Optically driven micromachines: design and fabrication

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Abstract

We design and fabricate optically driven micromachines which find the applications in microfluidics, manipulation of biological cells, microchemistry etc. The micromachines are driven by tightly focused laser beams. To aid the design of micromachines, we employ a number of modeling methods such as the Mie theory, the point matching method, finite difference methods, discrete dipole approximation (FDFD), sometimes in combination, to simulate the light scattering from the individual components. The micromachines prototypes are fabricated using a two-photon polymerization process.

1 Introduction

A 'micromachine', as we have defined it, may be a number of microdevices working in conjunction with one another or it may be as simple as a single rotor trapped by a tightly focused laser beam. For example, a single birefringent vaterite sphere is used to determine the viscosity of it's surrounding liquid medium by means of measuring its rotational speed and the torque applied by the trapping laser beam that carries spin angular momentum. We fabricate micromachine components with complex shapes using a two-photon polymerization process [1]. The components are generally about 1-9μm in size. The design of the micromachines are aided by computational simulations of the scattered field from which the torques and forces can be calculated. A survey on micromachines can be found on [2].

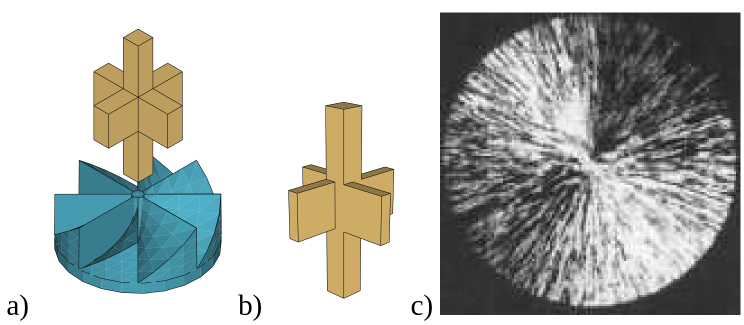


Figure 1: a) DOE and 'cross' rotor. b) 'Cross' rotor with offset blades. c) Spherulitic sphere.

2 Micromachines

There are a number ways a microrotor can be spun using its structure in combination with the nature of the incident tightly focused laser beam. Upon passing through a diffractive optical element (DOE) with 8 blaised blades as per figure 1a, a gaussian beam will aquire orbital angular momentum of $8\hbar$ per photon. The beam then can be used to spin a 'cross' rotor as shown in figure 1a. However, if the 'cross' rotor has offset blades (figure 1b), it will spin with just a gaussian incident beam due to the asymmetric forces at the blades.

A focused laser beam with spin angular momentum can be used to transfer torque to the birefringent object. The bifringent object works a waveplate to change angular momentum of the beam. Although, the spherulitic sphere in figure 1c is not uniformly birefringent, a nett birefringence is sufficient for the effect to take place.

3 Fabrication

A 3D microstructure is fabricated by curing the resin to the required shape [1]. This involves pulsing the the individual voxels of the structure with a femtosecond laser. Two coverslips, which sit on a pedestal, (figure 2) support the resin. The pedestal is moved in the required x, y and z direction such that each voxel is cured one at a time. When all the voxels are cured, the uncured resin is washed away with acetone, and we are left with the 3D structure.

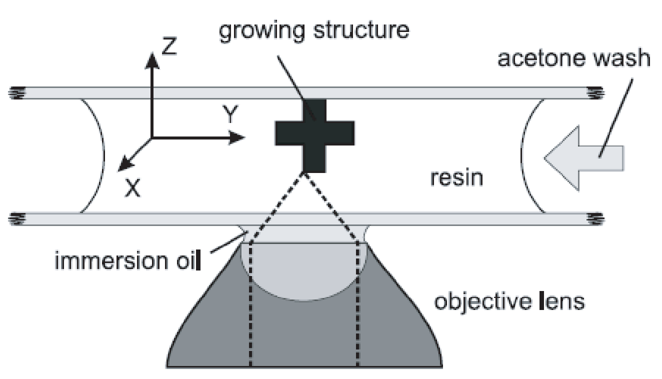


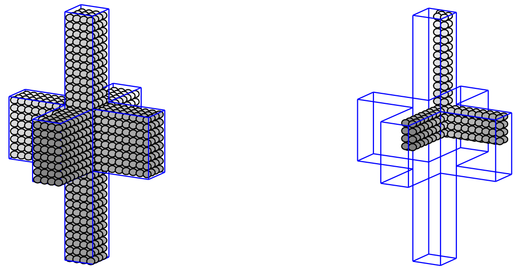
Figure 2: Two-photon polymerization fabrication.

4 Simulation Methods

We have used the FDFD/T-matrix method [3] to calculate the torque imparted on a vaterite particle by any given trapping beam with spin angular momentum. For larger and more complex structures, we have found the DDA method [5] to be suitable. Nonetheless, as the target model gets larger, we begin to hit the limit of available memory; the need for memory saving methods arises.

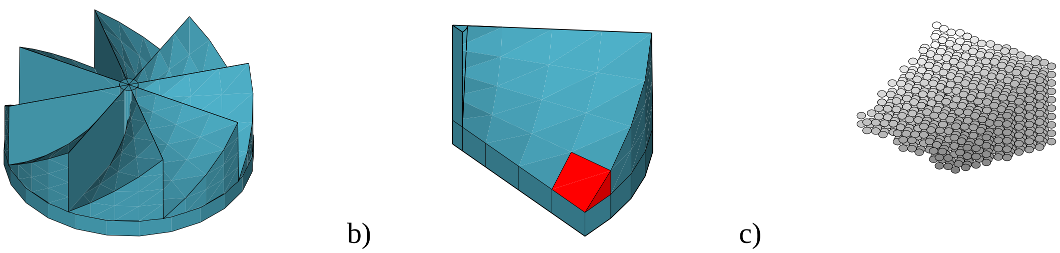
We developed a method to exploit the rotational symmetry of a target structure [4], whereby the interaction matrix of the DDA linear equations can be compressed to $1/m^2$ to that or the original size, where m is the order of rotational symmetry. The matrix can be further compressed by a factor of 4 by exploiting mirror symmetry. This is achieved by only constructing the interaction matrix from the reduced number of dipoles (figure 3) but still aggregating the contributions from their symmetrical counterparts. Once the linear equations are solved, the polarizations of the other dipoles can be calculated easily from just applying the appropriated rotations or 'reflections' which are merely phase corrections. This holds for the case of plane wave illumination. However, to generalize for arbitrary illumination, we would need to incorporate this method with the T-matrix [6].

We propose to exploit the rotational symmetry of the DOE in figure 4a. However the repeated 'wedge' (figure 4b) of the DOE presents the problem where there are sharp edges where we may need prohibitively



a) b)

Figure 3: a) Dipoles representing target 'cross' rotor. b) Reduced number of dipoles due to symmetry.



a) b) c)

Figure 4: a) Diffractive optical element (DOE). b) DOE segment. c) Precalculated block.

small (because of memory requirements) lattice spacing for the dipoles. To overcome this, we would divide the DOE segment into smaller blocks and precalculate the overall polarizability of the blocks using relatively small dipoles (figure 4c). The polarizability of those blocks that are repeated throughout the segment need not be calculated again. Effectively, we calculate the polarizability of arbitrarily shaped dipoles. We then assemble the DOE segment and hence apply the same symmetry method as for the cross to model the whole DOE.

5 Conclusion

The fabrication and design of micromachines can be made more efficient with the aid of computational modelling methods; the cycle time between design, fabrication and testing is greatly reduce due to the capability of modeling methods to realistically calculate the scattered fields and hence torques and forces. This means that a bulk of the testing can be done on the computer even before the first fabricated prototype is produced. The flexibility of modeling methods such as DDA allows for the design of exotic structures.

References

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