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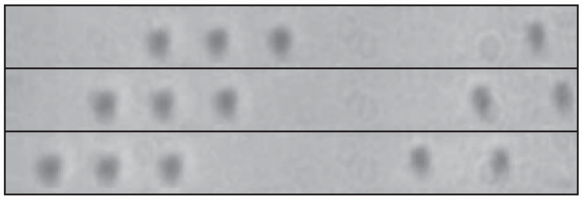
Abstract: We present a system employing a dynamic diffractive optical element to control properties of two counter-propagating beams overlapping within a sample chamber. This system allows us to eliminate optical aberrations along both beam pathways and arbitrarily switch between various numbers of laser beams and their spatial profiles (i.e. Gaussian, Laguerre-Gaussian, Bessel beams, etc.). We successfully tested various counter-propagating dual-beam configurations including optical manipulation of both high and low index particles in water or air, particle delivery in an optical conveyor belt and the formation of colloidal solitons by optical binding. Furthermore, we realized a novel optical mixer created by particles spiraling in counter-propagating interfering optical vortices and a new tool for optical tomography or localized spectroscopy enabling sterile contactless rotation and reorientation of a trapped living cell.



CP Bessel beams in a form of optical conveyor belt

The holographic optical micro-manipulation system based on counter-propagating beams

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1. Introduction

The geometry of two gently focused counter-propagating (CP) laser beams represents the first configuration ever used for stable three-dimensional confinement of micro-objects [1]. This scientific milestone, now called the dual-beam (DB) optical trap, was later simplified to the famous single-beam optical trap, commonly known as optical tweezers [2]. Whilst this single beam tweezers embodiment has had the strongest impact across the fields of colloidal science, molecular biology and many others [3–6], the original concept of CP-DB optical trap has sustained its popularity. A key advantage of this geometry can be seen in the possibility to use only moderately focused laser beams where lower optical intensity ensures safer optical trapping. Another advantage of this geometry, especially with respect to optical diagnostic techniques such as laser spectroscopy, microscopy or tomography, is the possibility to observe trapped objects perpendicularly to the optical axis of the trapping beams.

The original concept of the DB trap does not consider the interference of CP beams and only a single optical trap is expected. However in the case of coherent and interfering CP beams an array of optical traps is created along the beams propagation and so-called standing wave traps (SWTs) are created [7]. Due to the sub-micrometer dimensions of such an optical trap, SWTs are especially useful for the optical trapping of nanoparticles [8–10] and their

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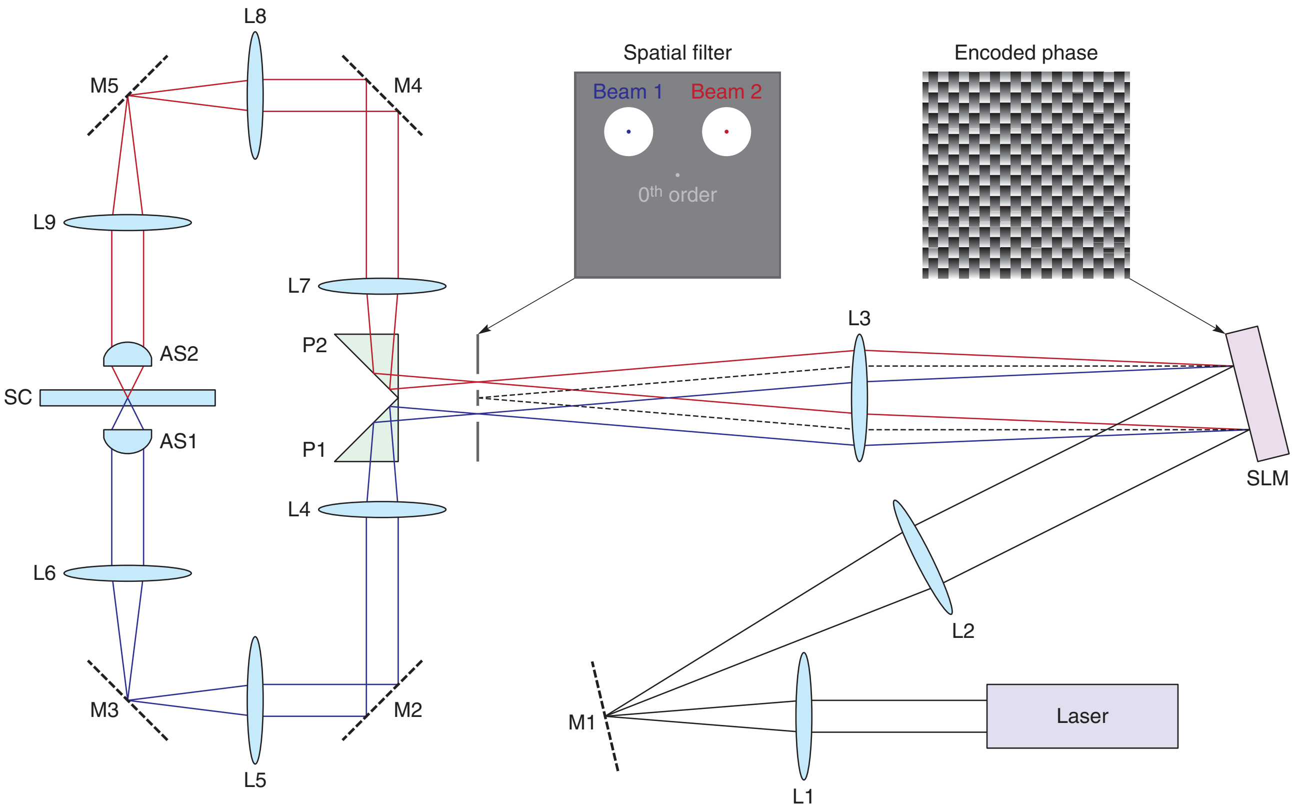

Figure 1 (online color at www.lphys.org) A collimated Gaussian beam from IPG ILM-10-1070-LP (wavelength 1064 nm) is expanded by the telescope made of lenses L1 ($f_1 = 150$ mm) and L2 ($f_2 = 300$ mm) and projected on the SLM (Hamamatsu LCOS X10468-07). Encoded phase at the SLM produces two light beams in the focal plane of lens L3 ($f_3 = 400$ mm) above the undiffracted zero-order light. Unwanted higher diffraction orders and the zero-order are blocked on a dual aperture spatial filter placed into a focal plane of L3. The first order diffracted beams are separated on prisms P1 and P2, sent in opposite directions and collimated by lenses L4 and L7 (both with $f_4 = 200$ mm), respectively. Each of the lenses L4 and L7 forms a telescope with L3 projecting the SLM plane on mirrors M2 and M4, respectively. The SLM plane is imaged onto the back focal plane of aspherical lenses AS1 (AS2) (both $f = 8$ mm) by a telescope consisting of lenses L5 (L8) ($f_5 = 100$ mm) and L6 (L9) ($f_6 = 150$ mm). AS1 and AS2 focuses both beams into a capillary (Vitrocells 8510) containing the sample (SC). A half-wave plate is inserted into one of the arms to control the polarization of the beam and thereby switch between the cases of interfering or non-interfering CP beams. To achieve sub-micron alignment precision and ensure stability of the system we omitted translational stages and properly placed the mirrors M2 and M4. This ensured lateral positioning of the focal points along the sample plane and the mirrors M3 and M5 to center the beams at the back aperture of the aspherical lenses

optical delivery by so-called optical conveyor belt [11–13]. Therefore, the geometry of two CP beams provides a universal tool for the optical manipulation of a wide range of particles sizes – from nanoparticles up to large particles of tens of micrometers [14].

To date, several concepts of DB traps were presented. The employment of single mode optical fibres [15, 16] makes this geometry very simple to use within a microscope sample and particularly amenable to a micro-fluidic environment [17,18]. Recently photonic crystal fibres have been employed to deliver multiple wavelengths into this type of trap [19] for interference free particle confinement. Other applications of the CP-DB trap include lab-on-a-chip systems [20,21], the optical stretcher for cancer diagnostics [17,22], Raman studies [23], or fundamental studies of optical binding [24–27]. CP geometries may also be employed in the generalized phase contrast trapping technique [28].

The methods of advanced and dynamic beam shaping using a spatial light modulator [29–33] or interferometric trapping [34–37] have extended the area of single-beam optical trapping towards generating hundreds of independently positioned optical traps (so-called holographic optical tweezers) or formation of complex optical potential energy landscapes rectifying stochastic motion of Brownian particles. These have led to extensive studies in the areas of colloidal science [38–40] and optical sorting [38, 41]. This includes the use of light fields such as Bessel beams [42, 43] or Laguerre-Gaussian (LG) modes [44] that have

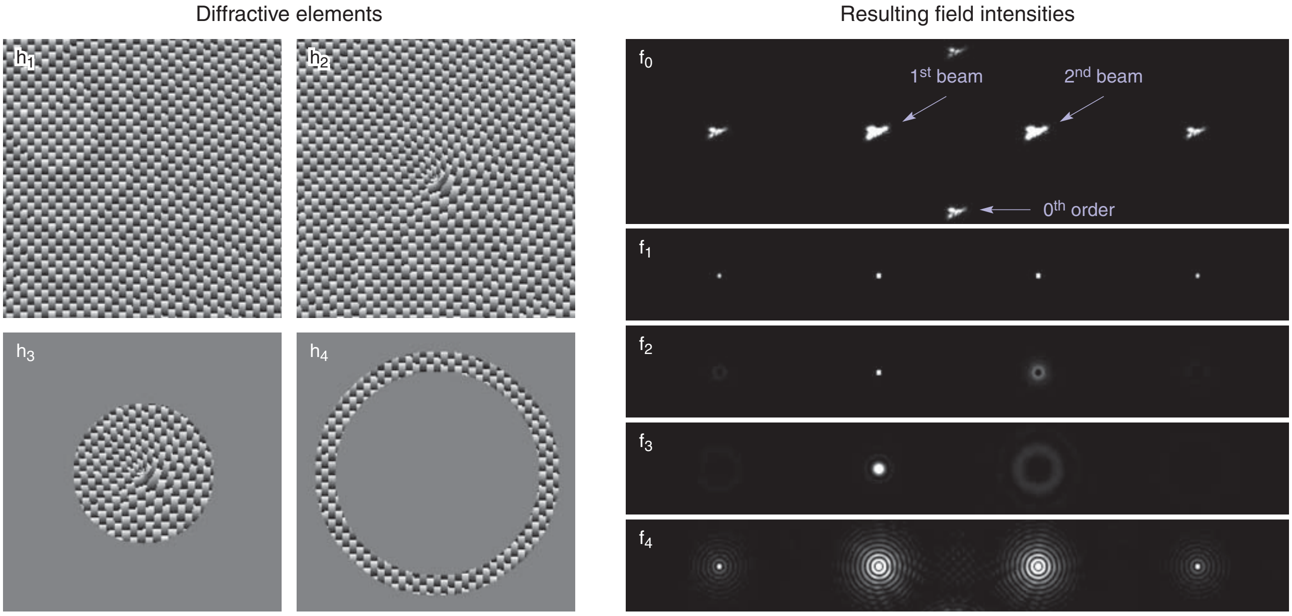

Figure 2 (online color at www.lphys.org) Demonstration of the interface possibilities. The left part shows the phase masks and the right part shows simulated intensity profiles of the beams at the plane of the spatial filter. f_0: original distribution of light using a simple phase grating without any correction as shown in Fig. 1. We indicate the positions of both desirable beams as well as the zero-order beam. Higher unwanted diffraction orders are clearly seen. h_1 shows central part of the used holographic element (1/9 of the whole area) and f_1 shows the corresponding intensity distribution after the wavefront correction. In the parts h_2 and f_2 an appropriate helical function has been added to the phase mask so that the right beam was converted to LG mode of azimuthal index of $l=5$. Following parts h_3 and f_4 illustrate the same case using narrower phase mask producing wider beams. An annular aperture filtering of the spatial spectrum by the phase mask results in the generation of Bessel beams shown in h_4 and f_4

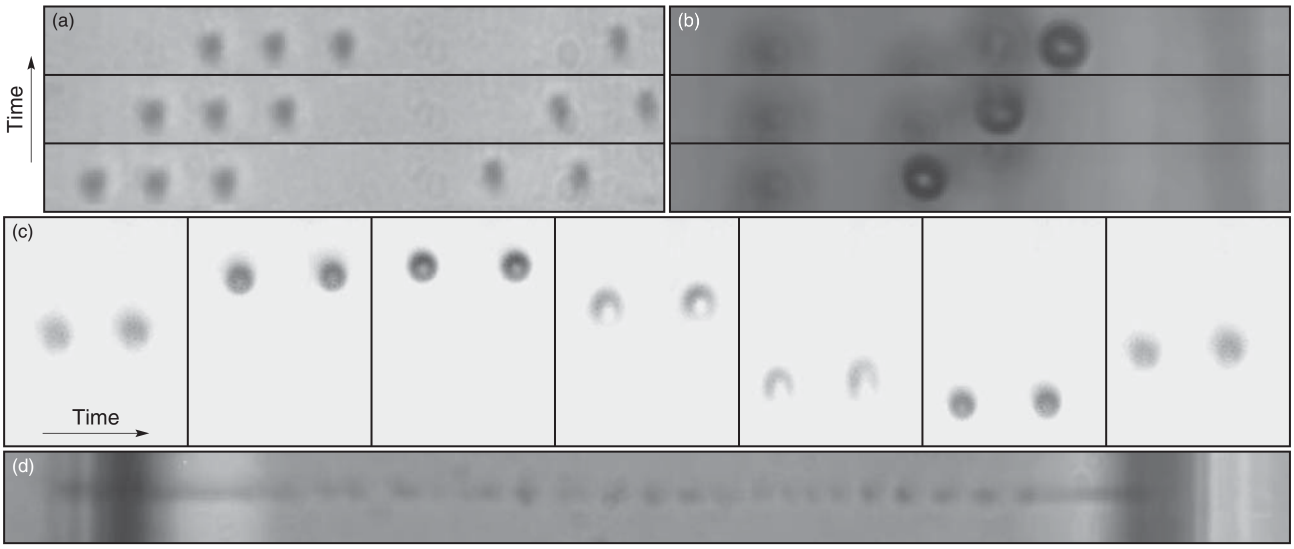

Figure 3 Demonstration of the system's flexibility: (a) – CP Bessel beams in a form of optical conveyor belt, (b) – manipulation of low-index hollow glass sphere with 10 μm in diameter in a system of non-interfering CP LG modes of $l=5$, (c) – polystyrene particles of diameter 1 μm revolving around optical axis under the influence of interfering CP LG beams with topological charges $l=\pm5$, and (d) – formation of "spatial solitons" in solution of polystyrene particles (600 nm in diameter) illuminated by non-interfering CP system of low NA Gaussian beams. See also movie at http://www.isibrno.cz/omitec/movies/fig3.mov

broadened the applicability of optical micro-manipulation techniques.

The ability to alter optical fields dynamically and introduce them within a CP DB geometry has, however, yet to be demonstrated. In this paper we present a holographic CP DB trapping system with the unique flexibility in delivering various non zero-order beam types, tailoring their parameters and show arbitrary switching between them within a given experiment. This opens up new vistas in this trapping geometry. As examples, we show for the first time three powerful new applications: Rotating a trapped cell along any axis which may be considered as a step towards full single cell optical tomography, confinement of large low-index particles, and rapid switching between different colloidal samples configurations based on the CP beams' properties.

2. Experimental geometry

Our novel CP optical trapping system employs a diffractive optical element that is imprinted on a single spatial light modulator (SLM) and dynamically addressed from a computer interface (Fig. 1). The system is based on a standard Fourier holographic encoding and spatial filtering of the beams in both CP arms and enhanced by a recently developed in situ wave-front optimization method [45] eliminating aberrations introduced in the optical pathways. We assumed that the sample capillary is symmetric and optical passage through each side of the capillary introduces equivalent aberrations to the propagating beam. We investigated the beams with and without the presence of the sample and minimized their focal spots imaged on a CCD camera. The averaged correction eliminates all aberrations introduced to the beam prior entering the sample and one half of aberrations introduced to the beam passing both its walls leading to optimal beam focusing inside the sample. The retrieved phase corrections obtained by this approach for both arms were used in all the further experiments. The phase masks for individual beams were evaluated independently by combining the particular phase corrections with linear and quadratic phase modulations (prisms and lens) determining the lateral and axial placement of the resulting focal spots in the sample, respectively. Additional helical masks and filtering of the spatial spectrum by circular apertures enable switching between Gaussian and vortex beams of various azimuthal index and beam waists in a controlled way. As all these modifications are pure phase functions, the resulting phase mask p modulating both beams simultaneously is obtained from the phase masks for individual beams p_1 and p_2 as:

$$p = \arg\left(e^{ip_1} + e^{ip_2}\right) .$$

Fig. 2 illustrates the generated beam profiles.

Finally, employing the algorithm of "superposition of prisms and lenses" [31], one can readily multiplex all the described modes and form various systems of parallel CP beams at the SLM frame rate. The trapping performance of the system was investigated with both interfering and non-interfering CP laser beams.

3. Examples of utilization

3.1. Standing wave trapping

Standing wave trapping is especially powerful for spatial confinement of nanoparticles in moderately focused laser beams. Here a Gaussian standing wave was created using CP interfering Gaussian beams with the maximal achievable numerical aperture NA = 0.5. To evaluate the optical trapping performance a fast CMOS camera (IDT X Stream VISION XS-3) acquired 50000 frames of confined polystyrene particle with 200 nm in diameter using 80 mW of laser output power. Boltzmann statistics distribution was fitted to the probability density of particle occurrence [3] to determine stiffnesses of the optical trap as $\alpha_\rho = 0.5$ pN/μm and $\alpha_z = 15$ pN/μm in radial and axial directions, respectively. Therefore, the particles are 30× better localized in axial direction comparing to radial one.

Single-beam optical trapping in air is more difficult than in liquid due to much higher contrast of refractive indices of the air and water. Therefore only a minority of reported optical micro-manipulation experiments have been performed in air (e.g. [46]). However, the DB configuration offers an excellent opportunity to confine particles in the air because the axial trapping is performed with the help of compensation of radiation pressure of both CP beams. Therefore, if the capillary was not filled with liquid but just air, the same setup was successfully used for the spatial confinement of polystyrene micro-particles delivered by air flow.

3.2. Optical conveyor belt

Introducing annular filtering at the SLM we converted the interfering CP Gaussian beams into *CP interfering zero-order Bessel beams*. Here the annulus radius at the SLM determines the propagation constant of the beams and the annulus thickness controls the axial range of the beam existence. Introducing an additional constant phase shift (piston) to the SLM mask we shifted the phase of one diffracted wave and thereby controlled the position of the nodes or antinodes of the resulting standing wave. By an SLM control of this phase shift we replicated the geometry of the optical conveyor belt [11] for bilateral particles transport along the optical axis between the walls of the sample (see Fig. 3a). Since no moving mechanical parts are used here, there exists no limitation for the extend of axial particles delivery when compared to other techniques using a movable mirror [11, 13].

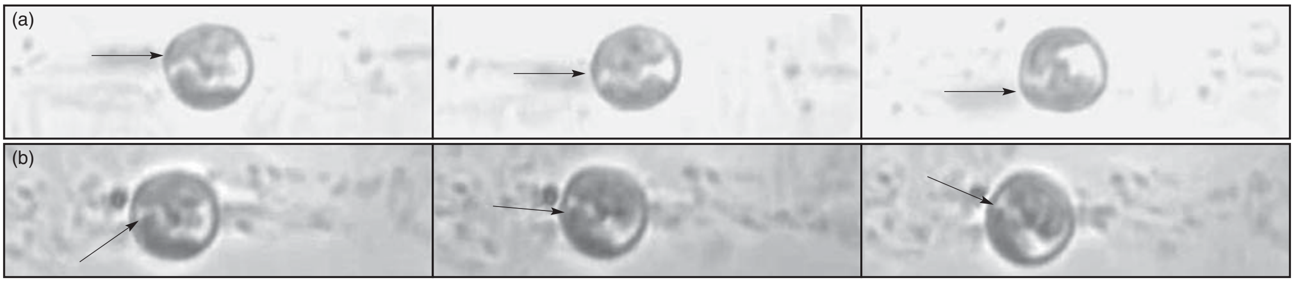

Figure 4 Alga *Trachidiscus minutus* reorienting using three pairs of CP Gaussian beams: (a) – the CP pairs revolve around the axis together with the trapped cell, (b) – the power balance between individual pairs of beams is altered to cause a torque acting upon the trapped object along any direction perpendicular to the optical axis. Arrows point to the same place of the organism. See also movie at http://www.isibrno.cz/omitec/movies/fig4.mov

3.3. Optical mixer

The addition of a helical phase component converts the Gaussian beams to annular LG modes with on-axis vortices that interfere in the CP geometry [47]. To date, such a geometry has been reported with sound waves [48] and for the guiding and trapping of carbon nanoparticles or their clusters in open air using photophoretic forces [49]. Here we present the first examples demonstrating behavior of optically confined micro-particles in a system of two *CP interfering LG beams*. The particles are held in the first high-intensity annulus of the vortex and due to the orbital angular momentum transfer move around its circumference (see Fig. 3c) if both CP vortices have opposite topological charge and form a toroidal train lattice [47]. In the ideal case there is no preferred azimuthal position of the particles and both particles shown in Fig. 3c should move independently. However, the light scattered between them leads to the so-called optical binding [27] and fixes their mutual position in the vortex during their orbiting around the beam axis. Such circular motion of micro-particles induces similar fluid flow in the formally static liquid and can serve as an "optical mixer". By switching the sign of the topological charge of one vortex a so-called twisted helical lattice is formed [47], however, the total orbital angular momentum is equal to zero. Consequently, the particles cease to move circularly and stay localized in the generated lattice.

The central intensity minimum in the vortex beam represents an optical force field offering a stable confinement of low index particles at the optical axis [50]. The system of *CP non-interfering optical vortices* allows stable 3-D confinement and axial transport of hollow glass microspheres shown in Fig. 3b.

3.4. Large-scale one-dimensional self-arrangement of micro-particles

Using *CP non-interfering Gaussian beams* we formed a 100 μm long stable chain of optically arranged particles along the whole sample extent between the capillary walls. This phenomenon is demonstrated in Fig. 3d and resembles the previously observed formation of spatial solitons in different experimental conditions [51, 52]. Their formation is the result of interplay between the optical forces pushing the particles to the places of the higher optical intensity and formation of colloidal waveguide. The concentration of particles is higher here and consequently the refractive index is higher, too. Therefore, a sort of colloidal waveguide is formed and it leads to consequent increase of the optical intensity at the core of this structure. These mentioned processes lead to interesting nonlinear optical phenomenon of colloidal suspensions when they behave as an artificial Kerr medium, i.e. the increase of the refractive index is proportional to the applied optical intensity.

Such structures can find practical applications in the visualization and mapping of the fluid flow. When the laser is switched off, the particles are released from the array and follow the streamlines of the fluid flow. Their video tracking provides an efficient method how to obtain the fluid velocity distribution.

3.5. Living cell manipulation

Advancements of the new system can be further extended by *multiplexing the CP pairs of beams* within the sample. Naturally, one has immediate access to parallelizing experiments simultaneously under the same conditions. The most important benefit of this, however, might be seen in the possibility to control the orientation of non-spherical objects or objects with heterogeneous internal structure, not limited to rotation along the optical axis [53]. Fig. 4 demonstrates this unique type of non-contact manipulation where we trap, rotate, and swing living alga *Trachidiscus minutus* in a system of three pairs of CP Gaussian beams thus making a major step towards full cell tomography and analysis in a CP trapping geometry.

4. Conclusions

We have presented a novel, universal, and flexible CP beam geometry for the optical trapping, delivery, guiding, orientation, and stretching of micro- or nanoobjects. The system is based on a single SLM controlled by a LabView interface with a software that enables online calculation of phase masks. These phase masks determine the parameters of each of CP beams such as beams widths, intensity, spatial profile and vorticity. We demonstrated that this concept is extremely versatile and does not require precise alignment of mechanical components [54]. We were able to replicate all known CP geometries within one experiment and we proved the highest degree of flexibility of this concept. It opens the way to various parametric studies of micro-particles behavior in different types of trapping beams and we have presented examples of system utilization to give a flavor of its possible applications. We demonstrated novel possibilities of optical manipulation including arbitrary reorientation of a trapped heterogenous object. Such a tool may open new vistas in combination with optical tomographic imaging of micro-objects [55–57], Raman micro-spectroscopy of several micro-organisms [58,59], imaging of laser-induced changes of scaffolds structure and micro-flows inside [60], or advanced optical microscopic or spectroscopic techniques using sequences or combinations of laser beams of different profiles [61, 62].

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