Giant optical forces in planar dielectric photonic metamaterials

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We demonstrate that resonant optical forces generated within all-dielectric planar photonic metamaterials at near-infrared illumination wavelengths can be an order of magnitude larger than in corresponding plasmonic metamaterials, reaching levels many tens of times greater than the force resulting from radiation pressure. This is made possible by the dielectric structures’ freedom from Joule losses and the consequent ability to sustain Fano-resonances with high quality factors that are unachievable in plasmonic nanostructures. Dielectric nano-optomechanical metamaterials can thus provide a functional platform for a range of novel dynamically controlled and self-adaptive nonlinear, tunable/switchable photonic metamaterials. © 2014 Optical Society of America

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Mesoscale forces act as a bridge between the domains of nanomechanics and nanophotonics. The changing balance of elastic and electrostatic, optical and other forces on the mesoscale opens up new possibilities for controlling photonic devices [1]. Optical forces, which have been exploited in various forms of optical tweezing, manipulation and binding [2–4], and in cavity optomechanics [5], are of particular interest for the actuation of nano-optomechanical devices as they provide great potential for the realization of optically tunable, nonlinear, and self-adaptive nanophotonic devices [6–8].

Recently, optical forces in exotic artificial photonic materials such as photonic crystals and metamaterials have been the topic of intense studies. Strong resonant optical forces between photonic crystal slabs have been theoretically studied [9–11]. Such enhancements are obtained due to the high quality optical resonances of photonic crystals. Plasmonic structures have also demonstrated extremely high confinement of electromagnetic fields and thus strong variations of field intensities, which can significantly enhance near-field optical forces [12–17]. Optical forces specifically in plasmonic metamaterials have recently attracted increased attention [18–23]. The capacity in such architectures for engineering electromagnetic properties with great freedom make metamaterials a highly flexible platform for harnessing optical forces and at the same time provides new approaches to the creation of tunable and nonlinear metamaterials [24–26].

The majority of prior studies of optical forces in photonic crystals and metamaterials have focused on multi-layer structures and considered optical forces between the different layers [10,11,18,19,21]. Here, we computationally analyse and compare optical forces within single-layer planar metamaterials. The generic metamaterial design selected consists of a periodic array of asymmetric nanorod pairs, such as illustrated in Fig. 1(a), made of either a plasmonic metal (such as, e.g., gold) or a high-refractive-index dielectric (e.g., silicon). Metamaterials composed of asymmetric metal nanorod arrays are well known and belong to a family of plasmonic nanostructures that support Fano-type resonances [27,28]. And with the plasmonic and photonic metamaterial communities now avidly seeking low-loss alternatives to noble metal frameworks [29], it has recently been demonstrated both theoretically and experimentally that geometrically asymmetric silicon structures can also support strong near-infrared resonances akin to the familiar trapped mode of metallic asymmetric split ring designs [30,31]. We show here that strong light-driven near-field forces may be generated among the nanorods of metal and dielectric metamaterials under plane wave optical illumination. These resonant optical forces can be resolved into two components: one perpendicular to the metamaterial plane (i.e., parallel/antiparallel to the direction of incident light and therefore radiation pressure) and one parallel to the metamaterial plane, which may act to attract or repel neighboring nanorods.

Within the framework of classical electrodynamics, the components of the total time-averaged force \( \mathbf{F} \) acting on an object illuminated with light can be calculated using the surface integral

\[
\langle \mathbf{F}_i \rangle = \oint_S \langle T_{ij} \rangle n_j dS,
\]

where \( S \) is a bounding surface around the object, \( n_j \) are the unit vector components pointing out of the surface, and \( \langle T_{ij} \rangle \) is the time-averaged Maxwell stress tensor defined by

\[
\langle T_{ij} \rangle = \frac{1}{2} \text{Re} \left[ e \varepsilon_0 \left( E_i E_j^* - \frac{1}{2} \delta_{ij} |E|^2 \right) + \mu \mu_0 \left( H_i H_j^* - \frac{1}{2} \delta_{ij} |H|^2 \right) \right].
\]

The stress tensor integral Eq. (1) encompasses both radiation pressure, which arises through the transfer of momentum between photons and any object on which they impinge, and the gradient force, which is associated with intensity variations in the local field around an object.
We first investigate optical forces in all-dielectric planar metamaterials. These exclude the Joule losses associated with metals and can sustain resonances with very high quality factors that are not achievable in metallic metamaterials [32,33]. Furthermore, the less-confined field structure of dielectric systems provides for strong interactions between neighboring resonator elements even at separations of hundreds of nanometers. Figure 1(a) shows dimensional schematics of the dielectric metamaterial considered in this work. The 900 nm square unit cell comprises two silicon rods with the same 200 nm × 200 nm cross section in the y–z plane and different lengths (760 and 680 nm) in the x direction. (Substrates are excluded from the numerical analyses presented here. In practice, the presence of a substrate will introduce some directional asymmetry to the optical properties of the metamaterial, while its material nature and geometry will determine the range of movement possible in response to forces generated within and among unit cells. But to a first approximation, these considerations apply similarly to both dielectric and metallic nanorod arrays. Thus, for clarity in a study concerned primarily with the relative magnitude of forces generated in the two systems, substrates can be ignored.) The optical properties of the metamaterial are evaluated in fully three-dimensional finite-element Maxwell solver simulations (COMSOL Multiphysics), which also provide electric E and magnetic H field distributions. By modeling a single unit cell with periodic boundary conditions in the x and y directions, these calculations assume an infinite planar array. Silicon is assumed to be lossless with a refractive index of 3.48 in the near-infrared range under consideration [34]. Via the Maxwell stress tensor integral [Eq. (1)], these E and H fields give the optical forces acting on the individual silicon rods within the unit cell. (Surfaces of integration S being defined as rectangular parallelepipeds separately enclosing each silicon nanorod. Integrals over the two walls of these domains that coincide with the periodic cell boundaries in the y–z plane cancel, making it necessary only to integrate over the other four faces.) Under x-polarized plane wave illumination normally incident in the +z direction, this structure presents a sharp (quality-factor Q ~ 340) transmission Fano-resonance at 1514 nm which is based on the antiphase oscillation of displacement currents generated in the two rods [30,31], as illustrated by the field map inset to Fig. 1(b).

At the resonance, optical forces more than an order of magnitude stronger than radiation pressure are generated within the metamaterial (Fig. 2). We define \( F_{y1} \) and \( F_{y2} \) as illustrated in Fig. 2(b) and identified in the top-left inset to Fig. 2(a). Other forces were measured similarly.

Fig. 1. All-dielectric nanorod metamaterial. (a) Dimensional schematic and plan views of a metamaterial unit cell comprising a pair of asymmetric silicon nanorods with identical y–z cross-sectional dimensions but different lengths. (b) Numerically simulated transmission spectrum of said metamaterial for normally incident x-polarized light. The insets show detail of the transmission spectrum around the resonance wavelength and the x-direction electric field distribution at resonance (\( \lambda = 1514 \) nm) in the x–y plane bisecting the nanorods.

Fig. 2. Optical forces in a dielectric (silicon) metamaterial. Spectral dispersion of (a) in-plane (y-direction) and (b) out-of-plane (z-direction) optical forces on the constituent nanorods of the dielectric metamaterial. Optical force is presented in units of \( \frac{P}{nc} \), where \( P \) is the incident power per unit cell and \( c \) is the speed of light in vacuum. The insets show detail of the transmission spectrum around the resonance wavelength and schematically illustrate the direction of forces acting at resonance.
force, respectively, as the \( y \)- and \( z \)-direction forces on the longer rod, and \( F_{y2} \) and \( F_{z2} \), correspondingly, as the \( y \)- and \( z \)-direction forces on the shorter rod. Figure 2(a) shows the spectral dispersion of optical forces in the metamaterial plane (\( y \) direction). Clearly, \( F_{y1} \) and \( F_{y2} \) must have the same amplitude and act in opposite directions. At resonance, the in-plane forces between the two rods are repulsive and the relative force reaches a level of \( 64 \, P/c \) at resonance (\( P \) being incident power per unit cell and \( c \) is the speed of light). Off resonance, there is a small (~1 \( P/c \)) attractive force between the nanorods. Out-of-plane (\( z \) direction) optical forces are also generated in the dielectric metamaterial [Fig. 2(b)]. These comprise a combination of radiation pressure and near-field force and achieve maximum levels of 16.08 \( P/c \) on the long rod and 14.2 \( P/c \) on the short rod at resonance (the positive direction of out-of-plane force being the direction of light propagation). The net optical force \( F_z = 1.88 \, P/c \) per unit cell area of the dielectric metamaterial is solely radiation pressure, which, in the absence of absorption is related to the reflection coefficient \( R \) by the expression \( F_z = 2R*P/c \).

The optical forces generated within a planar nanorod metamaterial can be considered and intuitively understood as a combination of time-averaged Coulomb and Lorentz forces. For example, the repulsive in-plane Lorentz force of resonant antiphase displacement currents in the two rods is much stronger than the attractive Coulomb force of dipole–dipole interactions, leading to a net repulsive optical force between the nanorods at resonance. Out-of-plane optical forces on the rods, which include radiation pressure, can be understood as the Lorentz force of oscillating displacement currents in the magnetic field of incident light. These greatly exceed radiation pressure at resonance and the antiphase displacement currents in the two rods lead to out-of-plane forces acting on them in opposite directions.

We now consider, for comparison, a plasmonic metal variant of the planar asymmetric nanorod metamaterial, sized [Fig. 3(a)] to achieve a similar near-infrared resonance wavelength to the silicon metamaterial while maintaining realistically practical dimensions (nanorod and unit cell size are reduced relative to the dielectric structure as electrons can oscillate more freely in plasmonic metals; in this example the center-to-center spacing between nanorods is reduced with cell size while the separation between their opposing faces is held at 150 nm). This model follows the above methodology for evaluation of optical forces, utilizing established experimental values of the complex dielectric parameters for gold [34]. Figure 3(b) presents reflection, transmission, and absorption spectra for the gold nanorod metamaterial, revealing a trapped mode resonance with a quality factor of ~20 centered at around 1500 nm. As one may expect, both in-plane and out-of-plane optical forces [Figs. 3(c) and 3(d), respectively] are maximized in the vicinity of this resonance: the relative in-plane optical force reaches a peak magnitude of 1.05 \( P/c \) at \( \lambda = 1500 \) nm, and the maximum out-of-plane force on the long rod is 3.2 \( P/c \) at \( \lambda = 1523 \) nm and on the short rod is ~1.7 \( P/c \) at \( \lambda = 1515 \) nm. These are not inconsiderable values in their own right, but the relatively low quality factor of plasmonic resonances, resulting from Joule losses in metals and the strong confinement of EM fields at the metal surfaces, means that the resonant optical forces here are almost an order of magnitude smaller than those generated in equivalent dielectric metamaterials. As a consequence, significant challenges, such as stringent requirements on fabrication tolerance and experimental sensitivity, are likely to be encountered in the pursuit and application of optical forces in plasmonic metamaterial systems as the distances between metallic objects required for strong resonant enhancement of optical forces must be comparable to or smaller than the decay range of EM near-fields from metal surfaces, which is typically a few tens of nanometers.

In conclusion, we demonstrate that resonantly enhanced optical forces arise in both all-dielectric and metallic planar photonic metamaterials in the vicinity of their trapped mode resonances. The forces generated in dielectric metamaterials can be many tens of times stronger than radiation pressure and an order of magnitude larger than those generated in an equivalent plasmonic metal metamaterial. These forces may be harnessed to realize a new generation of active and self-adaptive nanophotomechanically systems based on low-loss all-dielectric metamaterials. Indeed, as Ref. [35] has illustrated, by integrating resonant cell structures such as those considered above with an elastic support structure providing for differential movements between cell elements (e.g., based on existing free-standing membrane technologies), one may access a remarkable variety of powerful photonic functionalities including strong optomechanical nonlinearity, transmission asymmetry, and bistability.

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