DOCTORAL THESIS

An investigation into some novel areas of optical manipulation

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Abstract

Since its inception in 1970, optical manipulation has evolved into a versatile tool across many fields of science. Notably, the now widely employed optical tweezers invented in 1986 is a good example, which is in essence a strongly focused fundamental Gaussian beam. Although the optical tweezers remained as an important tool in optical manipulation, the shaped structured light such as an optical vortex beam also provides unusual light patterns and promotes exciting discoveries.

This thesis is devoted to some unsolved theoretical aspects of optical manipulation.

Since optical force acting on a micro-particle is typically on the order of pN and seldom larger than nN, it is a common belief that optical force is relevant in particle manipulation only when all other forces are comparable or smaller than the optical force. In chapter 2, surprisingly we showed that this is not always the case. Here, we find that under appropriate condition, optical vortices can make a sphere orbit around the beam center owing to the non-conservative optical force. If the sphere is attached to a mechanical spring, the spring can be stretched significantly even when the mechanical spring is orders of magnitude stronger than the optical force. To the best of my knowledge, this is the first demonstration on how a weak optical force can stretch a much stronger spring.

In chapter 3, through rigorous simulations, the light scattering induced optical binding of 1D dielectric photonic crystals (PC) is studied. The optical forces that correspond to the pass band, band gap, and band edge are qualitatively different. It is showed that light can induce self-organization of dielectric slabs into stable photonic crystals, with the lower band edge of the photonic crystal coinciding with the incident light frequency. To our knowledge, this is the first report of stable binding of PC consisting of infinitely many particles. Incident light at normal and oblique incidence, 2D photonic crystal consisting of dielectric cylinders, photonic quasi-crystal, and photonic crystals with parity-time symmetry are also considered.

In chapter 4, we extend and generalize effective medium theory to compute electromagnetic stress in metamaterials using effective medium theory and the Helmholtz tensor. For a metamaterial, which consists of a large number of sub-wavelength constituents, it will be extremely computationally expensive and difficult to solve the macroscopic electromagnetic fields. Fortunately, it is known that conventional effective medium theory can faithfully describe the wave propagation through these materials in the long wavelength limit. Here we find that the numerical values of the permittivity and permeability alone are insufficient in calculating the optical stress. We need the electrostriction and magnetostriction terms as well. We further generalize previous approach by treating the electrostriction and magnetostriction as operators. This approach turns out to be quite accurate, and we can easily go beyond previous limitation such as the requirement of low filling ratio. An effective medium theory that works for stress calculation is highly desired. Using effective medium theory to treat the metamaterial as a homogenous bulk material will greatly simplify the scattering problem. Additionally, the effective medium approach also captures the underlying physics.

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