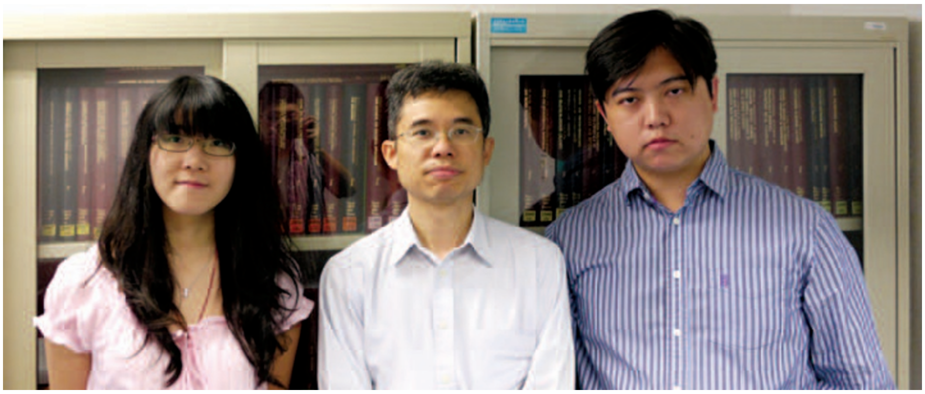
interview

Optical attraction

Optically pulling a particle towards a light source may be counterintuitive, but it is not impossible. Jack Ng tells *Nature Photonics* how this force can be achieved.

What is your work about?
We have theoretically and analytically demonstrated that, in certain situations, particles can travel towards a light source through what we call the 'optical pulling force'. Since the mid-1800s, scientists have known that light incident on a surface exerts a pressure; under normal circumstances, a particle illuminated by a light beam is pushed forwards, away from the source. It is also well known that the optical gradient force can draw small particles towards a high- or low-intensity spot for particle trapping and localization applications. In our case, we have used the generalized Mie scattering theory and the Maxwell stress tensor method to propose and analytically prove that dielectric spherical particles can experience an optical pulling force towards the illuminating light source. We note that this phenomenon is caused purely by the Lorentz force, and that it belongs to a class of optical force known as the optical scattering force.



ZHIHONG HANG

Scientists from Fudan University in China and the Hong Kong University of Science and Technology have theoretically demonstrated optical tractor beams. Left to right: Jun Chen, Che Ting Chan and Jack Ng.

How does the optical pulling force work?
Although the optical pulling force is certainly counterintuitive, there is no physical law that forbids its existence. Our study demonstrates that it is possible to induce the optical pulling force on a dielectric spherical particle. The radiation multipoles of the particle excited by the incident light can, in some cases, interfere to produce strong scattering in the forwards direction. For light beams that have less momentum along the beam axis than the forwards-scattered photons, the conservation of momentum provides the particle with a negative momentum and therefore 'pulls' it backwards. This is the basic idea of the optical pulling force.

What have you achieved?
Although the idea sounds simple, the implementation is far from trivial because each photon in a forwards-propagating beam carries a positive momentum. In addition, there may be gradient forces acting against such backwards motion, and there is no simple way to guarantee strong scattering in the forwards direction. We found that the influence of forwards momentum can be reduced by using propagation-invariant beams that have a finite converging angle and no (or negligible) intensity gradient along the beam axis. In our work, we chose to use the Bessel beam, which can be considered as a combination of plane-wave components whose propagating vectors form a cone at an angle to the propagation axis. Such a beam, when incident on the particle, cause the photon momentum along the beam axis to be smaller than the maximum value. We also found that certain combinations of particles and beams can induce strong scattering in the forwards direction. For example, for a medium-sized dielectric particle in a propagation-invariant beam of sufficiently large converging angle, the scattered momentum can be larger than the forwards momentum of the incident photons. When this happens, the particle gains a negative momentum and is therefore 'pulled' backwards.

How can the optical pulling force be used?
The optical pulling force provides an additional degree of freedom for long-distance particle transportation, such as for backwards transportation in a Bessel beam or other propagation-invariant beam. In situations where one has to manipulate small particles deep in a sample cell, spherical aberration may prevent the use of conventional optical tweezers. In this case, propagation-invariant beams can play an important role, and again the optical pulling force provides an alternative method of moving particles. A particle whose parameters are optimal for the optical pulling force can serve as a 'handle' to which other particles can be connected. For instance, one can attach the handle particle to a biological particle in water. The refractive index of a biological particle is usually close to that of water, so the pulling force acting on the handle particle will not be affected. Consequently, one can manipulate the biological particle indirectly using the optical pulling force — the obvious advantage being that the handle particle has better optical properties than the biological particle. Another potential application is particle sorting because, in a solution of size-dispersed particles, only particles of the correct size will be driven backwards, while the others will be driven forwards.

What are the challenges involved with the technique?
The theoretical challenge is optimizing particle morphology to achieve a stronger pulling force or produce the same force at a smaller beam converging angle, which is experimentally more preferable. The experimental challenge is to develop a set-up that requires only a small converging angle to demonstrate and utilize the optical pulling force.

INTERVIEW BY RACHEL WON

Jack Ng and co-workers have a Letter on the optical pulling force on page 531 of this issue.