

All-optical control of microfluidic components using form birefringence

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The reflection and refraction of light at a dielectric interface gives rise to forces due to changes in the photon momentum¹.

At the microscopic level, these forces are sufficient to trap and rotate microscopic objects^{2,3}. Such forces may have a profound impact in the emergent area of microfluidics, where there is the desire to process minimal amounts of analyte. This places stringent criteria on the ability to pump, move and mix small volumes of fluid, which will require the use of micro-components and their controlled actuation⁴⁻⁷. We demonstrate the modelling, fabrication and rotation of microgears based on the principle of form birefringence. Using a geometric anisotropy (a one-dimensional photonic crystal etched into the microgear), we can fabricate microgears of known birefringence, which may be readily rotated by manipulating the input polarization in a standard optical trap. This methodology offers a new and powerful mechanism for generating a wide range of microfabricated machines, such as micropumps, that may be driven by purely optical control.

Microfluidic flow and its manipulation are central to lab-on-a-chip biological diagnosis. The typical microfluidic environment exhibits laminar flow, that is, low Reynolds numbers, with diffusion as the only mixing mechanism. A real challenge is then the ability to develop driven micro-components that can be used to enhance such purely diffusive processes and enable mixing in a wide variety of microlaboratories. A significant step forward in the field would be the production of micro-components that may be readily positioned and rotated without moving parts or dynamic-light-field shaping, and at the same time offer full flexibility in terms of micro-object shape and size. Several techniques for rotation exist in optical tweezers including the use of rotating light patterns, scattering or the transfer of spin or orbital angular momentum. To rotate generic micro-objects with any desired symmetry remains a challenge, however. Scattering of the trap light⁸⁻¹⁰ can rotate microgears, but the mechanism requires some asymmetry or optimal spatial shape and is thus not suited to rotating rotationally and bilaterally symmetric objects. Additionally, scattering is typically detrimental to optical tweezing and thus one cannot truly decouple the position in the beam focus of the trapped object and its sense or rate of rotation. Alternatively, transferring spin angular momentum from a light beam to a micro-object by birefringence offers great promise as we can use this in a standard single-beam optical trap and obtain very

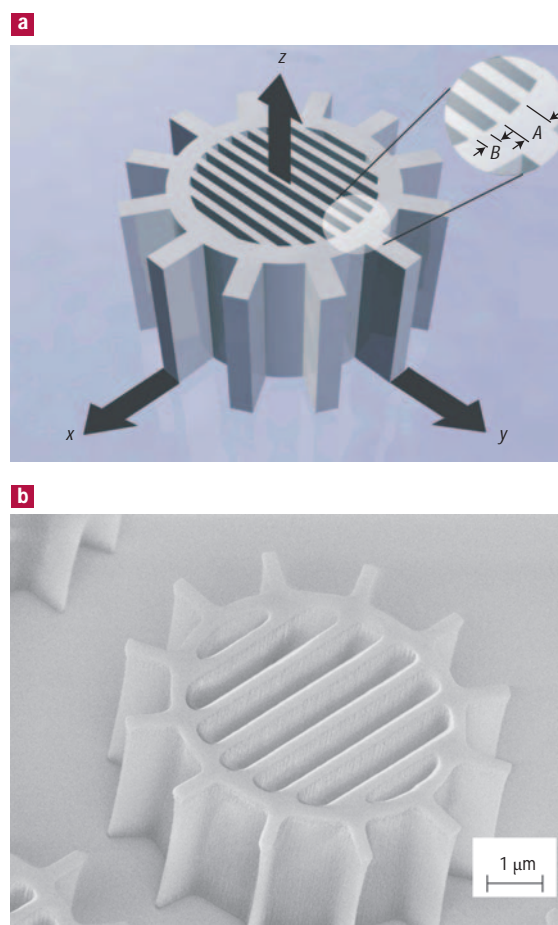


Figure 1 Form birefringent microgears. **a**, Diagram of a form birefringent microgear. A is the pitch of the photonic lattice, B is the rib width and the fill factor is B/A . **b**, SEM micrograph of an actual microgear before release from the substrate.

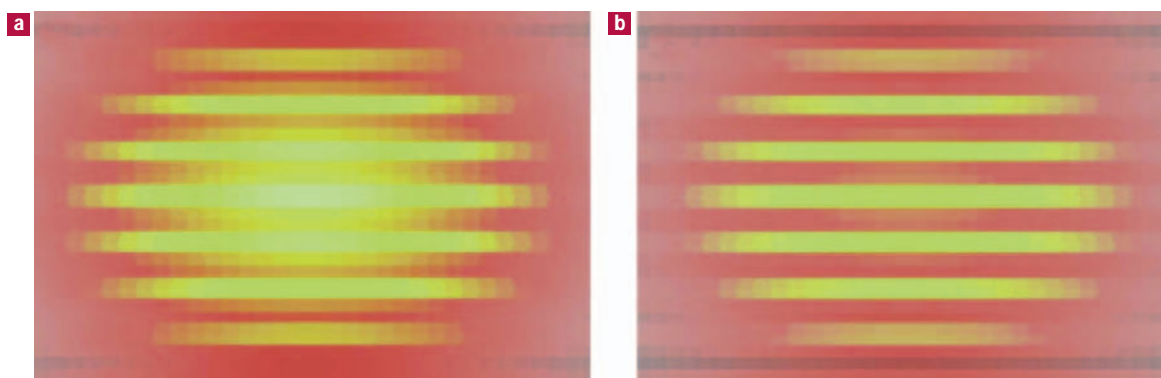


Figure 2 Modelling the birefringence. **a**, The fundamental TM mode of a one-dimensional photonic crystal with pitch $0.8 \mu\text{m}$, fill factor 0.3. **b**, The fundamental TE mode of the same structure is more confined in the high-refractive-index material increasing the effective refractive index.

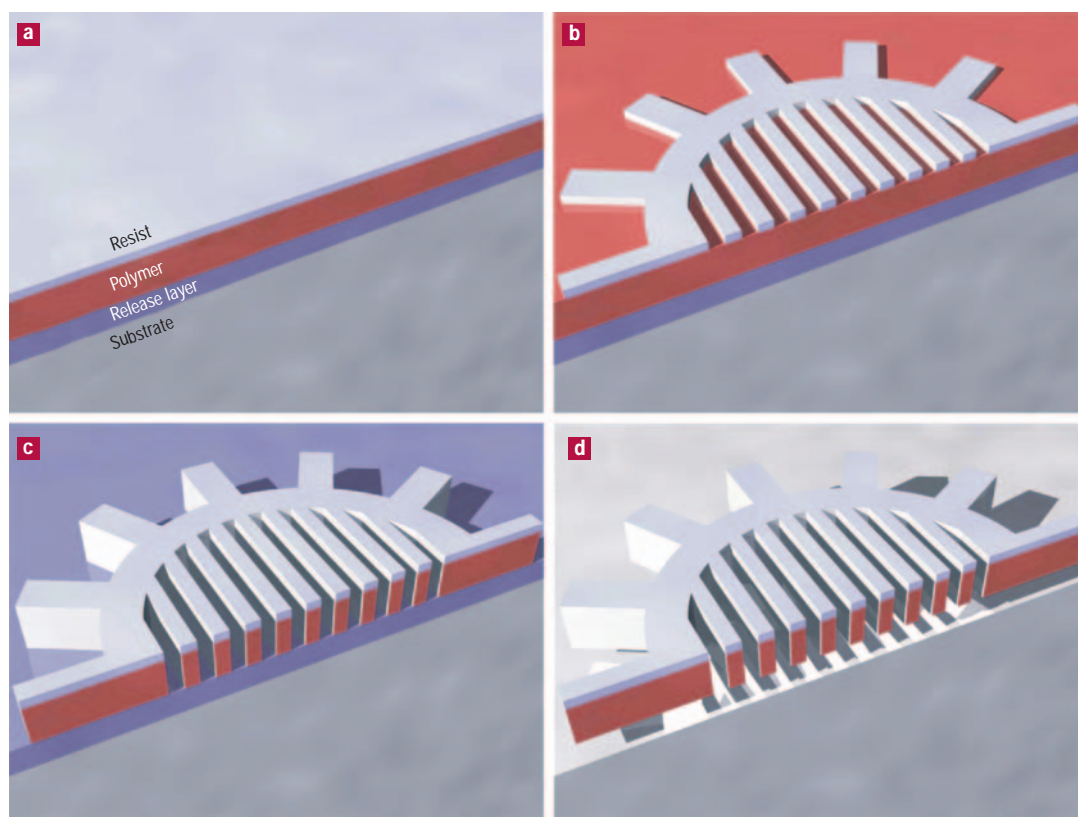


Figure 3 Fabrication of a microgear. **a**, Substrate with release layer, polymer layer and resist layer spun on. **b**, The resist layer is patterned by electron-beam lithography. **c**, The pattern is transferred into the polymer by reactive ion etching. **d**, The microgear is released by dissolving the release layer.

high rotation rates with no associated heating. Such rotation and optical micro-actuation have previously been demonstrated using birefringent fragments³, which potentially offers the most powerful means of rotation at high rates whilst being compatible with a standard optical trap, requiring only a modification of the input light's state of polarization. To date, this method has been hampered by the requirement of specialist materials (for example, calcite) that are not readily microfabricated.

The current drawback in the field of rotational control as a whole is the ability to initiate rotation for a wide range of microfabricated objects of arbitrary shape with a simple applicable technique. In this letter, we introduce a generic and widely applicable method of independently controlling the birefringence and specific function of a given micro-component, allowing, for example, optimization of both the shape and birefringence of a microgear for any given application. The birefringence is due to the fact that light

propagating through the photonic lattice experiences a different refractive index depending on its polarization (Fig. 1).

For polarization along the ribs, light will mainly occupy the high-refractive-index regions and therefore experience a higher effective index; if the polarization is across the ribs, it will average over the two respective materials and experience a lower effective index (Fig. 2). As this birefringence arises from the internal shape of the structure rather than an intrinsic property of the constituent material, it is commonly referred to as ‘form birefringence’^{11,12}. The difference between the two effective indices gives a measure of the birefringence Δn_{eff} . In the case studied here, using SU-8 polymer (material index $n = 1.56$ at $1.064 \mu\text{m}$ wavelength) immersed in water ($n = 1.33$), we obtained a form birefringence of $\Delta n_{\text{eff}} = 0.018$ for a lattice-pitch of $0.8 \mu\text{m}$ and a polymer fill factor of 0.3, that is, polymer ribs of 240 nm width. This value is sensitive to the fill-factor and increases monotonically with pitch, until it becomes limited by the finite size of the structure.

The fabrication of the microgears is outlined in Fig. 3 and is described in more detail below. Following fabrication and release, the gears are placed in an optical-trapping setup (see Methods and Supplementary Information Fig. S1 and caption for details) that is based on a fibre laser operating at $1,070 \text{ nm}$ with an output power of up to 1 W . We first verified the successful operation of the microgears by tweezing and rotating them with linearly polarized light. Inserting the microgear into a linearly polarized trapping beam resulted in the gear reorienting itself, due to a resultant torque, until the fast axis of the gear aligned with the linear polarization direction. Subsequent rotation of the direction of polarization by rotating a half-wave plate caused the gear to follow suit. The microgears did indeed follow the direction of linear polarization. Supplementary Information, Movie S1 shows rotation of a single microgear in a rotating linearly polarized light beam. The maximum rate of rotation is limited by the frictional Stokes drag on the microgear, and depends on the power of the tweezing beam (Fig. 4a). As the power is increased, the force due to the radiation pressure of the reflected light increases, pushing the microgear against the microscope slide. This eventually causes friction between the microgear and the microscope slide to dominate, giving an upper limit to the amount of power that can be used.

The exchange of momentum between the light and the micro-gear results in a torque given by³

$$\tau \propto E_0^2 [1 - (\cos kd \Delta n_{\text{eff}})] \quad (1)$$

where E_0 is the electric field, k the wave vector of the incident light, d the thickness of the microgear and Δn_{eff} its birefringence. From equation (1) we can see that the maximum torque will occur when $\Delta n_{\text{eff}} d = \lambda/4$. At present our $\Delta n_{\text{eff}} d$ is roughly a tenth of this value, which means we can increase the torque generated by either making the microgears thicker or increasing their form birefringence. Increasing the refractive index difference between the microgear and the surrounding medium can increase their form birefringence. This can be achieved by fabricating the microgears from a higher refractive material for example, a high-refractive-index polymer (OptiNDEX A14, $n = 1.95$, Brewer Science) or even a semiconductor such as silicon ($n = 3.6$ at $1,064 \text{ nm}$). Using higher-refractive-index materials will mean the scattering forces increase, making it necessary to use thin films of thickness $\lambda/4$ that act as antireflection coatings. However the benefits would be great as we estimate a maximum Δn_{eff} of 0.5 for Si/water (The absorption coefficient of Si at $1,064 \text{ nm}$ is 80 cm^{-1} , which creates negligible absorption in, for example, a $1\text{-}\mu\text{m}$ -thick microgear), which would exceed even that of calcite ($\Delta n = 0.16$). To increase the torque still further it may be possible to create a multipass system where the light is reflected through the microgear many times. This has the potential to increase

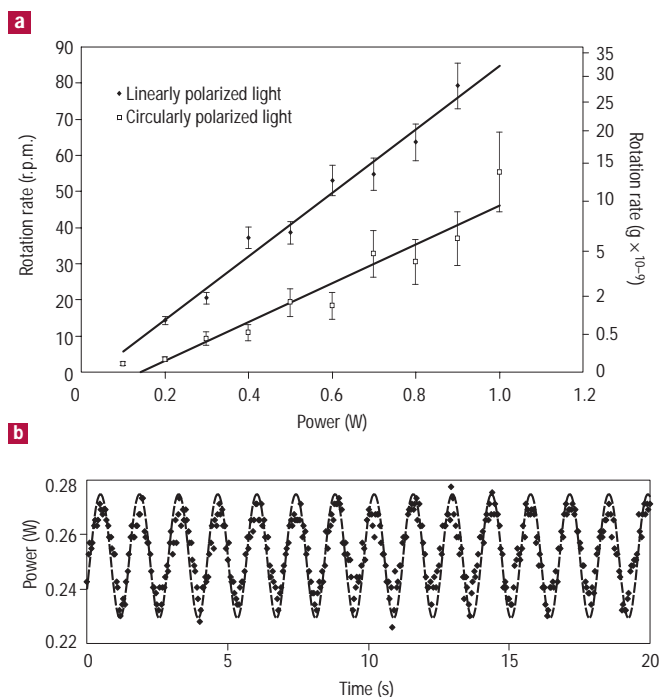


Figure 4 Rotation results. **a**, Maximum rotation rates with increasing power for both linearly and circularly polarized light. **b**, Light transmitted through the microgear that has been analysed by passing it through a polarizer. The amplitude of the power variation indicates the magnitude of the birefringence, and the rotation rate can be gained from the period. The error bars represent the deviation from the mean rotation rate when averaging over 12 revolutions of the microgear.

the torque (and hence rotation rate) many times over, limited only by the absorption of the material used.

On changing to circularly polarized light, without any moving parts, the microgears were also found to rotate (see Supplementary Information, Movie S2 and caption). The optimal condition (from equation (1)) is the exchange of angular momentum of $2\hbar$ per photon³ between the light and the microgear, with the microgear acting as a half-wave retardation plate. Our microgears rotated at a constant rate when illuminated with circularly polarized light. The mechanism of rotation was confirmed by illuminating with circularly polarized light of opposite handedness, which caused the microgears to rotate in the opposite direction. Furthermore, the rate of rotation again depended linearly on the illuminating power (Fig. 4a). To determine the birefringence experimentally, we measured the change in the polarization state of a circularly polarized light beam after passing through a microgear¹³. Placing a linear polarizer in front of the detector yields a sinusoidal signal of frequency twice that of the microgear’s rotation. The amplitude variation relates to the amount of birefringence (Fig. 4b), which we measured as $\Delta n_{\text{eff}} = 0.015 \pm 0.001$. This is in fairly good agreement with the simulated value of $\Delta n_{\text{eff}} = 0.018 \pm 0.001$. Once again we stress that the techniques mentioned above may readily allow us to generate a higher value of Δn_{eff} .

Finally, we demonstrated that one microgear can be used to rotate a second optically trapped microgear (Supplementary information, Movie 3). Here, a second microgear has been introduced that is being attracted to the same linearly polarized optical trap as the first microgear. The microgears are identical and so the torque due to the

light acts on both of them in the clockwise direction. The intermeshing teeth, however, prevent this and the strongest interacting microgear rotates clockwise, thus driving the other microgear anticlockwise. This clearly demonstrates how form birefringent microgears could be used to actuate a micromachine such as a microgear pump.

METHODS

SIMULATION

The simulations were performed with a vector mode solver (FIMMWAVE, Photon Design) that located the two fundamental modes of the one-dimensional photonic lattice, designated as TE (electric field along the ribs) and TM (electric field across the ribs). The difference between the respective effective indices is taken as the value of the form birefringence, Δn_{eff} .

FABRICATION

A silicon substrate was used as a carrier. First, a sacrificial lift-off layer (SU-8 Release Layer, MicroChem) was spun at 1,000 r.p.m. and cured at 230 °C. Second, the microgear material (here: SU-8 3:1 2000.5:2050, MicroChem) was spun on at 1,250 r.p.m. Finally, a layer of hydrogen silsesquioxane (HSQ; Fox 12, Dow Corning) was spun on at 5,000 r.p.m. and cured at 230 °C. The HSQ crosslinks under electron exposure and is therefore used as negative electron-beam resist. Patterning was performed by electron-beam lithography (LEO Gemini 1530 SEM with a Raith Elphy Plus pattern generator). The pattern was developed in MF319 developer (Shipley) to dissolve the unexposed HSQ. The specimen was then placed in a home-built reactive-ion-etching machine for oxygen etching, which removes the polymer except where it is protected by the patterned HSQ. Finally, the gears were released from the carrier by dissolving the lift-off layer in *N*-methylpyrrolidone (NMP, Aldrich). A drop of water containing the microgears was then moved from the substrate onto a microscope slide for testing.

SETUP

The optical trapping system uses a 1,070 nm fibre laser (IPG Photonics) that operates at up to 10 W. This is directed by a dichroic mirror through a final aspheric lens into a sample chamber (~100 µm thickness) to a beam focus of around 5 µm in diameter. The illumination runs co-linearly with the laser path. Imaging is performed from below using a microscope objective that images the light onto a charge-coupled-device camera and also a photodiode for analysis of the output polarization state of the light. More details may be found in Supplementary Information, Fig. S1. The microgears are trapped in two dimensions, greatly simplifying the requirements of the laser illumination. The use of 2D trapping for driving the microgears is ideally suited to microfluidics, where devices are built in a planar geometry and three-dimensional manipulation is either unnecessary or counterproductive.

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Competing financial interests

The authors declare that they have no competing financial interests.