Metamaterial Elliptical Cylinder for High Sensitive Single-Molecule Torque Detection

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Primary CNF Tools Used: ASML Deep Ultraviolet Stepper, Oxford 81 Etcher, Oxford 82 Etcher, Oxford PECVD, SC4500 Odd-Hour Evaporator, SC4500 Even-Hour Evaporator, Zeiss Supra SEM, Zeiss Ultra SEM

Abstract:

To facilitate the single-molecule torque measurement with the angular optical trap (AOT), we designed and fabricated novel metamaterial elliptical cylinders for higher torque resolution. By designing the cylinders to a smaller size, the torque resolution was improved over standard existing technique (quartz cylinders). The linear and angular trapping stiffness of the metamaterial elliptical cylinder can be controlled by tuning the mixing ratio of SiO_2 and Si_3N_4 to effectively modify the refractive index of the cylinder. These metamaterial elliptical cylinders can improve the utility of the AOT in investigating DNA-protein interactions.

Summary of Research:

Torsional stress results in one of the main topological challenges in cells and plays an important role in fundamental biological processes, for example transcription and replication. In replication, torsion can accumulate both upstream and downstream of the replication fork. We are specifically interested in how DNA responds to torsion and what kinds of DNA structures form in response to topological changes. To quantitatively study these questions, our lab developed the angular optical trap (AOT) to measure torque at the single-molecule level [1-3]. As a standard configuration of the AOT, linearly polarized light is used to trap and rotate a birefringent particle anchored with a torsionally constrained DNA molecule for manipulation and measurement [2,3].

Historically, functionalized nanofabricated quartz cylinders (n_e = 1.54 and n_o = 1.53 at 1064 nm) with typical dimensions of diameter D ~ 500 nm and height H ~ 1000 nm were utilized to simultaneously apply force and rotation to an attached DNA molecule for extension and torque measurements [2].

To facilitate the torque detection and allow better resolution, a smaller sample is required. However, a smaller quartz cylinder has a lower linear/angular trapping stiffness, resulting in the necessity of using high laser power, which may cause photodamage to a biological substrate [4].

To bypass this issue, we designed and fabricated multilayered elliptical cylinders with an effectively higher refractive index and a ~3-fold volume reduction in comparison to the previous quartz cylinders. These changes increased the torque resolution while maintaining strong linear/angular trapping stiffness. These cylinders were composed of silicon dioxide SiO_2 (n_1 = 1.45 at 1064 nm) and silicon nitride Si_3N_4 (n_2 = 2.01 at 1064 nm) (Figure 1), effectively resulting in a metamaterial [5].

As one can tell from the tensor (Figure 1), this metamaterial did not have birefringent effect at the xy-plane, thus we introduced shape anisotropy (i.e. utilizing elliptical shape) to generate torque for AOT manipulation (Figure 2).

Conclusions and Future Steps:

These metamaterial elliptical cylinders have a decreased γ_θ over our existing quartz cylinders, which facilitates an increased torque resolution for single-molecule AOT experiments. We believe these cylinders can have a significant impact on DNA torsional studies.

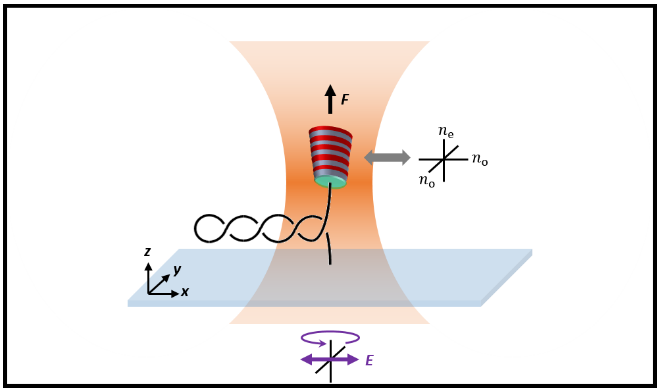

Figure 1: Experimental configuration of winding a DNA molecule with a metamaterial elliptical nanocylinder on the AOT. The long axis tends to align to the beam polarization when the beam is rotated.

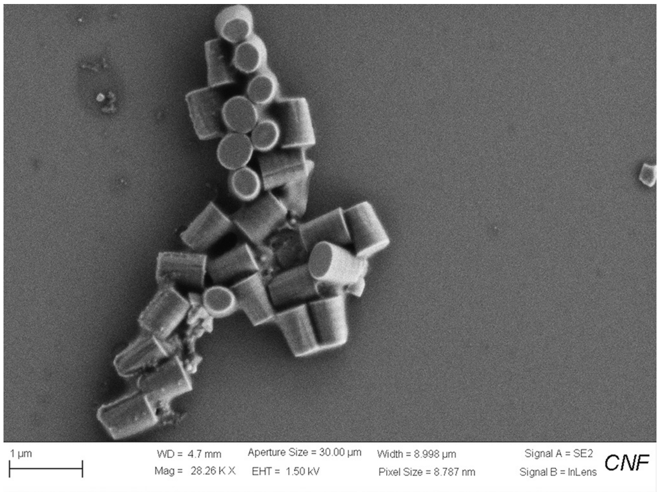

Figure 2: A scanning electron microscope image of metamaterial elliptical cylinders.

References:

[1] La Porta, A. and M.D. Wang, Optical Torque Wrench: Angular Trapping, Rotation, and Torque Detection of Quartz Microparticles. Physical Review Letters, 2004. 92(19): p. 190801.

[2] Deufel, C., et al., Nanofabricated quartz cylinders for angular trapping: DNA supercoiling torque detection. Nature Methods, 2007. 4(3): p. 223-225.

[3] Gao, X., et al., Torsional Stiffness of Extended and Plectonemic DNA. Physical Review Letters, 2021. 127(2): p. 028101.

[4] Neuman, K.C., et al., Characterization of Photodamage to Escherichia coli in Optical Traps. Biophysical Journal, 1999. 77(5): p. 2856-2863.

[5] Cai, W. and V.M. Shalaev, Optical metamaterials: fundamentals and applications. 2010, New York: Springer. xii, 200 p.