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Observation of optical guiding using thermal light

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Abstract
We report the use of light from a thermal source for optical guiding of microscopic particles. We demonstrate successful guiding of dielectric spheres using light from a high-pressure gas lamp shaped into an *ad hoc* Bessel wavefield with an enhanced transverse optical gradient and long focal depth. The broadband light source is spectrally characterized and potential applications of our observations are outlined.

Keywords: Bessel beam, optical tweezers, optical trapping

S Online supplementary data available from stacks.iop.org/JOpt/12/075702/mmedia

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The use of optical forces for the manipulation of microscopic objects [1] is currently a generalized tool with numerous applications in the study of the interaction of particles with electromagnetic fields [2]. Optical tweezers have been put to such diverse uses as transporting Bose–Einstein condensates over long distances [3], tracing the movements of induced knots along DNA strands [4], controlling the rotation of microscopic objects [5] and manipulating arrays of aerosol particles [6]. To date, a variety of light sources have been employed in optical manipulation experiments, including continuous-wave lasers [1], ultrashort laser pulses [7] and, more recently, supercontinuum laser radiation [8–10]. Despite their different spectral properties, light from all these optical sources possesses a high degree of spatial coherence by virtue of having originated in stimulated emission processes.

In this paper, we present the first experimental observation of optical guiding using a thermal light source *in lieu* of the traditional laser source. We show that dielectric particles can be effectively guided by appropriately shaping—both spectrally and spatially—a wavefield with practically no initial spatial nor temporal coherence, in contrast to using light from a laser source. Our observations represent an important contribution to the study of temporally incoherent light sources for use in optical manipulation, opening the possibility of guiding particles over extended distances at a reduced risk of radiation damage. Our results open up the prospect of simultaneous long-term confinement and interrogation in experiments that do not require stiff transversal forces, but where the use of low-coherence sources has proven advantageous, as is the case in incoherent photodynamic therapy of single cells.

2. Preliminary physical background

In this section we discuss briefly the advantages and disadvantages of using white light for optical manipulation. We then outline key characteristics of nondiffracting beams, particularly of the zeroth-order Bessel beam, that support our rationale for using them in our experiments.

2.1. Trapping with white light

Optical manipulation is possible due to the electromagnetic force associated with the gradient of an optical field, or the gradient force, as it is most often referred to. In a typical optical trapping set-up, the gradient force is achieved by tightly focusing a laser beam onto a sample using high numerical aperture (NA) microscope optics. The magnitude of the force that can be produced is determined by the resulting optical gradient at the focal plane, which is in turn limited, in the best-case scenario, by diffraction. In contrast, strong focusing of a broadband light beam results in the

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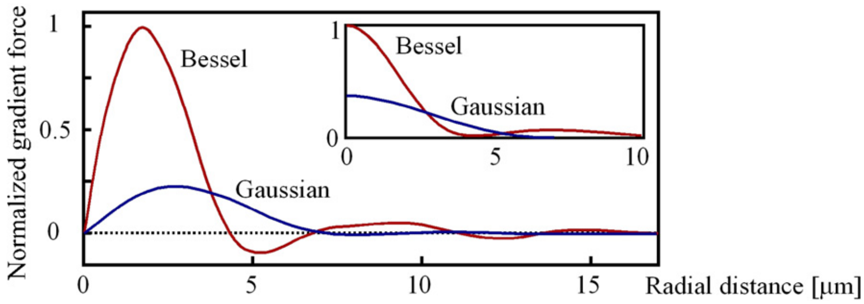

Figure 1. Gradient force for a scalar, nonparaxial zeroth-order Bessel beam (red line) and for a Gaussian beam (blue line) of identical spot size and fluence. Note that the force is significantly higher for the Bessel beam. The inset shows a comparison of the normalized intensities for both beams.

spreading of power along the optical axis due to material dispersion. As a consequence, each chromatic component of the wavefield results in a contribution to the gradient force shifted along the propagation axis, forming a longitudinally extended focal region. Under these circumstances, the magnitude of the scattering force associated with the wavefield becomes significant relative to the gradient force responsible for transverse optical confinement[1]. Furthermore, the large number of optical components in a corrected microscope objective results in a major insertion loss that becomes relevant at low light levels. Therefore, three-dimensional optical trapping with a broadband thermal light source may be difficult, if not impossible, to achieve using traditional high NA optics and a Gaussian wavefield. An efficient way to address these limitations of white light is to shape the transverse field of the trapping beam into a profile with increased transverse gradient so that particles under the influence of the beam migrate towards the paraxial zone by virtue of a washboard potential [11], where they are then guided downwards. The ideal candidate for this task is a zeroth-order Bessel field [12], which possesses a transverse gradient larger than that of a Gaussian beam of comparable spatial extent. Figure 1 shows a comparison of gradient force for a scalar, nonparaxial zeroth-order Bessel beam (red line) and for a Gaussian beam (blue line) of identical spot size and fluence. For the calculation of the forces we have assumed that particles are perfectly spherical and that their size is much greater than the wavelength of the optical fields such that the ray-optics approximation can be applied. The curves in figure 1 were calculated using the standard Mie theory where the trapping field is treated as a bundle of individual rays representing infinitely localized conduits of power, each with appropriate intensity, direction and state of polarization [13]. Since a zeroth-order Bessel beam can be readily produced by means of an axicon, insertion losses are significantly minimized in comparison to using multiple-element microscopy optics. Moreover, the inherently extended invariance length of Bessel beams, and in general, of all nondiffracting beams, represents an added advantage in particle guiding applications.

[1] Notice that every chromatic component produces a Bessel beam in slightly different positions and with different extents along the optical axis. Therefore, a small variation of the local value of the force as a function of the longitudinal coordinate should be expected.

2.2. Properties of the guiding wavefield

The zeroth-order monochromatic Bessel beam produced by an axicon of refractive index n and base angle α when a plane wave of wavelength λ impinges on its back aperture A is composed of a central maximum with spatial extent [14]

$$d \simeq \frac{2.405\lambda}{\pi \sin[\arcsin(n \sin\alpha) - \alpha]}, \tag{1}$$

surrounded by circular annular lobes of lower intensity. From (1), the transverse extent of the central spot for a fixed wavelength is entirely determined by the properties of the axicon alone, in contrast with a Gaussian beam where spot size is ultimately determined by the Gaussian beam waist. This fundamental difference is the key advantage of using a Bessel beam for optical guiding. For a constant fluence across A, the optical gradient in the vicinity of the central maximum depends on the axicon base angle and the amplitude of the plane wave, but not on the diameter of the collimated beam. The use of an axicon thus results in a higher optical gradient, regardless of the area of the incoming transverse wavefield. Certainly, diffraction imposes a limit to the minimum spot size that can be achieved in both cases. Note that illuminating a larger portion of the axicon increases the focal depth of the Bessel beam at the cost of energy being redistributed in multiple rings over a larger transverse distance. While an axicon can also exhibit residual material dispersion, an approach to compensate for the chromatic dispersion of the resulting beam has been successfully achieved by means of a prism [15]. Notice that, in the latter case, each chromatic component of the wavefield has an angular separation by virtue of the grating component encoded in the digital hologram, whereas in an axicon the separation is due to material dispersion.

3. Experiment and results

We have implemented an upright optical tweezers set-up to study the guiding of dielectric, microscopic particles under the influence of broadband light. For this purpose we have chosen to use the characteristic white light emitted from a high pressure, short arc xenon lamp (Perkin Elmer PE300BF) for its particularly wide spectrum spanning 0.75 μm, shown in figure 2(a). We have coupled the light from the lamp by

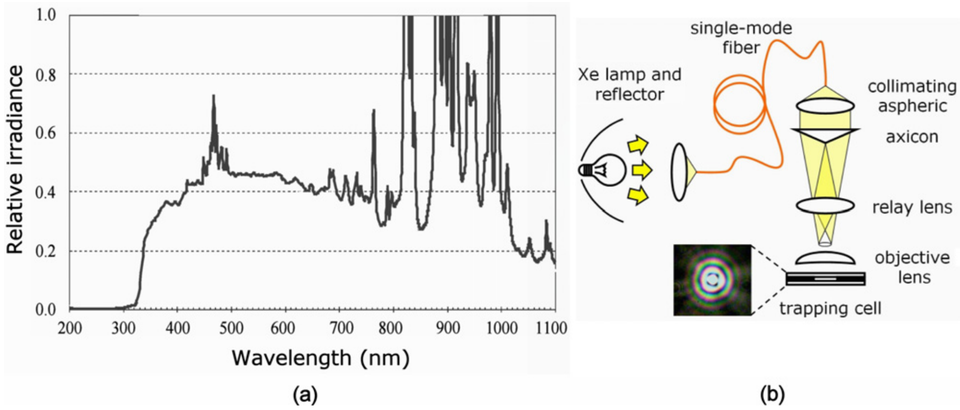

Figure 2. (a) Measured emission spectrum of the high-pressure Xe lamp. The optical bandwidth spans 750 nm across the visible (390–770 nm) and NIR (770–1100 nm), with 37% and 58% of the available optical power, respectively. (b) Experimental set-up for white light optical tweezers with zeroth-order Bessel beam.

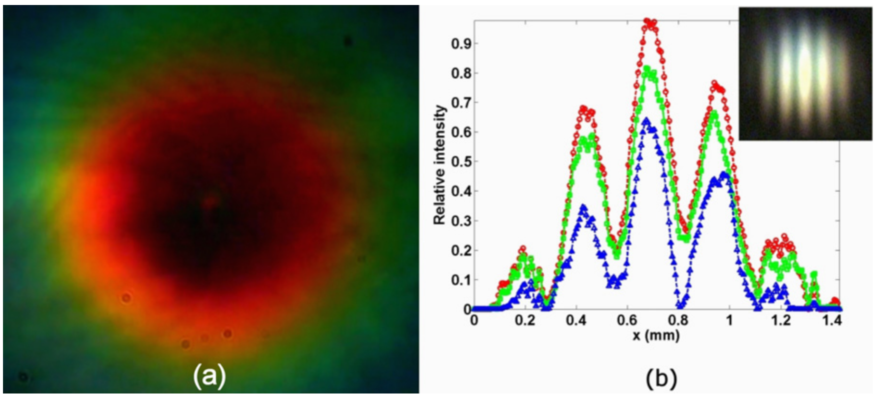

Figure 3. (a) Longitudinal evolution of the different chromatic components of the white light Bessel beam inside the trapping seen towards the vertex of the axicon (longer wavelengths are seen to form a Bessel beam further away from the axicon due to dispersion). Note the different radial frequencies present for different wavelengths. A slight diagonal transverse displacement of the intensity maxima corresponds to material dispersion in the optical path of the microscope imaging port. A movie version is available at stacks.iop.org/JOpt/12/075702/mmedia. (b) Spatial interference fringes from Young's interferometer for the Xe lamp. The red, green and blue plots correspond to 650, 550 and 450 nm, respectively. Measured visibility values were $\mathcal{V} = 0.60$ for $\lambda = 650$ nm, $\mathcal{V} = 0.52$ for $\lambda = 550$ nm and $\mathcal{V} = 0.83$ for $\lambda = 450$ nm.

means of an aspheric collimator into a single-mode optical fiber (Thorlabs P1-630A-FC-2) as shown in figure 2(b). The optical power launched into the fiber is an estimated 12% of the integrated radiant power (50 W) available from the lamp. Considering that the focused output at $f/1.0$ is specified by the manufacturer at 0.58, our relatively low coupling efficiency is due to the large numerical aperture mismatch between the fiber coupling optics and the parabolic reflector in the housing of the lamp, shown in figure 2(b). Although additional coupling optics could be employed, we have chosen to avoid the additional insertion losses involved with the use of further elements in the optical path of our set-up.

Light at the output of the fiber is collimated using a second aspheric lens. A Bessel beam is produced when the collimated light passes through a fused silica axicon with a 5° base angle (Altechna Co. Ltd). For this particular angle value, the field emerging from the axicon is best described by nonparaxial conical wavefronts that produce a highly localized central spot with size $d \simeq 6$ μm, for a central wavelength of 550 nm. An afocal system, formed by a relay lens and a large numerical aperture microscope objective, then relays the beam with a resulting radial period of 1.5 μm into a sample chamber imaged by an inverted microscope. The sample chamber is a cylindrical cavity 120 μm in height and 6 mm in diameter which contains a dilute solution of 1.5 μm monodisperse polystyrene spheres. The spheres are imaged by illuminating the sample with low-power diffuse light from a fiber illuminator so as to keep the external illumination from overcoming the beam profile. The longitudinal evolution of the beam can be monitored along the entire depth of the chamber when the external illumination is turned off, as shown in figure 3(a) and the accompanying movie available at stacks.iop.org/JOpt/12/075702/mmedia.

3.1. Spatial coherence of the light source

Beam shaping techniques using refractive optics assume full spatial coherence of the wavefield to be shaped. Emission from a gas discharge lamp, however, is of comparatively lower spatial coherence than laser light. The optical fiber in our

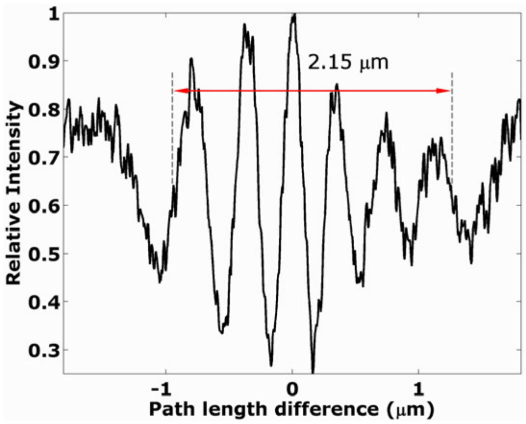

Figure 4. Time domain interferogram for the Xe lamp, FWHM is 2.15 μm. Significant side lobe amplitude shows the modulation of the spectrum and variability of the SNR at the detector across the source bandwidth. The skew in the interferogram is due to nonlinearity of the scanning velocity. The effective detection bandwidth of the photodiode is $\Delta\lambda = 400$ nm and is centered at $\lambda_o = 700$ nm.

set-up serves the purposes of transporting the light and increasing its degree of spatial coherence prior to shaping. We have assessed the spatial coherence of the light at the fiber output using a Young's interferometer and a CCD camera (Watec WAT-250D) fitted with interference filters to image and analyze the corresponding interferograms at different wavelengths, as shown in figure 3(b).

3.2. Temporal coherence of the light source

The Xe light source used in our experiments has a spectrum centered at $\lambda_o = 700$ nm and a spectral width $\Delta\lambda = 600$ nm FWHM, from where the coherence length can be estimated at $L_c = 0.81$ μm. We have verified the temporal coherence of the source using a scanning Michelson interferometer and an Si photodiode as a detector. The measured visibility of the temporal fringes is $\mathcal{V}_t = 0.61$ with FWHM $= 2.15$ μm as shown in figure 4(a). Despite the low temporal coherence of the source, previous work with broadband laser sources suggests that poor temporal coherence does not influence the trapping ability of the source, as optical guiding is an average power effect [8, 10].

3.3. Discussion

Particles within the sample chamber are observed to migrate progressively towards the central spot of the Bessel beam attracted by the transverse gradient force. Optimal transverse transit rates are achieved by adjusting the longitudinal position of the axicon [11]. After spontaneous migration towards the central maximum, particles are pushed by the downwards force due to radiation pressure once they reach the center of the beam, as previously reported in particle guiding experiments [8, 10]. In our case, radiation pressure is partially counteracted by the buoyancy of particles in the aqueous solution. Particles are easily guided in the direction of the propagation axis because the radiation pressure contribution of the wavefield source is more significant than its longitudinal optical gradient by virtue of the long invariance distance of the Bessel beam. This situation contrasts with the case of the longitudinal gradient associated with the beam waist of Gaussian beams. As a consequence, we have been able to successfully guide particles for a total length of 120 μm, which corresponds to the entire height of the sample chamber (see figure 5), whereas particles do not experience any ordered displacement nor confinement when under the influence of a Gaussian beam of equal spot size and fluence formed with the same source.

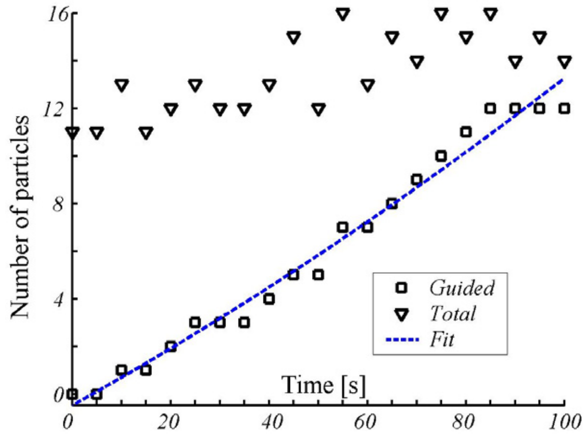

Figure 5. Particle transit towards the lower plane of the sample chamber. The squares represent guided particles over time.

Particles under the influence of the Bessel beam experience lower fractional force contributions per spectral bin when compared to a laser source. This feature of a thermal source represents a potential advantage for applications that require low radiation levels or are carried over long periods of time in the presence of radiation-sensitive species. Studies in photodynamic therapy, where the heating of specimens constitutes a serious problem, are a typical example of such applications [16, 17].

4. Conclusions

We have demonstrated optical guiding of dielectric particles using temporally incoherent light from a thermal source. We have used an axicon to sculpt the spatially filtered light into a beam with a transverse optical gradient larger than that of a comparable Gaussian beam and we have established that temporally and spatially incoherent light can be used for optical guiding provided that an adequate optical gradient is imprinted onto the trapping beam. We have characterized the light source and demonstrated that effective optical guiding is possible despite the low temporal coherence of the source. Our results open up the prospect of using thermal light for applications that do not require steep transverse confinement and where low fluence represents a major advantage, as is the case in cell-level photodynamic therapy, in which the effect of radiation damage over extended periods of time can be significantly minimized using low brightness sources.

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