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Published in:
Laser & Photonics Reviews

Link to article, DOI:
10.1002/lpor.201200030

Publication date:
2013

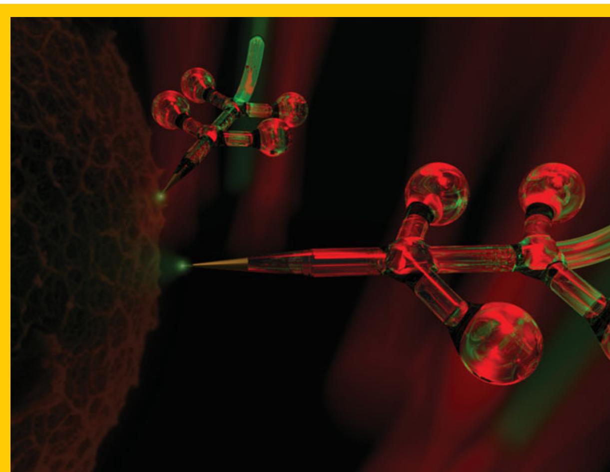
Document Version
Publisher's PDF, also known as Version of record

LASER & PHOTONICS REVIEWS

Laser Photonics Rev. **7**, No. 4, 478–494 (2012) / **DOI** 10.1002/lpor.201200030

REVIEW ARTICLE

Abstract Optics is usually integrated into robotics as part of intelligent vision systems. At the microscale, however, optical forces can cause significant acceleration and so optical trapping and optical manipulation can enable the noncontact actuation of microcomponents. Microbeads are ubiquitous optically actuated structures, from Ashkin's pioneering experiments with polystyrene beads to contemporary functionalized beads for biophotonics. However, micro- and nanofabrication technologies are yielding a host of novel synthetic structures that promise alternative functionalities and new exciting applications. Recent works on the actuation of synthetic microstructures using optical trapping and optical manipulation are examined in this review. Extending the optical actuation down to the nanoscale is also presented, which can involve either direct manipulation of nanostructures or structure-mediated approaches where the nanostructures form part of larger structures that are suitable for interfacing with diffraction-limited optical fields.



Gearing up for optical microrobotics: micromanipulation and actuation of synthetic microstructures by optical forces

Darwin Palima * and Jesper Glückstad *

1. Introduction

Robotic solutions are indispensable in modern industrial production systems but creating similar robotic manipulation solutions in the micro- and nanoscale domains must face scaling laws and other challenges [1–4]. At the same time, scaling down to the microscale means that the minuscule force from optical fields can effect considerable acceleration on microscale objects, as Ashkin realized in 1970 [5]. The now established use of optical fields for exerting mechanical forces in optical trapping and optical manipulation and its demonstrated capabilities is similar to atomic force microscopy (AFM)-based nanorobotics [6], where the overall system is large but is capable of precision operations on tools and components at the micro- and nanoscale. With optics already forming a vital imaging component of intelligent vision systems for robotics [7] and with novel synthetic microcomponents amenable to optical trapping and manipulation, optical actuation can be a driver for carving a niche for optical microrobotics by enabling mechanical manipulation in the micro- and nanoscale domains using macroscale optical trapping systems, which can complement approaches based on developing autonomous self-powered mobile micro/nanorobots for programmed tasks.

The field of optical trapping and optical manipulation has grown into a large area of study and rapid development continues across many fronts. For newcomers to the field, a way to keep track of the developments is to compare their novelty with Ashkin's pioneering demonstration [5], i.e. using a single pair of static counterpropagating beams focused by regular lenses onto a sample chamber to trap polystyrene microbeads, one at a time, while observing them through a microscope. It is now common to employ single-beam trapping that reuses the same observation microscope lens [8]. We now have multiple simultaneous traps [9], with options to independently control each trap both in the single-sided and counterpropagating/dual-beam geometries using beam manipulation techniques like time-multiplexing [9, 10], diffractive optics [11], and generalized phase contrast [12] for three-dimensional (3D) trapping and manipulation. Aside from microscope objectives, the trapping beams may also be delivered using fibers [13–15] or micro-optical elements custom-built onto the sample chambers themselves [16]. Trapping with minimal laser power is also possible with aberration corrections [17]. The particle position detection system [18] can serve a range of functions from simple visualization to feedback control [19–22] and quantitative optical force measurements based on the position fluctuations [23], the latter demanding stringent vibration isolation and laser pointing stability.

These technical developments in trapping implementation (i.e. the 'how' of optical trapping) enable the trapping of different types of particles ('what') in a variety of working environments (where). More importantly, from a practical perspective, these developments can enable and

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define novel applications and purposes for optical trapping ('why'). Taken together, the how, what, where and why of optical trapping can define the uniqueness and novelty of an optical trapping setup and experiment. Hence, although polystyrene microbeads have been trapped since 1970, it can be very valuable when such beads are attached to macromolecules and trapped in a technically refined system for accurate force measurements of the mechanical properties of the molecule [23]. This vibrant subfield dedicated to quantitative optical force measurements has taken a life of its own with active developments in both the instrumentation and the biological applications. However, one should keep an eye out for other applications of optical trapping, since another so-called 'killer application', which may not necessarily involve quantitative force measurements, could be lurking in the horizon.

Various reviews of optical trapping and its various aspects have been published to keep readers abreast of the rapid developments in this field. A resource letter by Lang and Block in 2003 lists scientific articles grouped into different categories for easy reference [24]. Ashkin has previously reviewed the field from its early days up to the trapping of neutral atoms and biological particles [25, 26]. A review by Neuman and Block provides a general overview, with special emphasis on the instrumentation, particularly for particle-based force measurements [27]. This is extended in a recent review by Moffitt et al., which looks at the instrumental limits of optical tweezers [28]. Optical trapping has been a breakthrough single-molecule technology and this is emphasized in reviews of single-molecule techniques by Neuman et al [29,30] and Perkins [31]. Banerjee et al recently reviewed indirect optical manipulation, where biological cells, nucleic acids and motor proteins are manipulated while tethered to optically trapped beads [32]. A growing technology for direct optical trapping of nanoparticles using plasmonic effects is reviewed in [33], while the conventional trapping of nanoparticles with focused light is reviewed in [34]. Among the general reviews on optical trapping, Grier's 2003 review dubbed 'a revolution in optical manipulation' counts among the most cited [35]. More recent general reviews include those by Dholakia et al [36], who also published reviews focusing on the biophotonics [37] and the light-shaping aspects [38, 39] of optical trapping and manipulation. Padgett et al have reviewed the angular momentum aspect of optical trapping [40] and the relevance of optical tweezers to lab-on-chip systems [41]. Lab-on-chip solutions have been demonstrated for particle sorting and analysis, but this is another area where optical forces can play a role, as described in the review of Jonás and Zemánek [42].

In this review, we will focus on the optical trapping and optical manipulation of synthetic objects, which form rudimentary elements of optical microrobotics. With optics and photonics technologies for micro- and nanoscale imaging [43], activating [44], fabricating [45], and optical trapping and manipulation, optical microrobotics can be integrated into an all-optical workstation [46], which incorporates various allied functionalities, as visualized in Fig. 1. Contemporary micro/nanofabrication techniques

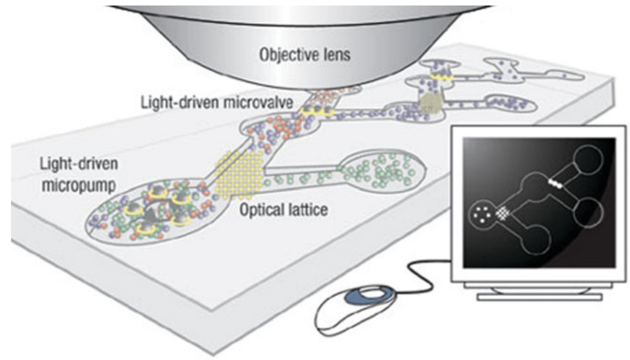

Figure 1 (online color at: www.lpr-journal.org) Optical microrobotics can be integrated into a multifunctional, all-optical microlaboratory where microprocesses are optically actuated, activated, controlled and monitored. (Adapted from [46]).

support optical microrobotics by providing a host of novel synthetic structures for optical trapping and optical manipulation. Optical traps can transport and manipulate nanostructures such as nanoparticles [49,50], nanowires [51–53], nanotubes [54, 55], optical probes/tools [56–60] and building blocks for micro-assembly [62, 63]. However, whereas microstructures are amenable to arbitrary translational and angular positioning in 3D space (the so-called six degree of freedom [6DOF] control), nanostructures are steerable only with limited angular control when using optical traps. One workaround, akin to indirect optical manipulation of biomolecules [32], is to attach the nanostructures onto spherical trapping handles. These handles can be attached on the fly using optical traps and they can be made detachable [55] or fixed to the structure [57], depending on the attachment mechanism. Using our BioPhotonics Workstation [61], we have previously demonstrated 6DOF control of microfabricated structures [60], as well as automated assembly [62] and proof-of-principle demonstration of optically reconfigurable microenvironments [63] using 3D structures fabricated via two-photon polymerization (2PP). The 3D resolution in 2PP fabrication (reported with down to sub-25nm feature sizes in [45]) offers possibilities for creating novel structures for optical trapping.

The optical actuation of various synthetic microstructures is explored further in Section 3. Aside from examining demonstrations of optical trapping of synthetic objects, Section 3 also surveys recent developments in the microfabrication of synthetic objects that promises interesting results when controlled by optical traps. However, as the nature of the trapped objects is closely linked to the optical system used for trapping them, we first provide a brief overview of optical trapping and manipulation concepts in Section 2 together with a brief survey of various optical trapping geometries.

2. Optical trapping and optical manipulation

How an optical trapping system is implemented strongly determines its trapping capabilities, which, in turn, limit

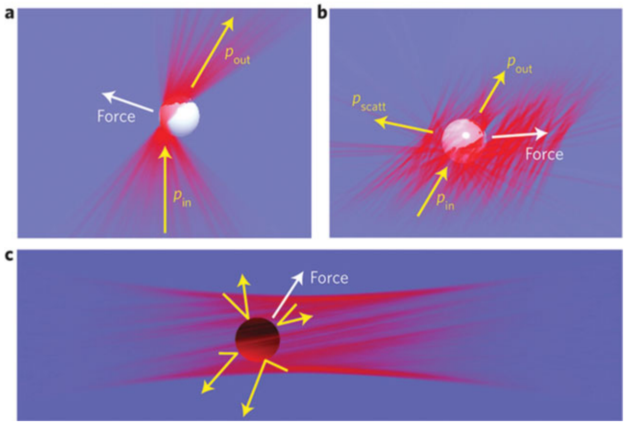

Figure 2 (online color at: www.lpr-journal.org) Optical force generation. At the fundamental level, optical force arises when incident light changes its momentum upon interacting with matter. (Adapted from [40]).

what structures can be trapped and/or manipulated. Optical trapping and optical manipulation exploit the optical force generated during the interaction between light and matter. When the light–matter interaction alters the momentum of light, momentum conservation dictates that the negative time rate of change of the momentum of the light quantifies the optical force exerted on the material (see Fig. 2). The optical force can be quantified, for example, by using ray optics for assigning photon trajectories [64], or via electromagnetic theory as summarized by the Maxwell stress tensor [65–67] or numerical solutions to the electromagnetic scattering problem [69–71]. Note, however, that optical trapping and optical manipulation are two different aspects of the momentum exchange between light and microscopic matter. This means, for example, that optical trapping can occur without manipulation, as in static traps. Similarly, optical manipulation can occur with limited or without trapping, as when beams are used to deflect particles e.g. in particle propulsion through hollow fibers [72], optical particle pulling [67, 68], optical sorting [73–75], or optical lift [76]. Optical trapping and manipulation can be combined, e.g. when a particle is manipulated by reconfiguring the optical trap. In the following, we therefore separately discuss these three cases: (1) optical manipulation without trapping, (2) static optical trapping (i.e., trapping without manipulation), and (3) optical manipulation via trap manipulation.

2.1. Optical manipulation without trapping

Optical manipulation (i.e. light-induced mechanical effects) is an expected consequence of the optical force when the length scale is small enough for the optical force to become significant. Optical trapping occurs only when the spatial variation of the interaction is characterized by a potential well, which effectively defines a stable equilibrium point where the particle can be trapped. Hence, creating an interaction that satisfies the trapping condition typically requires spatially sculpted optical fields, e.g., by focusing. Without such preparation, the interaction typically produces optical forces that can mechanically manipulate objects without trapping them. In the beginning this effect was necessary for establishing that light can, indeed, exert mechanical forces to accelerate microscopic matter [5]. In recent years, the light manipulation effect has been used, for example, to demonstrate that a broad beam can generate stable optical lift on a suitably shaped microscopic material to draw analogies with hydrodynamic thrust in macroscopic airfoils [76]. Similar hydrodynamic analogies were earlier observed in ‘light mills’ [77, 78], where microturbines rotate upon illumination. Drawing direct comparison with macroscale machines would indicate that particle rotation can be considered a fundamental element of micromachines, which is discussed further in Section 3. Other examples of manipulation without trapping include microbeads orbiting the dark core of optical vortices [79] or optical twisters [80], and sorting by optical fractionation [73], optical chromatography [84, 85] and particle deflection [74, 75]. It has also been shown recently that light can pull particles under certain conditions that favor forward scattering [67, 68], which drew popular interest partly due to a similar pulling effect from so-called ‘tractor beams’ depicted in popular science fiction [81]. Some examples are illustrated in Fig. 3).

2.2. Trapping geometry

Trapping and holding an optically manipulated particle in place (subject to Brownian fluctuations) can be achieved by using physical mechanisms to counteract any imbalance in the optical force, e.g. opposing mechanical force from direct contact with the chamber wall, gravity [82, 83], or hydrodynamic drag [84, 85]. One can also use feedback control systems that dynamically readjust the manipulating beam based on particle position feedback to maintain the particle’s position [19–22]. For an all-optical trap (the 3D optical trap) one can use two opposing beams or a single highly focused beam that creates a sufficiently high axial intensity gradient [8], the so-called optical tweezer. All things being equal, the relative simplicity of single-beam systems makes them easier to mechanically stabilize and so they are commonly used in high-performance systems for calibrated force measurements based on high-speed detection of particle position statistics. On the other hand, counterpropagating beam systems do not require tightly focused beams and so can be suitable for trapping and observing larger objects using lower magnification objective lenses. In contrast to the single-beam trap where the particle is trapped in the vicinity of an intensity hotspot of a strongly focused beam, counterpropagating beams can trap particles outside these intense regions, which can be desirable for avoiding unwanted nonlinear effects, though at some expense to the trapping stiffness [86]. The first all-optical trap was realized with counterpropagating beams [5], and is also the common geometry for fiber-based traps [13, 87] and in our BioPhotonics Workstation [61]. The counterpropagating beam geometry can also be mimicked by so-called mirror

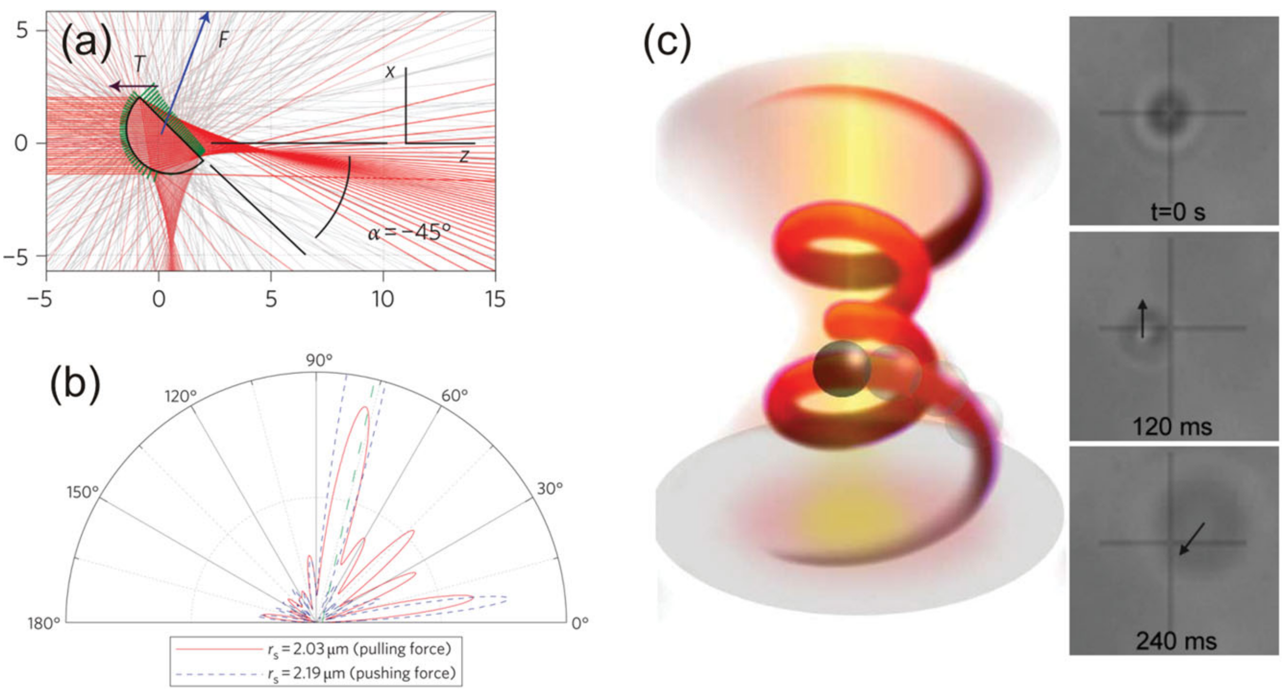

Figure 3 (online color at: www.lpr-journal.org) Examples of unbalanced optical forces that enable optical manipulation with limited or no trapping: (a) optical lift [76], (b) optical pulling force [67], (c) orbital and translational motion in an 'optical twister' [80]. (Images from respective references).

traps, where holographic projection creates two axially separated traps and the second trap is reflected to create a region where the two traps are counterpropagating [88, 89].

2.3. Manipulating optically trapped particles: beam control and modulation

Although particles can be optically manipulated without being trapped, improved control can be attained when optical manipulation is implemented by manipulating the trap itself. For example, deflecting the trap along a well-defined trajectory can guide a particle along such a trajectory. The trapping beam can be deflected by directed reflection on scanning mirrors, programmed refraction through electro-optic deflectors, adjustable diffraction through acousto-optic modulators and spatial light modulators, or interference effects using programmable phase patterns and, for example, common-path-synthesized reference waves. So, just as the higher-order Laguerre-Gaussian beam can manipulate a particle to revolve around its dark core, so a trapped particle can be moved around such a path, but with the added advantage that the latter scheme can arbitrarily accelerate, stop, or even reroute the particle. Similarly, the motion of a particle that is optically lifted by flood illumination can be replicated with more versatility by a targeted trap lifting a particle. Moreover, the targeted illumination in trap manipulation more efficiently utilizes the available photons in contrast to the diffused ring or flood illumination. However, trap manipulation requires active smart processing of the trap whereas manipulation-without-trapping approaches, in principle, can work just by shining light without smart targeting and control of the beam.

Figure 4 shows some typical geometries for spatial beam modulation, which can be extended to spatiotemporal modulation by using dynamic spatial light modulation. Although shown as transmitting optical elements, the beam modulators can also operate in reflection mode. For example, the modulating element in Fig. 4(a) could represent a scanning mirror that dynamically encodes phase tilts on the incoming beam to create a time-averaged spatial pattern [9, 10, 90]. The modulator can also be an electro-optic or acousto-optic deflector [91–93], or a Fresnel hologram that creates multiple beams e.g., an array of holographic lenslets [94, 95]). For the 2f geometry in Fig. 4(b) the modulator typically encodes Fourier-type diffractive optical elements or computer-generated holograms [11, 96–98] to create the desired beam pattern on the lens focal plane. Fig. 4(c) illustrates a 4f optical processor that uses two beam modulators, one of which serves as a filter since it is located at the Fourier plane. Commonly used filters include generalized phase contrast filters [99], correlation filters [100], spiral filters [101], optimized diffractive elements [102, 103], or even a blank one to just image the input modulator [104]. These basic geometries can be combined to form hybrid geometries [105, 106].

In practice beam modulation forms part of a light modulation module whose output is relayed and rescaled to the sample chamber through a microscope (e.g., the schematic for our BioPhotonics Workstation is shown in Fig. 5, which depicts the light modulation system with an expanded view of the beams near the sample chamber). Spatiotemporal

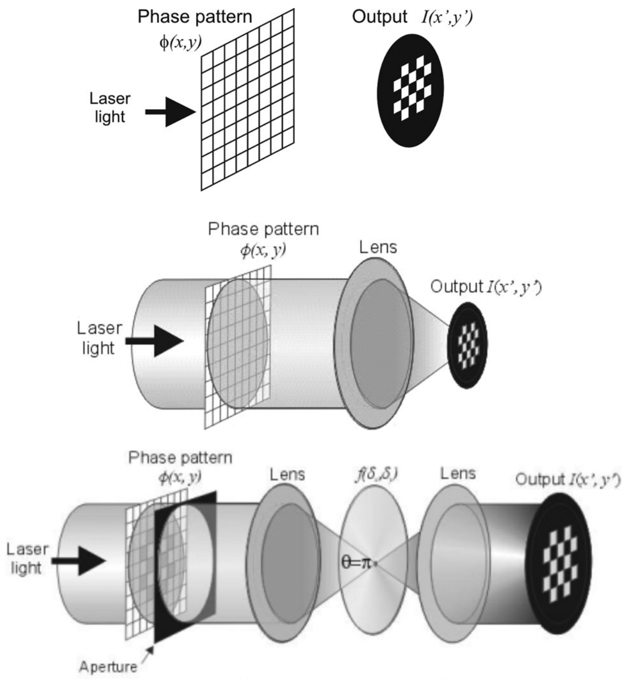

Figure 4 Beam modulation: spatial light modulation geometries for trapping beam synthesis. (a) Free space propagation after the spatial modulator (b) Fourier hologram (c) Optical processor (see also the 'beam modulation block' in Fig. 5).

beam modulation not only enables control of the trap location and strength, but also allows addition and removal of other controllable traps on demand. Reconfigurable multiple traps are crucial for handling multiple particles and for controlled steering of larger and more complex microstructures, where multiple traps, acting in concert, can grab different parts of the structure for stable control of position and orientation.

2.4. Integration: optical trapping and manipulation without bulky microscopes

As with many beam delivery systems, waveguides can provide an alternative to free-space optics for sending the trapping beams to the sample [13–15]. With laser pigtails and fiber immersion within the sample, fiber-delivered traps relax alignment restrictions and open the way for miniaturization. Although fibers are typically used in the counterpropagating beam trapping geometry [13, 87], some customized fibers are able to create single-beam traps [14, 107, 108]. Various fiber tip profiles can be fabricated, including axicons [108, 109] and hemisphere lenses [110], and these can be grown by polymerization [111] or by lithography [112]. The same fiber used for delivering the trapping beam can also be simultaneously used for other allied functions, such as multiphoton excitation [108] and light collection, e.g. Raman scattering [113]. Fiber-based traps can therefore be attractive for developing dedicated applications [87, 113], as it is not trivial to extend the customized fiber solutions to create multiple dynamic 3D traps. There has been some initial work done on using spatially modulated inputs to multimode fibers in order to generate multiple controllable transverse traps at the other end [15, 114] (a limited refresh rate is reported in [114]). However, in cases where the microstructures would anyway require conventional microscopic imaging during optical

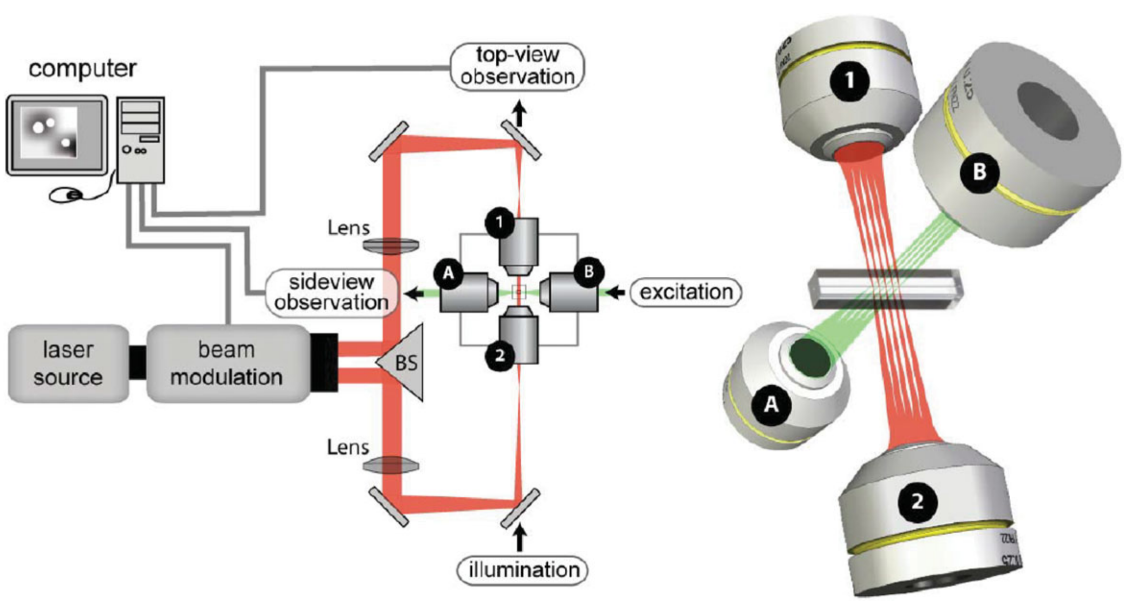

Figure 5 (online color at: www.lpr-journal.org) Light delivery and detection in the BioPhotonics Workstation (BWS). The BWS uses lower numerical aperture long-working-distance objectives that leave sufficient space for combining light delivery and detection systems along orthogonal axes. Eliminating the need for microscope objectives can be an option when high-numerical aperture systems restrict available space for experimentation. (Image from [61]).

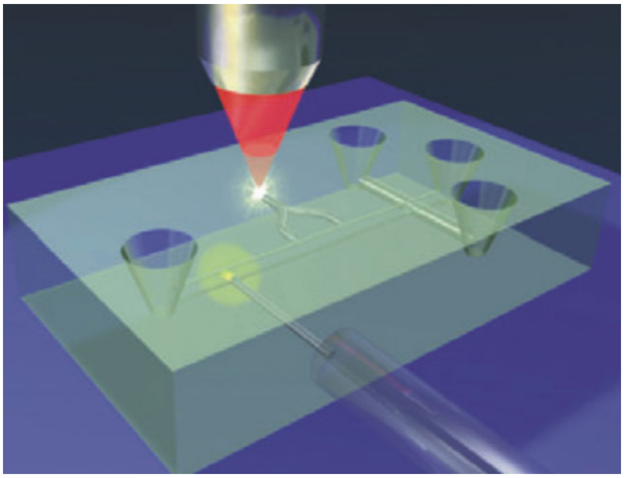

Figure 6 (online color at: www.lpr-journal.org) Femtosecond laser microstructuring can enable three-dimensional integration of optofluidic devices. (Image from [116]).

manipulation, adding beam-modulation-based optical manipulation only adds modest extra complexity [41]. On the other hand, developments in lens-free on-chip holographic imaging are shrinking microscopes [115], which would be attractive for compact integrated optical manipulation systems.

Advances in 3D microfabrication open opportunities not only for creating novel optically actuated tools, as discussed in Section 3, but also for enabling 3D integration of optofluidic devices for these tools (Fig. 6, adapted from [116]). Integrated solutions can eliminate the need for external beam modulation and do away with microscope objectives by creating optofluidic devices with built-in micro-optical elements for creating the optical traps [16,117–119]. Figure 7 illustrates system integration for the case of optically driven micromotors. Figures 7(a–d) show the micromotor that is optically trapped and being actuated using a conventional optical tweezer system [77] and integrated solutions are shown where the actuating light is delivered though an optical fiber in Fig. 7(e) [120] and through an integrated waveguide shown on the upper right-hand corner of the scanning electron microscope image in Fig. 7(f) [78]. Various optofluidic devices with integrated waveguides have been developed recently for various light delivery applications, including optical trapping and manipulation [116].

3. Optical trapping and manipulation of synthetic microstructures

The working definition for microrobotics adopted in [1] identifies two key components: (1) micromanipulation and (2) microfabrication. Having gone through the optical micromanipulation techniques in the previous section, we will now briefly turn to microfabrication techniques and then proceed to survey pioneering and recent work in the optical actuation of these synthetic microstructures.

Creating microstructures for optical manipulation can adapt established cleanroom technologies, such as silicon-based lithographic systems and thereby ride on industry targets for increasingly finer nanometric features (i.e., Moore's law). Many micro- and nanofabrication alternatives are also coming from research, which promise attractive features such as variety in constituent materials and possibility for arbitrary 3D architectures that can be equipped with engineered surfaces or bulk chemistry, without requiring expensive cleanroom environments. For example, soft lithography can be used for micro- and nanoscale patterning of soft matter such as organics and polymers [121, 122]. The syntheses of micro- and nanostructures also follow bio-inspired tracks, both from an overlying synthesis concept (e.g., self-assembly and hierarchical assembly) as well as

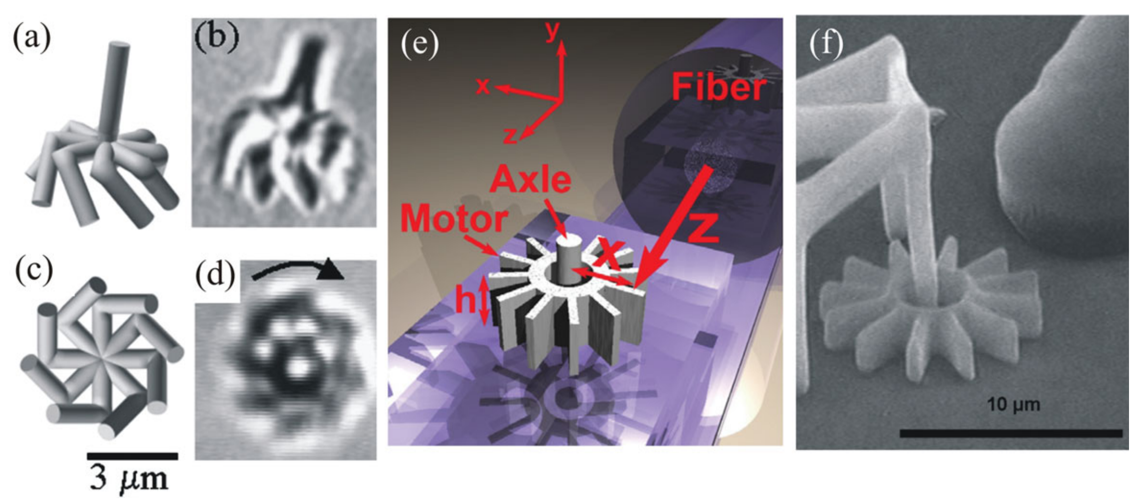

Figure 7 (online color at: www.lpr-journal.org) System integration: the optically driven motor. (a)–(d) Free-standing micromotor rotated by a trapping beam in a microscope (graphics rendering and optical microscopy) [77]. (e) Integration using an optical fiber to supply the driving light [120]. (f) Integration where an integrated waveguide supplies the driving light [78]. (Images from respective references).

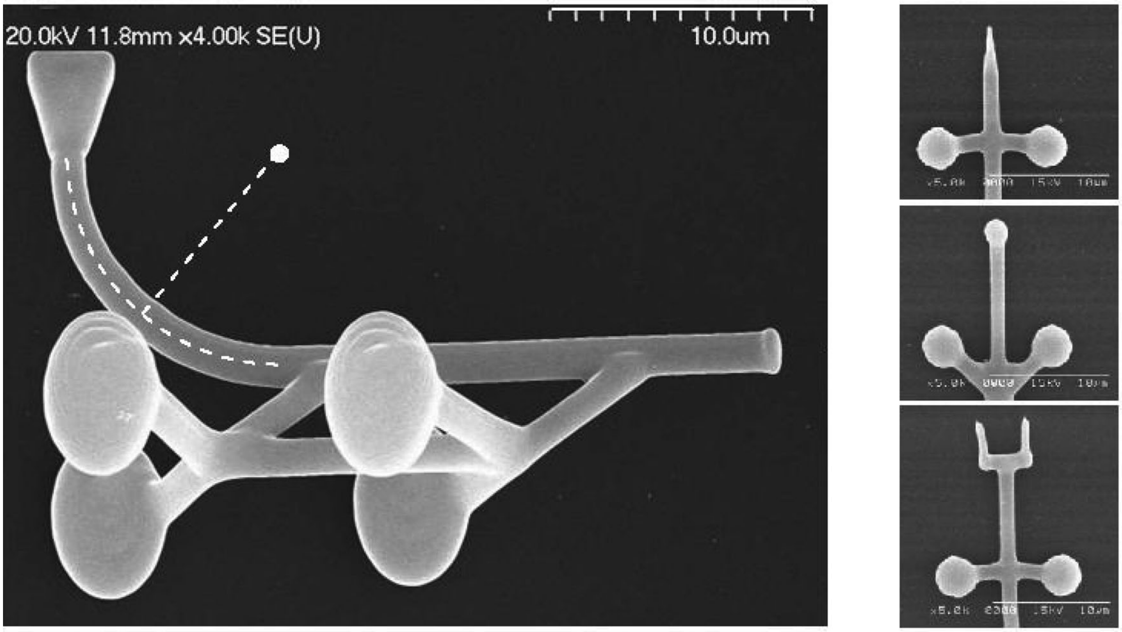

Figure 8 SEM images of sample microstructures fabricated by two-photon photopolymerization. The structure here is equipped with spherical handles for optical trapping for accurate control of a mounted waveguide. Various tip structures can be fabricated (From [125]).

in the actual use of biological molecules like DNA as construction materials [123, 124].

Laser and photonics technology can also fabricate user-designed microstructures using direct-write techniques (e.g., see sample structures in Fig. 8 [125]). Here a focused pulsed laser acts as an optical pen for writing 3D structures in a host material [126]. Feature sizes beyond the diffraction limit can be achieved using multiphoton absorption, e.g. 2PP 2pp-orig,2pp-nature2001 with materials science providing an expanding selection of candidate materials [129–131]. Subwavelength feature sizes have also been demonstrated using light-suppressed polymerization [132–134], analogous to deep subwavelength imaging by fluorescence suppression in stimulated emission depletion microscopy [43]. As with most scanning techniques, however, the fabrication speed can be a concern and the elaborate 3D structures mean that replication techniques for mass production would be difficult. Nonetheless, it is a powerful tool for rapid prototyping ('rapid' referring to the lag time when altering designs) and complete systems are now available from commercial suppliers if one doesn't want to bother with optics and software development for building such systems [136]. Potential speed gains can be obtained from using multiple foci (e.g [137]), which can simultaneously create replicas [138] or different sections of the same structure [139]. Orders of magnitude speed gain in a single-beam scanning system, using materials design and optimized beamsteering, has been recently claimed in a news release [140], with the system reaching scanning speeds of 550 mm/s when used as a multiphoton grafting system for 3D functionalization [141].

3.1. Optical actuation of micromechanical tools and micromachines

The scaling laws, e.g. for electrostatic and dissipative forces, imply that miniaturized versions of many macroscale machines and robots will not function as intended. There is, hence, a need to rethink the building blocks and machines that would be appropriate for miniaturized tasks [142]. Many turn to biology for inspiration (e.g., [123]), but novel twists on mechanics-based tools can also be useful (e.g. a fluctuating trapped microbead becomes a spring scale for precision force measurement [29]). Hence, although in most cases microgears and micromotors probably will not be implemented as part of scaled down copies of macromachines, the rotational and orbital actuation of microelements nonetheless can have its uses, albeit with a new twist.

Microstructures can be rotated by exchanging angular momentum with light. When using the spin angular momentum of light, this exchange manifests as a change in the polarization of the light. In this case, rotation requires the use of birefringent structures [143–146] and polarization controllable optical traps. Another way is to exploit the orbital angular momentum(OAM) of light, as shown in [147], where 2PP-fabricated microstructures, effectively working as mode converters that alter the orbital angular momentum of incident light, get rotated due to angular momentum exchange. This also exemplifies the general case of applying torques using optical forces that are displaced from the axis of rotation.

One of the proposed applications of optical rotation, that directly mimic macroscale applications, is for optically driven motors [148–152], which can be used as micropumps for microfludics [153–155]. The noncontact trapping and rotation of such micropumps allows versatile deployment, e.g. in microbiological environments. In a recent example, an optical micropump was used to apply controlled fluid flow in the vicinity of a neuron allowing the study of how localized flows affect neuronal growth [155].

Another mimicry of macroscale device function uses rotating microparticles as microviscosimeters to measure viscoelastic properties of submicroliter volumes [156]. These micromechanical functions do not always require rotation and, hence, aside from their use in measuring the mechanical properties of biomolecules by being tethered to optically trapped beads, the fluctuations of trapped microparticles can also be used for microrheology to reveal the local mechanical properties of the surrounding fluid [157–160].

Other activities within micromechanical tools echo developments in microtechnology, such as robotic microgrippers [161] and similar tools, but with optical force replacing the actuation mechanism [162–166]. When pivoting around supporting shafts, the optical actuation of micromechanical tools can create simple machines, e.g. for achieving so-called mechanical advantage or force amplification of the weak optical force using a lever [163], or for amplifying an optically actuated motion using a lever that can be further developed into a multilink system for motion amplification [164]. On the other hand, the use of free-standing grippers, e.g. a group of synchronously manipulated optically trapped microbeads [165, 166], would offer more flexibility in terms of operating volumes. As a performance target, optically controlled mechanical manipulators should ideally be capable of so-called 6DOF control (Fig. 9).

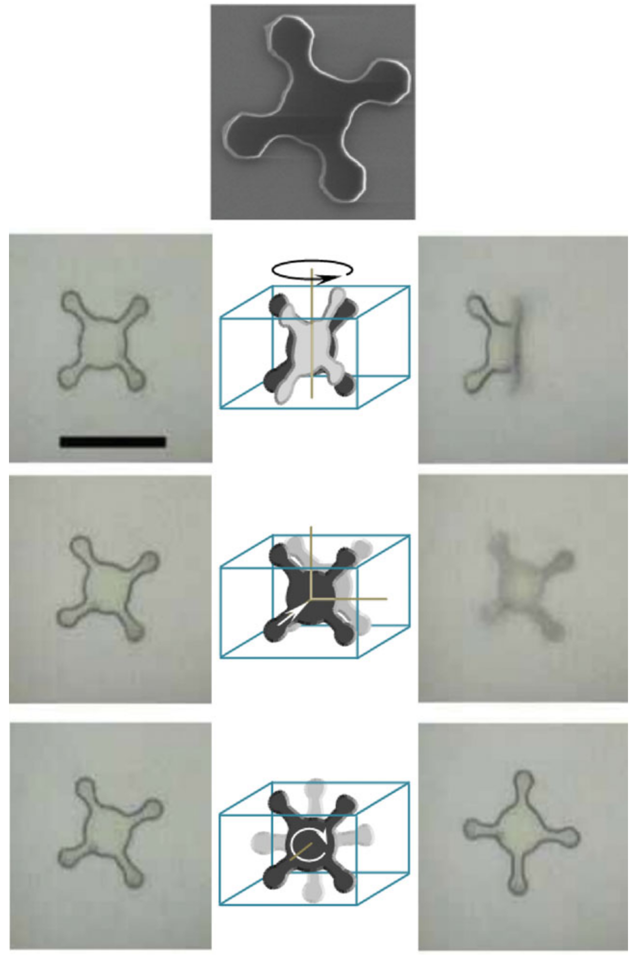

Figure 9 (online color at: www.lpr-journal.org) 6DOF control over a microfabricated structure. Scale bar: 20 μm. (Modified from [60]).

3.2. Optical assembly

Robotic systems are common in industrial assembly lines and one area of interest is in achieving similar robust systems for the assembly of micro- and nanoscale building blocks into functional structures. With microgrippers employed as micromanipulators in non-optical microrobotic assembly systems [161, 167], optically actuated grippers also come to mind when designing optical micro-assembly systems [162]. We can do away with the grippers when the building blocks can already be directly gripped by the optical traps.

Demonstrations in 1992 showed the serial assembly of a few polystyrene beads into a linear structure using two independently scanned optical traps with the structure glued together by photopolymerizing the touching surfaces [9]. The serial assembly of multicomponent 3D structures was shown in 2000 by optically trapping biological cells and treated microbeads and relying on biorecognition to hold the structure together [168]. Furthermore, disassembly was shown by introducing competing interactions and the work also pointed to other recognition systems that can be used for bonding (protein–ligand, complementary DNA, capillary forces, electrostatic forces, and hydrophobic interactions).

The advent of real-time multiple beam trapping techniques opened the way for the realization of optical assembly workstations [57, 62, 63, 169–172], capable of parallel optical micro-assembly. Among others, these have been used to assemble a large number of microbeads in three dimensions [170], manipulate nanowires [171], create probes by installing spherical handles onto microrods [57], and assemble 2PP building blocks into reconfigurable structures [62, 63] (Fig. 10). Moreover, there is also the possibility for light-guided self-assembly either through optical binding [173] or by using shaped beams [174, 175].

3.3. Manipulating nanostructures: direct handling and structure-mediated approaches

Bringing optical microrobotics to the nanoscale can be challenging due to the classical diffraction barrier. Moreover, trapping nanoparticles requires high optical intensities that can potentially exceed the damage threshold of a material. One technique for mechanically controlling

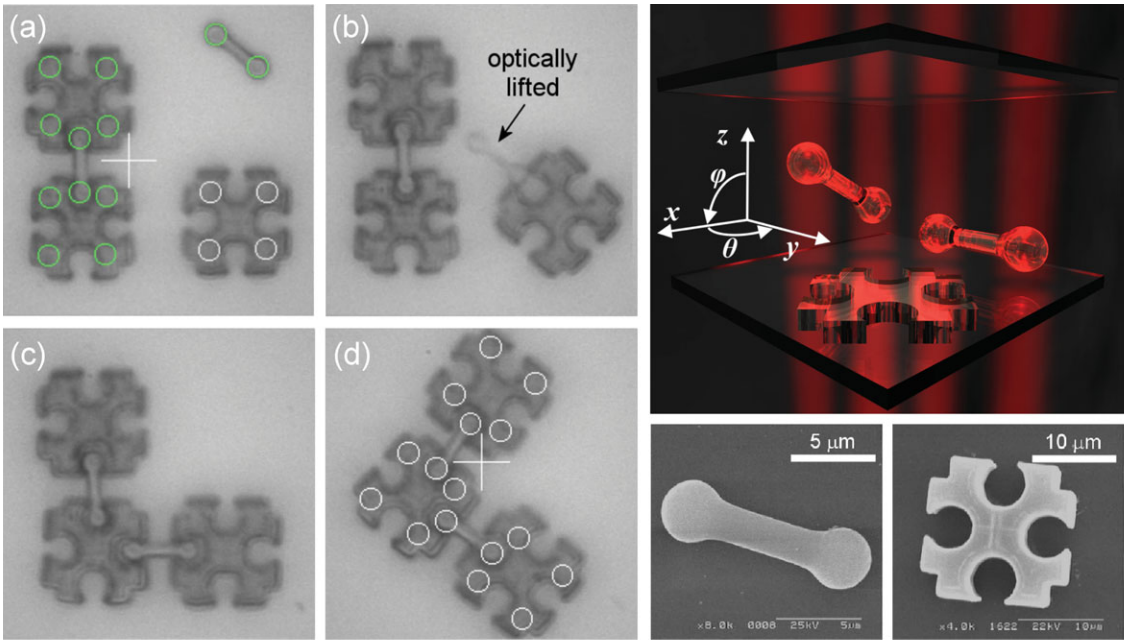

Figure 10 (online color at: www.lpr-journal.org) Optical micro-assembly of 2PP structures using 3D optical micromanipulation (Adapted from [177]).

nanometric components is by reconfiguring AFM tips to work as nanomanipulators [176]. These AFM tips can also be retrofitted to transport light and matter. Given the breadth of nanophotonics applications, it is enticing to envision a multifunctional optorobotics workstation for steering and monitoring nanoscale processes by exploiting optical force and energy to drive nanophotonic tools, including light sources and optics. Besides its generic appeal in nanotechnology, this can be appealing in the life sciences, where control over nanoscale processes promises accelerated biomedical explorations and innovations. In contrast to surface-based manipulation with AFM tips, noncontact optical manipulation offers more versatility for 3D positioning, including subsurface manipulation (e.g., intracellular components). Optical traps provide a noncontact alternative for 3D nanoscale manipulation [47–55, 179–182]. The nonlinear effects in optically trapped nanowires can be used to create tunable, subwavelength light sources [52]. A recent work combines optical trapping with AFM metallic probes [178].

In earlier work, the optical force on nanometric particles was modeled as an optical gradient force [47, 48] arising when inhomogeneous fields act on induced dipoles. For example, the sharp gradients of evanescent components from nanometric tips would be desirable [48]. In a reversal of roles, the optical gradient force can also act on the subwavelength waveguides themselves [186]. This has generated some excitement due to the possible optomechanical actuation of nanophotonic devices (e.g. photonic chips and mechanical biosensors [187]), which can rely on established silicon lithography for fabrication (see [188, 189] for recent reviews of the field).

Novel combinations of optical trapping with micro-/nanofabrication can help optics leap the diffraction barrier down to the nanoscale domain. Nanoapertures in a metal film can trap dielectric nanoparticles without high and damaging optical intensities [183, 184]. A trapped microbead can etch nanopatterns [185]; a trapped nanowire can work as a tuneable light source and a versatile optical probe [52]. However, whereas microstructures are amenable to arbitrary translational and angular positioning in 3D space (so-called 6DOF control), nanostructures are steerable only with limited angular control when using optical traps.

One way around this problem is through a structure-mediated paradigm by creating a structure as a micro-to-nano coupler for channeling optomechanical effects from microscopic handles into a nanoscale tip (Fig. 11). Instead of directly manipulating nanotools, the structure couples trapping force to the nanotip for manoeuverability to address the challenge of real-time, optical manipulation of such nanotools. Examples of this paradigm are 6DOF optical steering of planar silica structures [60] or scannin probe microscopy (SPM)-like optical probes [56–59] showing that the nanotip mechanics (such as position statistics and mechanical forces) can be inferred from the convenient observation of their microscopic handles. In [58] an optically controlled nanotip, used analogous to an SPM probe, is raster scanned to image the side surface of highly curved and scattering surfaces that is not accessible to conventional SPM (see Fig. 11 top inset).

In recent work on wave-guided optical waveguides [125], we designed and demonstrated 2PP microstructures capable of being optically manipulated into any arbitrary orientation (see Fig. 11 bottom insets). By integrating

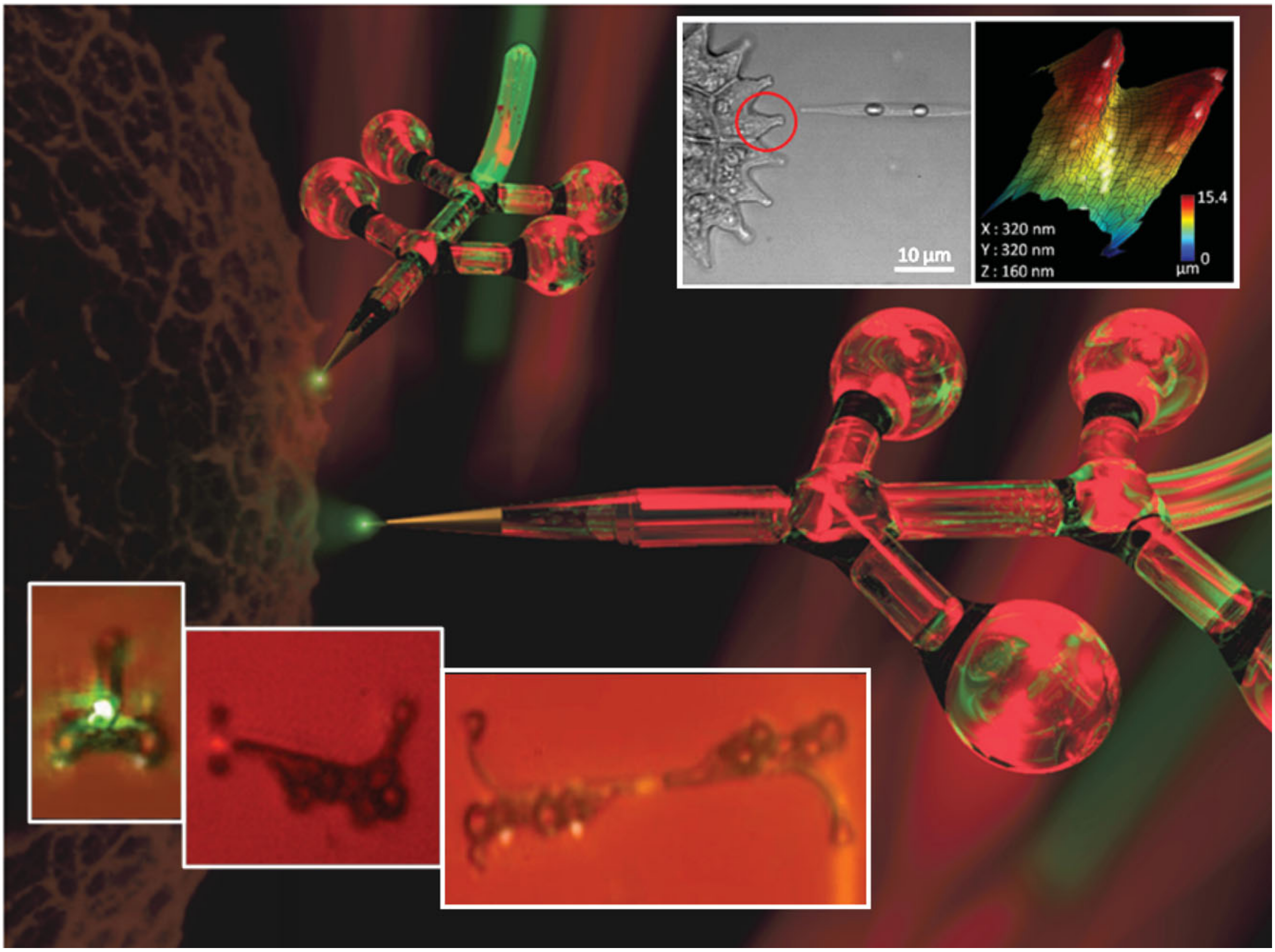

Figure 11 (online color at: www.lpr-journal.org) Visualization of structure-mediated nanotip manipulation where a functional tip forms part of a bigger structure that is well-controlled by optical traps. Top inset: a tip scans a surface, analogous to scanning probe microscopy, to image sharp spikes of *Pseudopediastrum* [58]; Bottom insets: a tip couples out light from an optically steered freestanding waveguide to channel light from far-field optics to selectively excite fluorescence from a certain microsphere within a vertical stack; the tip can also capture emission from another waveguide, which is otherwise beyond the light cone that the microscope can capture [125].

optical waveguides into the structures, we created freestanding waveguides that can be optically positioned and oriented arbitrarily in the sample. The waveguide allows redirecting of the incident illumination and, at the same time, demonstrating a marked increase in the numerical aperture as well. In this example, the structure-mediated approach enables trapping from a relatively broad beam and then generating a more tightly confined light at its tip.

4. Conclusions and outlook

The development of intelligent and even humanoid and biologically-inspired autonomously functioning robots remains a driver of popular fascination in robotics. However, even human-controlled, non-autonomous robots that extend human ability can be practical in some applications. In surgical robotics, for example, a surgeon performs image-guided surgical operations using a control console that actuates non-autonomous robotic arms to enhance dexterity, stability and precision [190], which can even involve transatlantic separation between the surgeon and the operating table in robotic telesurgery [191]. Similarly, the optical actuation of synthetic microstructures helps extend human ability to access micro- and nanoscale domains and, hence, can be considered as gearing up for optical microrobotics.

Micro-/nanorobotics is an emerging field within mainstream robotics facing challenges that can require multidisciplinary approaches [4]. Although optical microrobotics has its share of scientific and technical challenges, the marriage of micro-/nanofabrication and optical manipulation can potentially give valuable contributions to the field. Optically controlled microstructures can be developed not only as microrobotic arms for mechanical manipulations, but also as controllable structures for targeted

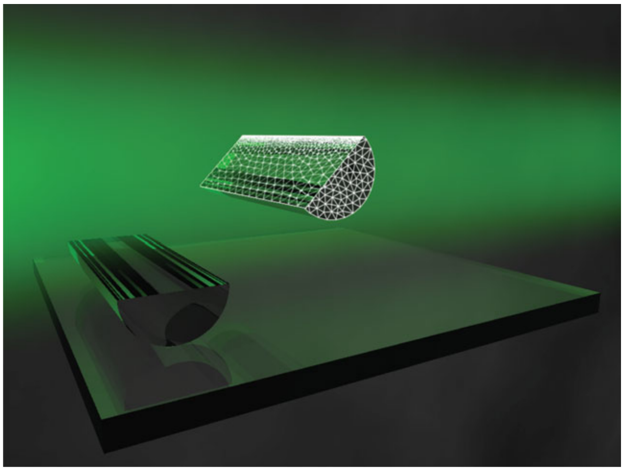

Figure 12 (online color at: www.lpr-journal.org) Microstructures with optimized internal topology for optimal light-matter interaction. (Image courtesy of A. Bañas).

delivery of optical energy. Various functionalization techniques can endow microstructures with sensing possibilities (e.g. [141], [192]). Even without functionalization, optically actuated microstructures can work as precision force probes upon proper calibration to account for the shape-dependent thermal fluctuations [56]. The calibration of structures consisting of microspheres joined by thin rods has been treated theoretically in [193] while more arbitrary structures have been numerically studied in [70, 194]. Aside from thermal fluctuations, the fluidic environment also leads to geometry-dependent hydrodynamic coupling between simultaneously manipulated structures [195]. As in conventional robotic manipulation systems, the use of feedback control can help stabilize optical manipulation systems [19–22] and similar solutions can be tested for mitigating hydrodynamic coupling effects.

One optimization target is to expand the range of achievable forces in optical manipulation. One approach is to utilize optical trapping handles that can efficiently convert the incident optical momentum flux to usable force such as antireflection-coated high-index materials [196]. Another promising approach, suggested in [197], is using topology optimization, which has been successful in various engineering disciplines ranging from optimizing the material distribution of an aircraft wing to the design of tiny microrobotic grippers [198]. A substantial amount of work has recently been focused on extending topology optimization to applications involving fluid flows and wave propagation in photonic crystals and meta-materials. The results often lead to surprisingly new designs of existing structures. When used together with modeling tools for optical manipulation systems, applying computational optimization techniques can help determine the optimal structural topology of the microelements for a given task or design. For example, to design optimal structures for optical lift (Fig. 12), one starts by defining the structural boundaries and then uses iterative computer-based optimization steps to improve the structural topology and gradually arrive at the optimal 'lightfoil' shape. This approach can arrive at a reasonably optimized structure for predetermined light illumination patterns. In general, however, optimization must explore all available design freedoms in both the material and optical fields to achieve the figure of merit that is demanded by the application such as strong optical force, torque, or light efficiency.

Owing to the nature of optical actuation, the two main aspects of microrobotics—i.e., micromanipulation and microfabrication—are highly intertwined for the case of optical microrobotics. Optical actuation is influenced not only by the properties of optical fields, but also by the properties of the fabricated microstructure and the micromanipulation environment. A general optimization strategy must jointly optimize the fields and the microstructures in a properly modeled manipulation environment. Hence, there is plenty of room for new and/or hybrid optimization methods that can address the actuation challenges to develop optical microrobotics systems that can enable new applications and carve a niche in science and industry. The development of intuitive and interactive control interfaces, such as game controllers, touchscreens, and force feedback haptic devices [61, 199, 200], should not be underestimated since it can contribute towards bringing optical robotics out of the developers' laboratories and into the hands of end users, which can then create synergy for stimulating further progress in the field.

Acknowledgements. We thank the Danish Technical Scientific Research Council (FTP) for financial support. We thank A. Bañas for rendering graphics in Fig. 12 using POVRay www.povray.org.

Received: 16 May 2012, **Revised:** 4 September 2012, **Accepted:** 7 September 2012

Published online: 31 December 2012

Key words: Optical trapping, microfabrication, microrobotics.

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