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Giant Optical Forces On Nanoparticles Near Hyperbolic Metasurfaces

N. K. Paul, D. Correas-Serrano, and J. S. Gomez-Diaz*
Department of Electrical and Computer Engineering, University of California Davis
One Shields Avenue, Kemper Hall 2039, Davis, CA 95616, USA. *E-mail: jsgomez@ucdavis.edu

Optical forces acting at the nanoscale, i.e. on particles with radius between ~1 and 100 nm, have been elusive for many decades due to the challenges present in this range [1]: scaling-down common techniques for manipulating microparticles, based on electric dipole interaction energy, leads to thermal fluctuations large enough to allow the particles to escape from the trap whereas scaling-up the efficient laser cooling of atoms requires scattering processes with very narrow spectral lines and with small radiative losses, features that most nanostructures do not possess. Recent years have witnessed the emergence of nano-optical plasmonic tweezers able to enhance optical forces thanks to the excitation of surface plasmon polaritons (SPPs) with evanescent fields that can be concentrated well beyond the diffraction limit [2]. Indeed, illuminating a Rayleigh particle located above a plasmonic surface generates optical forces that compensate the momentum of the directional SPPs excited on the structure, leading to an exponential-like dependence between the induced forces and the SPPs wavenumber [3]. A wide variety of nano-optical tweezers have been put forward, including optical antennas, nanostructured substrates, or micrometer-sized patterned metals [1-2]. In a parallel development, hyperbolic and extremely anisotropic metasurfaces [4] – realized using nanostructured metals or 2D materials such as graphene and black phosphorus – have recently attracted significant attention thanks to their unusual electromagnetic responses, including an ideally infinite wave confinement and the photonic spin Hall effect [5], and their ability to enable exciting applications such as routing SPPs within the surface, empowering planar hyperlensing with deeply subwavelength resolution, and achieving broadband super–Planckian thermal emission, among others. Large part of the success of hyperbolic metasurfaces relies on their ability to significantly alleviate some of the challenges of bulk hyperbolic metamaterials [4] by simplifying the fabrication process, removing volumetric losses, providing an easy access and processing of the stored energy, and facilitating compatibility with other devices.

Here, we combine the photonic spin Hall effect with ultra-confined SPPs available in hyperbolic and extremely anisotropic metasurfaces to dramatically enhance and accurately tailor the optical forces induced on nanoparticles located nearby. Replacing standard, isotropic plasmonic materials such as a gold, silver, or graphene with engineered hyperbolic and anisotropic metasurfaces permits to take full advantage of ultra-confined hyperbolic plasmons and huge light-matter interactions supported by such structures [4]. In this scenario, the adequate illumination of a nanoparticle will polarize it with a desired handedness. Then, thanks to the photonic spin Hall effect [4,5], the subsequent scattering process will excite directional anisotropic SPPs with very large wavenumbers, which in turn will-induce giant optical forces – with values much larger than those attainable with isotropic plasmonic materials – on the particle. Furthermore, the direction of such plasmons can be controlled with sub-wavelength resolution [4], enabling the in-plane manipulation of the particle. Such forces are derived using a semi-classical anisotropic Green's function formalism combined with the Lorentz's force formulation and are validated using numerical simulations. Results confirm an enhancement of the induced forces of several orders of magnitude compared to those found in previously reported structures. Importantly, this enhancement is inherently broadband and it exhibits strong resilience against laser misalignments. Finally, several promising applications are devised and discussed, including the manipulation of nanoparticles – including biological ones – well below the diffraction limits using lasers with very low intensities, thus preventing their potential damage due to photoheating, and the subsequent characterization of such particles using surface enhanced Raman spectroscopy. We envision that the proposed technology may open a new paradigm in nano-optical plasmonic tweezers, with important implications in biology, force measurements, and physics.

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