Waveguide optics

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Optical Coriolis force guides light along Trojan beams

Tomáš Tyc & Tomáš Čižmár

Trojan beams, which are optical counterparts of Trojan asteroids that maintain stable orbits alongside planets, have been successfully showcased in experiments, opening up possibilities for transporting light in unconventional settings.

Entirely unrelated physics phenomena frequently follow the same mathematical formalism, as is often the case with mechanics and optics. For example, the trajectories of classical particles with a given energy within a specific potential landscape take the same shape as light rays in a medium with a square-root refractive index distribution[1]. Therefore, just as particles are attracted towards local potential minima, light is attracted towards locations of higher refractive index — the very principle that underpins light guidance in optical fibres. Well-recognized mechanical phenomena can thus spark fresh concepts within the field of optics. Writing in *Nature Physics*, Haokun Luo and colleagues have now used this mechano-optical analogy to demonstrate a light-guiding approach based on Lagrange points[2].

Conventional optical waveguides confine light by combining regions of high and low refractive index. For example, in optical fibres, it is most common for the refractive index to reach its maximum at the waveguide's axis, surrounded by a lower-index cladding. This refractive index distribution influences light in a manner reminiscent of how mechanical forces act on massive particles. It effectively constrains the trajectories of light rays to lie close to the axis, thereby precluding their escape from the waveguide.

In the case of gradient-index fibres, in which the refractive index decreases gradually away from the axis, the resulting bending of light rays occurs in a smooth manner. Conversely, in step-index fibres, the redirection of light rays manifests abruptly, following the principle of total internal reflection. Another notable class of fibre waveguides are photonic crystal fibres, in which light is prevented from escaping by a photonic bandgap chosen to coincide with the operational wavelength band of the fibre[3]. Instead of a low-index cladding, photonic crystal fibres contain a layer of photonic crystal into which light cannot enter because no optical states exist in the bandgap.

For several decades, optical fibres have played a pivotal role across diverse applications encompassing communication[4], illumination, sensing, imaging and numerous other domains. Specifically, harnessing the complex transport of light made possible by multimode optical fibres is currently advancing rapidly while spurring a variety of applications, including that of deep-brain imaging[5].

The mechanism of light guidance introduced by Luo and colleagues differs from the standard conception, and it emerges from the optical equivalent of celestial mechanics. When two massive objects, such as the Sun and Jupiter, orbit each other in circular paths, in the co-rotating frame they create five specific positions where the combined gravitational pull from both masses on a small test particle precisely counterbalances the inertial centrifugal force. These specific points are known as Lagrange points, and only two of them remain stable[6]. In this context, the Coriolis force plays a crucial role because, without it, the gravitational and centrifugal forces alone would render the Lagrange points unstable. Asteroids located in these stable Lagrange points within the Solar System are commonly referred to as Trojans.

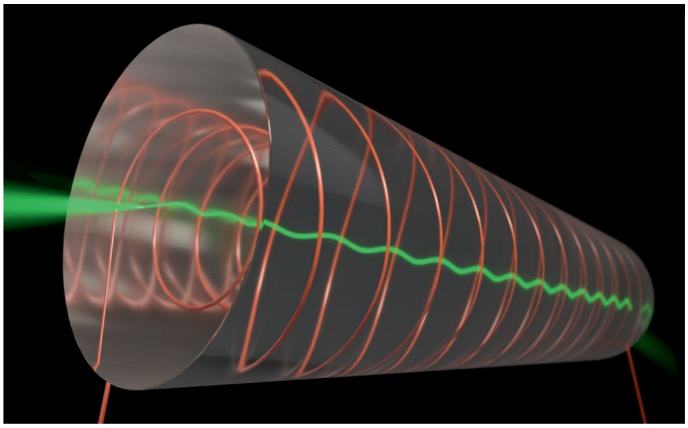

Fig. 1 | Trojan beam in laboratory settings. A helical iron wire is embedded into a material with a temperature-dependent refractive index. Passing an electric current through the wire creates an inhomogeneous index distribution in the surrounding medium with a minimum at the wire surface, creating conditions analogous to Lagrange points in celestial mechanics. Consequently, light (green) propagating through this waveguide is confined along a stable trajectory that spirals around the waveguide axis — a Trojan beam.

Luo and colleagues have integrated the unique characteristics of Lagrange points through the mechano-optical analogy into a compact laboratory system, leading to an innovative approach for guiding light. They introduced a helically shaped iron wire (Fig. 1) into a medium with a refractive index dependent on temperature. Subsequently, by passing an electric current through the wire to achieve inhomogeneous heating in the surrounding medium, they created a refractive index distribution with a minimum value at the wire's surface. The helical shape functions similarly to rotation in the corresponding mechanical system, bringing about an analogue of the Coriolis force. This force stabilizes the Lagrange point and helps to guide light along a trajectory spiralling around the axis of the system, forming what can be described as a Trojan optical beam (Fig. 1). Without the helical shape of the wire, this light-guiding phenomenon would not occur.

The team conducted a thorough analysis of light propagation, examining it from both geometrical and wave optics perspectives.

They identified the ray trajectory associated with the stable Lagrange point and determined the corresponding fundamental mode by using the paraxial wave equation. In their experiments, Luo and colleagues aligned the focus of a converging Gaussian beam at the Lagrange point within their apparatus and monitored its propagation. Over a distance of about 30 cm, the beam's initial diameter of approximately 100 µm exhibited only minimal spread, underscoring its effective guidance.

Without this guidance, diffraction would have caused a much larger beam broadening, a fact confirmed by a control experiment with the electric current switched off. Further, to check that the guided light did indeed conform to the characteristics of a Trojan beam, the researchers measured its phase distribution with a Mach–Zehnder interferometer. They observed very good agreement with the theoretically predicted hyperbolic phase distribution, providing further evidence of the efficacy of their proposed light-guiding mechanism.

Although this innovative method of light transport holds considerable promise, numerous questions must be addressed before one can fully assess its application potential. The simplicity of the approach suggests that it can be scaled up and down, potentially achieve dimensions and precision levels surpassing current technological boundaries, and be applied across a wide range of media, including those with optical gain. Exploring the attainable optical mode structures, the adjustability of mode numbers, and the evolution of guided light polarization is of great interest.

The dependence on temperature gradients in the implementation used by Luo and colleagues may pose challenges, as it requires both a stable power supply and heat dissipation. Nevertheless, various alternative methods to modify the refractive index and create suitable background profiles for Trojan beams can be considered, which would provide the optical Coriolis force necessary for guidance. One promising technological candidate may be found in the production of twisted optical fibres[7], achieved by rotating the preform during the drawing process.

Tomáš Tyc [1,2] ✉ **& Tomáš Čižmár** [2,3,4]
[1]Department of Theoretical Physics and Astrophysics, Faculty of Science, Masaryk University, Brno, Czech Republic. [2]Institute of Scientific Instruments of CAS, Brno, Czech Republic. [3]Leibniz Institute of Photonic Technology, Jena, Germany. [4]Institute of Applied Optics, Friedrich Schiller University Jena, Jena, Germany.
✉e-mail: tomtyc@physics.muni.cz

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Competing interests

The authors declare no competing interests.