Nanomanipulation using Silicon Nitride Photonic Crystal Resonators

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Abstract:

Silicon nitride photonic crystal resonators are designed and fabricated for manipulating nanomaterials in aqueous solution. The electric fields are strongly confined by the photonic crystal resonators to provide high trapping stiffness. To minimize thermal heating in the cavity, which is usually a major problem in nanomanipulation using near-field nanophotonic devices, we use silicon nitride instead of silicon to fabricate the device and choose 1064 nm as the operating wavelength. Our preliminary results show that our device can trap nanomaterials that are very difficult to be trapped by other optical trapping techniques.

Summary of Research:

We designed and fabricated silicon nitride photonic crystal resonators for trapping nanomaterials in solution. Trapping and manipulating micro- and nano-objects becomes increasingly difficult when the objects are smaller. The fact that the spot size of a focused laser beam is limited by diffraction limits the trapping stiffness of conventional optical tweezers. Therefore, the useful range of optical tweezers has been limited to dielectric targets with sizes larger than about 100 nm. To overcome this limitation, various kinds of near-field nanophotonic devices [1-3] have been developed to provide trapping stiffness that is higher than that of conventional optical tweezers. The problem of many of these near-field optical trapping devices is that significant thermal heating is generated at the trap point [3]. Thermal heating is an important issue when we want to trap and manipulate biomolecules in aqueous solution because biological targets can be damaged even at moderate temperature increases. In addition, our earlier trapping experiments conducted with silicon photonic crystal resonators show that thermal effects caused by the highly localized electric fields can prevent nanoparticles from coming to the cavity and thus made trapping difficult [2].

To provide high trapping forces while minimizing thermal heating, we have developed a near-field optical trapping device based on photonic crystal resonators that operate at 1064 nm. Although almost all silicon-based photonic crystal resonators demonstrated so far were designed to operate at a wavelength of ~ 1550 nm, we chose 1064 nm as the operating wavelength of our device to reduce heat absorption in water (Figure 1). In addition, we used silicon nitride instead of silicon to fabricate photonic crystal resonators and waveguides because of the consideration of energy loss at 1064 nm. The reduced thermal heating not only makes trapping of nanomaterials more feasible, but also reduces the possibility of damaging biological targets in a biological experiment.

Figure 1: Absorption spectrum of water.
To achieve high confinement and amplification of the optical fields, our silicon nitride photonic crystal resonator has 53 holes of different sizes on either side of the cavity to form a pair of modulated Bragg mirrors. The sizes of the holes were designed by following the deterministic design method proposed by Quan et al. [4]. In addition, a small hole is added to the center of the cavity to enhance the field gradient [5]. According to the results of finite-difference time-domain simulation, the quality factor of our resonator is about 5000, and the mode volume is about \(4.4 \left(\frac{\lambda}{n}\right)^3\). As shown in Figure 2, the field intensity is significantly enhanced within the center hole, which leads to high trapping force.

To experimentally verify our designs, we fabricated the silicon nitride photonic crystal resonators and the waveguides that couple light to and from the resonators (Figure 3). Stoichiometric silicon nitride is deposited using the low pressure chemical vapor deposition process on silicon wafers that have 3.5 \(\mu\)m of thermal silicon dioxide on the top. MaN-2403 electron beam resist is spun on the wafer and then patterned with an electron beam system. The silicon nitride structures are defined by inductively coupled reactive ion etching with the electron beam resist as the mask. A sputtering system is then used to deposit an oxide layer of 3 \(\mu\)m on most of the wafer except for the regions where the resonators are. This oxide layer, which is patterned using the lift-off process, functions as the cladding layer of the waveguides. Since we want the fields in the cavity to interact with particles to be trapped, we do not cover the resonator with a silicon dioxide layer.

Our preliminary results show that we can use our silicon nitride photonic crystal resonator to trap 22 nm polymer spheres, Lambda deoxyribonucleic acid (DNA), and quantum dots, which are very difficult to be trapped by other optical trapping techniques because of their small size. Figure 4 shows that 22 nm fluorescent polymer spheres are trapped by the resonator when they are in close proximity to the resonator. The spheres can be released from the resonator when the laser is switched off.

**References:**


