supplement Section 3). Particles with radius $R > \lambda$ were found to converge on profiles that achieve ENTRAPS, as evidenced by a particle-position-dependent redirection of power between distinct scattering fringes with fixed propagation directions (see polar plots in Fig. 2a and Supplementary Section 3). We therefore postulate that, for particles that exhibit significant Mie scattering fringes, any trapping field that is near-optimized for trap stiffness will exhibit ENTRAPS.

In general, Mie scattering profiles become increasingly complex as the particle size increases. This is apparent in the transmitted intensity patterns of ENTRAPS, which feature an increasing number of bright fringes as the particle size increases (Fig. 2a). ENTRAPS relies on this complexity, and uses it to control the transmitted wavefront. Consequently, we find that the achievable enhancement in trap stiffness increases with particle size and exceeds an order of magnitude for sizes above 5 µm (Fig. 2a). A drop in stiffness enhancement is evident above 8 µm, which may indicate that the calculated holograms are not fully optimal. For particles between 7 and 10 µm in size, the predicted trap stiffness exceeds 3 mN m$^{-1}$ W$^{-1}$. This is comparable to the current record demonstrated with antireflection-coated high-refractive-index particles, even though the particles considered here are silica and thus low contrast.

To test the predictions described above we implemented a holographic optical tweezer (Fig. 3; see Methods). Silica microspheres were trapped either with Gaussian input light or with the pre-calculated ENTRAPS holograms. Thermal position fluctuations of the trapped beads were monitored using a position-sensitive detector (PSD). Freely moving beads in water exhibit Brownian motion, which has a mechanical power spectrum that scales with the inverse square of frequency. The optical trap suppresses low-frequency motion, resulting in a spectrally flat region at low frequency$^2$. The corner frequency quantifies the transition between these two spectral regions and is directly proportional to the trap stiffness $\kappa$. The ENTRAPS enhancement factor could therefore be determined by comparing the corner frequencies obtained with ENTRAPS and Gaussian traps.

Experiments were performed with particles with diameters of 3.48, 5.09, 7.75 and 10.0 µm. These sizes are relatively large for optical tweezers, with 10 µm near the upper limit for particles that are conventionally trapped$^3,10$. To illustrate these measurements, Fig. 2 shows mechanical power spectra measured with 7.75 µm particles. The corner frequency measured with ENTRAPS is $73.2 \pm 2.8$ Hz, compared with the $2.66 \pm 0.38$ Hz measured for the Gaussian trap (Fig. 2b,c). This constitutes an increase in trap stiffness by a factor of $27.5 \pm 4.1$, consistent with the predicted enhancement of 26.1. The enhancement was close to theory for all particle sizes, as shown in Fig. 2a (for mechanical spectra see Supplementary Section 4).

In addition to improving the trap stiffness, ENTRAPS also provides a dramatic improvement in the measurement signal-to-noise ratio (SNR). Laser tracking in optical tweezers is based on measurements of the centroid position of the transmitted light. This centroid...
is proportional to the applied optical force. As such, the observed signal at a given displacement is enhanced as the trap stiffness increases. When using 7.75 µm particles, ENTRAPS improved the SNR by a factor of 249, allowing the thermal motion of the particle to be measured with an order of magnitude higher bandwidth (Fig. 2b,c). Substantial SNR enhancements were observed for all particle sizes and exceeded two orders of magnitude for both 5.09 and 10.0 µm beads.

ENTRAPS complements a range of novel approaches to optical micromanipulation that have only recently been demonstrated. It has been shown that the direction of optical forces need not align with the propagation of light, including a lateral force applied with Airy beams and a pulling force applied with a Bessel beam and an interference-based tractor beam. Recently, negative torque opposing the optical angular momentum has also been demonstrated.  

has been shown for over two decades that structured light fields can be used to improve optical traps, but no previous proposal or experiment has made use of the spatial structure of scattering to improve trap stiffness. As such, ENTRAPS represents a fundamentally different approach. Furthermore, compared with the order-of-magnitude enhancements possible with ENTRAPS, previous experiments have only allowed relatively modest enhancements. Higher-order Laguerre-Gaussian modes have been shown to increase the axial restoring force on 5 µm particles by a factor of 1.60 (ref. 16), while radially and axially polarized modes have been predicted to provide even better trapping strengths, with experimental realizations enhancing the axial and lateral trapping forces by factors of 1.30 and 1.16, respectively.

To date, the most powerful method to improve trapping forces has been to engineer the particle rather than structure the light. Most notably, antireflection-coated high-refractive-index titania particles allow transverse trapping forces double those achieved with polystyrene microspheres, which continue to have the strongest trapping forces and trap stiffness ever reported. The axial trapping was simultaneously improved, although with a smaller (1.3-fold) enhancement. Alternatively, back-scatter can be minimized for a homogeneous sphere by careful choice of the diameter, which also improves trap stiffness. Another recent demonstration achieved strong static optical forces, although not optical trapping, on a bent waveguide structure that redirects the light with near-perfect efficiency.

Despite achieving substantial enhancements in trap stiffness and measurement signal to noise, we note that our current implementation of ENTRAPS has significant limitations. First, unlike the three-axis enhancement achieved, for example, in ref. 8, it achieves enhancement only along a single axis. It is possible that this could be overcome in the future using three-axis-optimized phase profiles. Second, it can be seen from Fig. 1a,c (bottom) that ENTRAPS has a reduced trapping region compared with a Gaussian trap. In the case of a 10.0 µm particle, for instance, our theory and experimental force calibration (Supplementary Fig. 4) show a reduction from 10 µm to ~500 nm. Indeed, a general trade-off exists between trap stiffness and trapping region. The scattering force on a trapped particle initially increases linearly with displacement in proportion to the trap stiffness. However, because photon scattering events cannot exert transverse momentum kicks larger than ħk, where ħ is the reduced Planck constant, this cannot continue indefinitely, with the region of linear response reducing as the trap stiffness increases. In the present experiments the momentum kick per photon reaches a maximum of ~ħk/7. It is therefore conceivable that the trapping region could be enlarged by a factor of seven without compromising stiffness. Finally, due to the
presence of intricate phase structure, ENTRAPS favours particles with volumes large enough to accommodate interference. ENTRAPS is therefore best achieved using particles larger than an optical wavelength.

Optical trapping has many important applications for particles larger than the wavelength. However, these applications are much less well explored than the small particle regime, as Gaussian traps lose trap stiffness with increasing diameter\(^2\) (Fig. 2a, inset). For instance, cells are often manipulated optically, but in many cases they are too large for a single-beam optical trap to be used efficiently, and require counter-propagating fields\(^3,4\). Similarly, aerosols up to 10 µm are regularly trapped and studied in optical tweezers to gain insights into pollution, vapour-based drug delivery and atmospheric physics\(^5\). Micro-robotics also often relies on optical control of large spherical particles, either as handles that are attached to larger compound structures, or with the microsphere itself acting as the micro-robot\(^6\). Microspheres are also levitated in vacuum, where high mass can be important in studies of gravitational forces and particle physics\(^7,22,23\).

The improved stiffness and measurement precision of ENTRAPS could greatly improve such applications.

The improved trapping efficiency of ENTRAPS allows larger particles to be handled in optical tweezer experiments. For instance, particle motion is expected to decouple from its surrounding fluid envelope only at very short timescales, beyond the reach of state-of-the-art technology for a 1 µm sphere\(^3\) but accessible with ultraprecise tracking of 10 µm particles. Hydrodynamic resonances are predicted to allow coherent energy exchange between the particle and fluid flow. Such resonances have recently been observed\(^3,4\), but with a trap stiffness a factor of five below the strong resonance condition. ENTRAPS may allow this condition to be met, which would provide a test of hydrodynamic theory in a previously uncharted regime. The highly localized fluid flow generated near the particle could also provide a new avenue for non-contact and low-damage manipulation of cells, similar to experiments using fluid flow near rotating particles\(^3,4\). It may also allow mechanical sensing of fluid properties within the localized flow region, thus allowing nanoscale microrheology\(^3\).

We envision that ENTRAPS could greatly improve these applications and others like them and thus play an important part in the future of optical manipulation.

**Methods**

Methods and any associated references are available in the online version of the paper.

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**Author contributions**

M.A.T. and W.P.B. conceived and led the project. M.A.T. developed the theoretical concepts and performed the calculations and analysis. A.B.S. and H.R.D. developed the experimental apparatus. M.W. and M.A.T. performed the experiments, with assistance from A.B.S. M.A.T. and W.P.B. wrote the paper with input from all co-authors.

**Additional information**

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.A.T.

**Competing financial interests**

The authors declare no competing financial interests.
Methods

Optimization algorithm. ENTRAPS phase profiles were determined using a ‘method of steepest descent’ algorithm, with trapping forces calculated using the Optical Tweezers Toolbox26, as described in more detail in Supplementary Section 2. This algorithm deterministically converges on the local optimum, although this may not correspond to the global optimum. More efficient optimization protocols are available. In particular, with the ‘optical eigenmode method’ it may prove possible to efficiently identify globally optimal profiles27,28. However, implementation of these profiles, in general, would require arbitrary control over both phase and amplitude. It would be interesting in the future to compare global optima to the phase-only solutions used here and thereby establish the additional benefit provided by amplitude control. We note that there is a very large parameter space to explore and it is unlikely that ENTRAPS is the only new characteristic trapping behaviour that can be achieved with structured fields.

Effect of trapping beam polarization. A surprising result is that the optimized phase holograms show some deviations from perfect mirror symmetry, and are instead symmetric under a 180° rotation. This is because the optimization was performed for circular polarization, which breaks the mirror symmetry of the trapping light. The slight deviations from mirror symmetry are important to the performance of the trap. The hologram shown in Fig. 3 provides a 15% higher trap stiffness with mirror-symmetric holograms. However, left-circularly polarized light performs best with the mirror image of the hologram shown, and both horizontal and vertical polarizations trap most efficiently with mirror-symmetric holograms.

Experimental implementation. The haphrographic optical tweezer used a reflective spatial light modulator (SLM, Holoeye HEO-1080P) imaged onto the back-focal plane of the trapping objective with relay lenses to allow arbitrary phase control of the trapping light. The input optical power was kept constant between experiments, and was focused onto a silica microsphere using an oil-immersion objective (Zeiss EC-Plan Neofluar, NA = 1.3). After trapping the microsphere, the light was collected with a charge-coupled device using light-emitting diode illumination to visually identify the particles.

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