On-chip push-pull effect

Hong Tang from Yale University spoke to *Nature Photonics* about how attractive and repulsive optical forces in nanophotonic waveguides could help advance integrated photonics and optomechanical systems.

■ What is the background to your research on optical forces?

Optical forces are used by optical tweezers to move microscale particles and molecules in free space. When confined to the nanoscale in photonic integrated circuits, the forces involved can be significantly stronger, making them potentially useful in optomechanical systems. The theory of optical gradient forces in nanoscale photonics is well established. In 2005, John Joannopoulos' group at the Massachusetts Institute of Technology and Federico Capasso's group at Harvard predicted the existence of an enhanced optical gradient force in photonic waveguides. This force was predicted to be highly engineerable by simply laying out the photonic structure on a chip. The sign of the force was also predicted to be tunable by varying the relative phase between interacting light waves. Indeed, such a force was demonstrated in substrate-coupled devices, reported in our recent paper (*Nature* **456**, 480–484; 2008), in which we detected an attractive optical force between a waveguide and a substrate, and used it to drive a nanoscale mechanical resonator. However, only an attractive optical force was observed, and so the drive behind our most recent work has been to detect a repulsive optical gradient force using light in waveguides. However, the difficulties associated with *in situ* phase control of waveguides have been a major obstacle. Without active control of waveguide phase, waveguides tend to bind with each other and yield only an attractive force. To generate a repulsive force, the two interacting light waves need to be controlled individually to maintain opposite phase shift. This cannot be easily done in coupled photonic waveguides.

■ What about your latest results?

In this issue of *Nature Photonics*, we experimentally demonstrate a system that shows the classical repulsive force between two neutral interacting bodies. Through precise phase engineering in planar coupled nanophotonic light waves, we are able reversibly switch the force from repulsive to attractive, and *vice versa*.

Hong Tang says that the observation of bipolar optical forces gives a new fundamental understanding of light wave interactions between dielectric structures.

To achieve this, we developed a butterfly-shaped photonic integrated circuit with two 'wings'. In the left wing, the light was split equally into a top and bottom arm, with the top arm being about 90 μm longer than the bottom to delay the light. We then directed the waves from each arm to recombine at the centre of the butterfly at a coupling region. The coupled waveguides were suspended, forming nanomechanical structures. The light then proceeded into the identical right wing, to make the whole structure symmetric. This schematic, essentially a cascaded Mach-Zehnder configuration, allows the input and output to be reversible, so that the relative phase difference established by the left wing can be maintained.

By adjusting the input wavelength, we show that the phase difference between the incoming light waves can be controlled *in situ*, thus allowing the sign of the force to be controlled. Specifically, we are able to manipulate the phase of two guided light waves, and thus the conditions under which they interact with each other. When the two waveguides are in phase, they attract each other; when they are out-of-phase, they repel. The force alternated between repulsive and attractive sinusoidally with the wavelength.

■ What are the potential applications of such optical forces?

Our implementation and analysis provides new tools for the development of integrated

photonics compatible with complementary metal-oxide-semiconductors (CMOS), and micro- and nano-electromechanical systems. In addition to the potential applications in the classical domain, this bipolar force may re-energize the emerging field of cavity optomechanics. In light-matter interactions, radiation pressure can only provide a push effect, whereas optical tweezers are used to pull. Here, the push-pull function of the bipolar force will enable full control of cavity optomechanical systems in an active way. It can be exploited to reversely control the sign of so-called optical springs and will allow for either cooling or amplifying functions simply through external phase adjustment. In tunable photonics, the push-pull action demonstrated here will allow reversible control of photonic structures and will lead to more flexible mechanically tunable photonic circuits with larger dynamic range.

■ What are the theoretical implications of this work?

The understanding of electrodynamic forces at nanoscale dimensions is of fundamental importance. The bipolarity of optical forces is intrinsic to Maxwell's tensor equations but had not previously been demonstrated. This work thus presents a unified picture of optical forces and verifies current theories. It brings about a new fundamental understanding of light wave interactions between dielectric structures.

As a proof of principle, we have demonstrated bipolar optical forces in parallel waveguides. It is expected that such bipolar force behaviour should also be found in other coupled photonic structures, such as coupled cavity-waveguide systems or coupled cavities. In both cases, the bipolar force should be enhanced by high circulating power in the optical cavities. As the cavity introduces a phase delay, owing to the finite photon lifetime, it is expected that the bipolar force can be observed through cavity spectrum tuning.

INTERVIEW BY RACHEL WON

Hong Tang and his co-workers have a Letter on tunable bipolar optical force on page 464 of this issue.