Optical trapping with superfocused high-M^2 laser diode beam

G. S. Sokolovskii[a], V. V. Dudelev[a], V. Melissinaki[b], S. N. Losev[a],
K. K. Soboleva[c], A. G. Deryagin[a], V. I. Kuchinskii[a,d], M. Farsari[b],
W. Sibbett[e], E. U. Rafailov[f]

[a]Ioffe Physical-Technical Institute, St. Petersburg, Russia
[b]IESL-FORTH, Heraclion, Greece
[c]St. Petersburg State Polytechnical University, St. Petersburg, Russia
[d]St.Petersburg State Electrotechnical University “LETI”, Saint Petersburg, Russia
[e]University of St. Andrews, St. Andrews, UK
[f]Aston Institute of Photonic Technologies, Aston University, Birmingham, UK

ABSTRACT

Many applications of high-power laser diodes demand tight focusing. This is often not possible due to the multimode nature of semiconductor laser radiation possessing beam propagation parameter M^2 values in double-digits. We propose a method of ‘interference’ superfocusing of high-M^2 diode laser beams with a technique developed for the generation of Bessel beams based on the employment of an axicon fabricated on the tip of a 100 μm diameter optical fiber with high-precision direct laser writing. Using axicons with apex angle 140^0 and rounded tip area as small as ~10 μm diameter, we demonstrate 2-4 μm diameter focused laser ‘needle’ beams with approximately 20 μm propagation length generated from multimode diode laser with beam propagation parameter $M^2=18$ and emission wavelength of 960 nm. This is a few-fold reduction compared to the minimal focal spot size of ~11 μm that could be achieved if focused by an ‘ideal’ lens of unity numerical aperture. The same technique using a 160^0 axicon allowed us to demonstrate few-μm-wide laser ‘needle’ beams with nearly 100 μm propagation length with which to demonstrate optical trapping of 5-6 μm rat blood red cells in a water-heparin solution. Our results indicate the good potential of superfocused diode laser beams for applications relating to optical trapping and manipulation of microscopic objects including living biological objects with aspirations towards subsequent novel lab-on-chip configurations.

Keywords: Bessel beams, laser diodes, superfocusing, optical manipulation

1. INTRODUCTION

Optical tweezer configurations (or laser-based gradient-force optical traps) have become powerful tools since their invention by Ashkin and co-authors few decades ago [1, 2]. Optical traps exploit the forces originating from the pressure of tightly-focused laser light. Given that a micrometer-sized living cell or dielectric particle located near the focus experiences a force that is proportional to the gradient of light intensity, this force can be sufficient to draw the trapped object towards the beam focus and (combined with light-scattering force and gravity) thus provides a stable trap position. Dynamical stability is typically ensured by viscosity of the fluid medium that damps oscillations.

The ability of optical tweezers to manipulate intact cells makes them useful for optical sorting of mixed colloidal particles and populations of living cells based on their size and refractive index [3, 4]. Optical tweezers have been used to probe the cytoskeleton, study cell motility and have enabled the targeted delivery of nanoparticles into a specified region of the interior of an individual living cell (so-called optical injection) [5]. Optical tweezers were used to resolve the step-like motions of motor proteins such as kinesin [6] and myosin [7] and for demonstrating the ability of such motors to advance for hundreds of steps [8]. However, the broader development of optical-tweezer-based techniques and related advances into the smaller research budgets and day-to-day applications are hindered by their cost that is largely dictated by use of expensive and cumbersome vibronic lasers in typical setups. Utilization of low-cost and efficient laser diodes for optical trapping and tweezing that might replace their gas and solid-state counterparts would have a major impact on future progress of this technology. However, such developments have to date been constrained either by the

Laser Resonators, Microresonators, and Beam Control XVII, edited by Alexis V. Kudryashov, Alan H. Paxton,
Vladimir S. Ilchenko, Lutz Aschke, Kunihiko Washio, Proc. of SPIE Vol. 9343, 93430Q · © 2015
SPIE CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2078957

poor beam quality of the broad-area multimode semiconductor lasers or by insufficient optical powers delivered by the single-mode laser diodes.

2. SUPERFOCUSING OF BEAMS WITH HIGH PROPAGATION PARAMETER M^2

In general, broad-area and/or higher-power laser diodes are prone to multiple transverse mode generation and filamentation that make it difficult to deploy these laser beams in applications that require tight focusing of the laser radiation. Such laser beams are typically described with the beam propagation parameter M^2 [9, 10] (often termed as beam 'quality' parameter) where M^2 is defined as the ratio of the given beam divergence to the divergence of an 'ideal' Gaussian beam (i.e., a beam with M^2=1), corresponding to the diffraction limit. Similarly, the parameter M^2 determines the ratio of the focal spot of the quasi-Gaussian beam to that produced by focusing the 'ideal' Gaussian beam by the same optical system. This parameter M^2 is useful because it facilitates a description for the quasi-Gaussian beams using the mathematical formulation developed for Gaussian beams. In this case, use is made of a simple replacement $\lambda \rightarrow M^2\lambda$, i.e., the wavelength is increased numerically M^2-fold. The typical values of the beam propagation parameter M^2 for high-power laser diodes are in double digits with figures normally in the 20 or 30 range. Therefore, the quasi-Gaussian beam emitted by such multimode semiconductor lasers has a focal-spot size typically one or even two orders of magnitude greater than the diffraction-limited value.

Fig.1 shows the calculated transformation of the Gaussian beam width ω during propagation along a z axis for two beams: the 'ideal' one with M^2=1 and the quasi-Gaussian beam with M^2=18. The scales are normalized to the diffraction-limited beam waist ω_0 and the corresponding Rayleigh range z_0. From Fig.1, one can easily see that focusing of multimode laser diode beams is probably the most significant problem that hinders the deployment of high-power semiconductor lasers in many spatially-demanding applications.

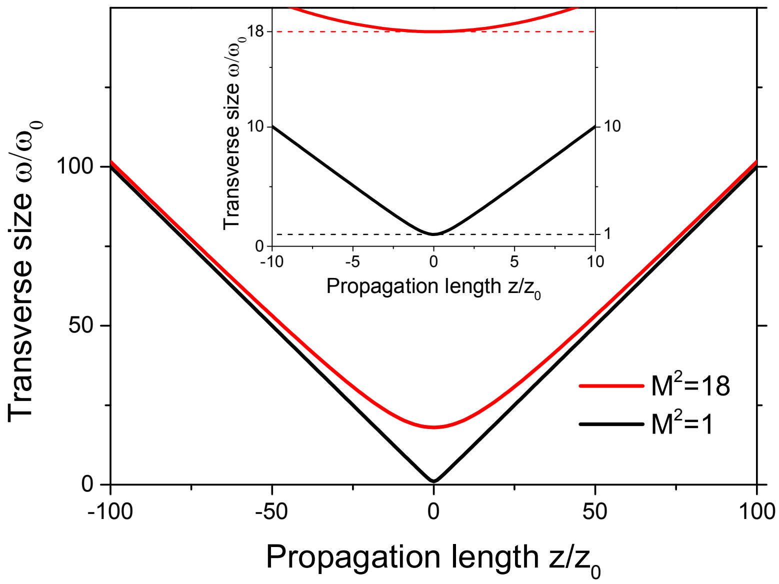

Figure 1. Calculated transformation of a Gaussian beam of width ω during propagation along the z axis for beams with M^2=1 (black) and M^2=18 (red). The scales are normalized to the diffraction-limited beam waist ω_0 and the corresponding Rayleigh range z_0.

Recently, the idea of 'superfocusing' for high-M^2 beams was proposed [11] and demonstrated experimentally [12]. Superfocusing relies on a technique developed for the generation of so-called Bessel beams from laser diodes using a cone-shaped lens (axicon) [13-16]. This type of non-diffracting beam (i.e. capable of retaining its intensity during propagation) was proposed by Durnin [17] and earlier by Zel'dovich et al. [18] and McLeod [19] and is so-called because the amplitude profiles can be described by a zero-order Bessel function of the first kind. In a projection onto a transverse plane (perpendicular to the propagation direction) such a beam appears as a bright spot surrounded by concentric fringes. Bessel beams are generated through the interference of convergent beams taking place when a collimated Gaussian beam transits a cone-shaped lens (axicon). The central lobe diameter of the Bessel beam is determined by the axicon apex angle and can be of the order of the optical wavelength. With traditional focusing of multimode radiation, different curvatures of the wavefronts of the various constituent modes lead to a shift of their focal points along the optical axis that in turn implies larger focal-spot sizes with correspondingly increased values of M^2. In contrast, generation of a Bessel-type beam with an axicon relies on 'self-interference' of each mode thus eliminating the underlying reason for an increase in the focal-spot size.

It should, of course, be borne in mind that there will be a gradual increase of the transverse size of the central lobe of the Bessel beam formed from a collimated multimode quasi-Gaussian beam during its propagation behind the axicon because of considerable divergence of the initial beam [20]. This limits the propagation length of the resulting quasi-Bessel beam. However, the primary size of the central lobe in the Bessel beam may actually be a few-fold smaller than the diffraction limit of the focal spot size of a quasi-Gaussian beam having a high M^2.

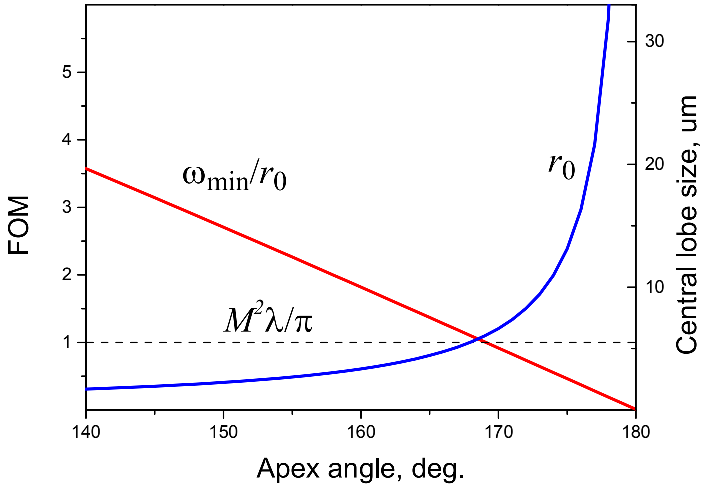

Figure 2. Figure of merit for superfocusing of the quasi-Gaussian beam with M^2=18 vs axicon apex angle (red) and the minimal central lobe size for the resulting Bessel beam (blue). The black dashed line indicates the minimum quasi-Gaussian beam waist size for M^2=18 and λ=960nm when focused with a lens of unity numerical aperture.

The figure of merit for such 'interference' superfocusing of a high-M^2 quasi-Gaussian beam was proposed as the ratio of the minimum quasi-Gaussian beam waist size when focused with a lens of a unity numerical aperture $\omega_{min}=M^2\lambda/\pi$ to the minimum central lobe size r_0 of the Bessel beam produced from the collimated quasi-Gaussian one:

$$FOM = \frac{\omega_{min}}{r_0} = \frac{2M^2}{\kappa}(n-1)\cos{}^{\alpha}\!/_{2} \approx M^2(n-1)\cos{}^{\alpha}\!/_{2} \tag{1}$$

where α is the apex angle and n is the refractive index of the axicon and κ=1.75 is dimensionless coefficient defining the size of the central lobe of the squared Bessel function at $1/e^2$ level of maximum [12].

Fig.2 shows a FOM for superfocusing of the quasi-Gaussian beam with M^2=18 vs axicon apex angle and the minimal central lobe size for the resulting Bessel beam for M^2=18 and λ=960nm. The black dashed line indicates the minimum quasi-Gaussian beam waist size when focused with a lens of unity numerical aperture. One can see that with such an 'interference' focusing technique an almost two-fold superfocusing is achievable with a 160^0 axicon and more than 3.5-fold superfocusing is possible for a 140^0 apex angle.

3. EXPERIMENT

In our earlier experiments we demonstrated optical trapping with Bessel beams generated from semiconductors lasers [20-22]. In this work we utilize a superfocused high-M^2 laser diode beam for optical trapping and manipulation of microscopic biological objects. When considering superfocusing of the high-M^2 beam with an axicon, account should be taken of the rounding of its apex because this defect is commonplace for all commercially available conical lenses. Typically, the radius of rounding is of the order of ~100 μm. The overall size of the rounded area can be less than 50 μm for any high-end conical lens, so its influence is not important for many applications or can be minimized by spatial filtering of the Bessel beam [23]. However, the rounding of the axicon apex compromises the axicon performance when used for superfocusing because it enlarges the minimum achievable size of the central lobe of the resulting beam [24]. It thus follows that the sharpness of the axicon tip is a crucial factor in any experimental demonstration of superfocusing [12].

The axicons used in the experiments reported here were fabricated by direct laser writing (DLW) using multi-photon polymerization [25] on the edge of an optical fiber with 100 μm core terminated with FC/PC fiber coupler. The experimental setup, specially adapted for fabrication on fiber, has been described previously [26]. A Ti:sapphire femtosecond laser beam (Femtolasers Fusion, 800 nm, 75MHz, <20fs) was focused into the photopolymer using a high numerical aperture microscope objective lens (40x, N.A. = 0.95, Zeiss, Plan Apochromat). The axicon was designed in SolidWorks® and sliced in 100 nm horizontal slices. Each slice was "written" into the photopolymer by moving the focused laser beam using a galvo-scanner (ScanLab), adapted for the microscope objective. Subsequently, the sample was lowered 100nm and the next slice was "written". The z-axis movement was achieved using a linear stage (Physik Instrumente) and the average power used for the fabrication of the axicon structures was 40 mW, measured before the objective, while the average transmission was 20%. The scanning speed was set to be 200 μm/s.

The fabrication of the axicon was done using an zirconium-silicon organic-inorganic hybrid composite [27]. Its main components are methacryloxy-propyltrimethoxysilane (MAPTMS), methacrylic acid (MAA) and zirconium *n*-propoxide (ZPO) 70% solution in 1-propanol. The molar ratios were 8:2 for MAPTMS/ZPO and 1:3 for ZPO/MAA. The photo-initiator used was 4,4-bis(diethylamino) benzophenone (Michler's ketone) at a 1% w/w concentration to the final solution. After DLW processing, the sample was developed and the material not exposed to the laser radiation removed by immersion in a 1:1 isopropanol/1-propanol solution.

All fiber microaxicons used in our assessments featured a sharp apex with less than 10 μm rounding area and apex angles of 140^0 and 160^0. The other end of the optical fiber was also terminated with FC/PC fiber coupler to eliminate unwanted wavefront distortions on the cleaved fiber tip. A typical image of the laser output superfocused with the microaxicon and registered with CCD camera is shown in fig.3. The diameter of the bright spot corresponding to the central lobe of the Bessel beam produced with the fiber microaxicon is approximately 4-5 μm. Given the wavelength λ=960 nm and the beam propagation parameter of M^2=18, the minimum achievable focal spot size $2\omega_{\min}=2M^2\lambda/\pi$ for such a laser beam focused with a lens of unity numerical aperture would be approximately 11 μm as indicated in fig.3 with red circle. Using axicons with apex angle 140^0 we could demonstrate laser 'needle' beams of 2-4 μm diameter with approximately 20 μm propagation length generated from the same multimode diode laser with M^2=18. This is almost an order of magnitude reduction compared to the minimum focal spot size that could be achieved if focused by an 'ideal' lens of a unity numerical aperture.

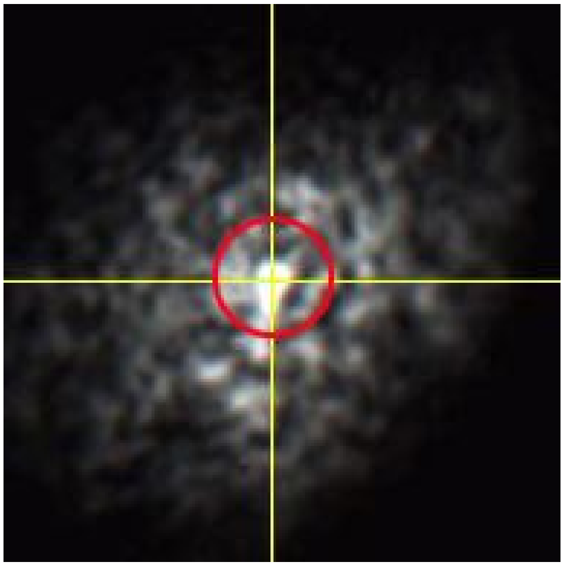

Figure 3. Cross-section of the multimode laser diode output superfocused with microaxicon with an apex angle of 160^0 fabricated on the edge of the optical fiber with 100 μm core terminated with FC/PC fiber coupler. The diameter of the central lobe is approximately 4-5 μm and, for comparison, the red circle indicates the minimum focal spot size achievable for such a laser beam with M^2=18 and λ=960nm if focused with an 'ideal' lens of unity numerical aperture.

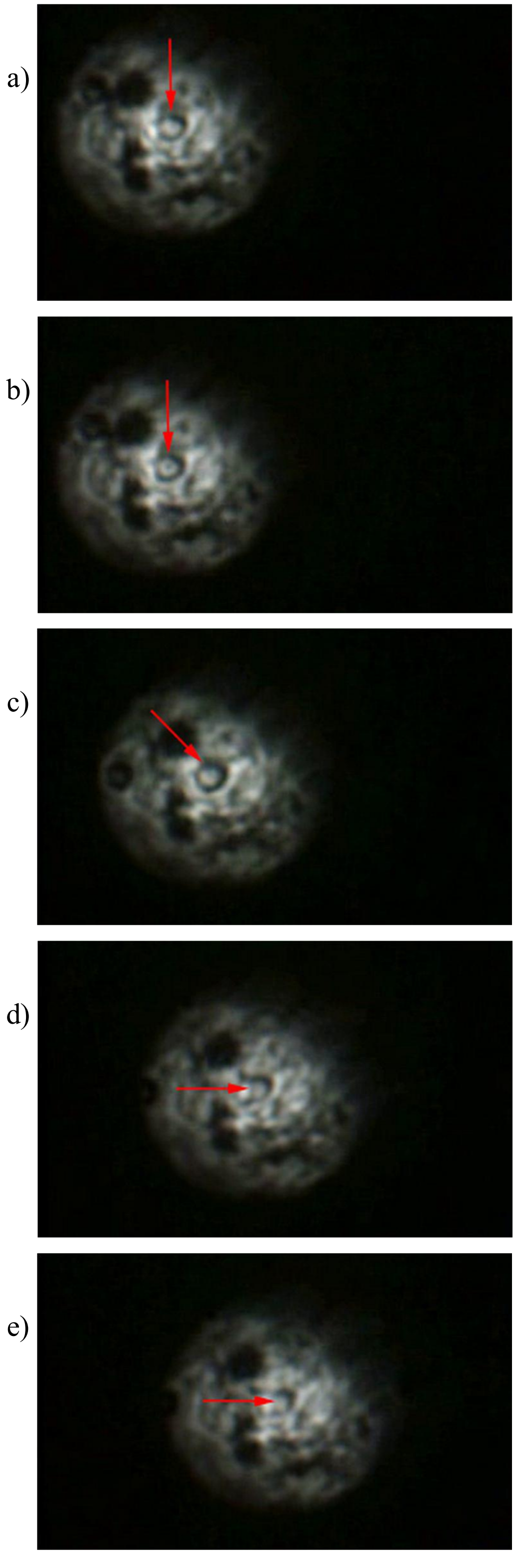

Figure 4. Optical trapping and manipulation of a red cell of rat blood with the superfocused beam of the semiconductor laser with M^2=18 emitting at the wavelength of 0.96μm. The arrows indicate the movement of the trapped object

The superfocused laser beam produced with the 160^0 microaxicon was utilized for the optical trapping of living red cells of rat blood. In this assessment, the blood was dissolved in water with addition of heparin to prevent clotting. The mean size of the cells was approximately 5-6 μm. Fig.4 shows a series of experimental images demonstrating the two-dimensional optical trapping and manipulation of a living red cell of rat blood with the superfocused beam from a high-M^2 semiconductor laser and the arrows indicate the movement of the trapped object.

These preliminary results demonstrate a very good potential for this superfocusing technique with high-M^2 laser diodes. As illustrated for the optical trapping and manipulation of biological micro-objects, this suggests that this approach bodes well for a range of 'lab-on-a-chip' applications.

4. SUMMARY

In this paper, we report the utilization of the superfocused radiation of semiconductor laser with beam propagation parameter $M^2=18$ for optical trapping and manipulation of the microscopic biological objects. The superfocusing was achieved with an 'interference' focusing technique similar to that developed for the generation of Bessel beams from laser diodes. It is based on a design involving an axicon fabricated on the tip of a 100um-diameter optical fiber. Using this technique, we demonstrated focusing of a 960 nm laser diode beam with $M^2=18$ down to a 4-5 micrometer-wide 'needle' beam, which is more than a two-fold reduction compared to the minimal focal spot size of ~11 μm that could be achieved if focused by an 'ideal' lens of unity numerical aperture. These results indicate the good potential of superfocused diode laser beams for applications relating to optical trapping and manipulation of microscopic objects including living biological objects with possible extension towards novel lab-on-chip configurations.

REFERENCES

[1] Ashkin, A., "Acceleration and Trapping of Particles by Radiation Pressure," Phys. Rev. Lett. 24, 156-159 (1970).

[2] Ashkin, A., Dziedzic, J. M., Bjorkholm, J. E., Chu, S., "Observation of a single-beam gradient force optical trap for dielectric particles," Optics Letters 11, 288–290 (1986).

[3] Ladavac, K., Kasza, K., Grier, D., "Sorting mesoscopic objects with periodic potential landscapes: Optical fractionation," Physical Review E 70, 010901 (2004).

[4] MacDonald, M. P., Spalding, G. C., Dholakia, K., "Microfluidic sorting in an optical lattice,' Nature 426, 421-424 (2003).

[5] McDougall, C., Stevenson, D. J., Brown, C. T. A., Gunn-Moore, F. J., Dholakia, K. "Targeted optical injection of gold nanoparticles into single mammalian cells," Journal of Biophotonics 2 12, 736-743 (2009).

[6] Svoboda, K., Schmidt, C. F., Schnapp, B. J., Block, S. M., "Direct observation of kinesin stepping by optical trapping interferometry," Nature 365, 721–727 (1993).

[7] Finer, J. T., Simmons, R. M., Spudich, J. A., "Single myosin molecule mechanics: piconewton forces and nanometre steps," Nature 368, 113–119 (1994).

[8] Asbury, C. L., Fehr, A. N., Block, S. M., "Kinesin moves by an asymmetric hand-over-hand mechanism," Science 302, 2130–2134 (2003).

[9] Siegman, A. E.,"How to (maybe) measure laser beam quality," OSA Trends in Optics and Photonics Series 17, (1998).

[10] ISO Standard 11146, Lasers and laser-related equipment – Test methods for laser beam widths, divergence angles and beam propagation ratios (2005).

[11] Sokolovskii, G. S., Dudelev, V. V., Losev, S. N., Deryagin, A. G., Kuchinskii, V. I., Sibbett, W., Rafailov, E. U., "Superfocusing of Mutimode Semiconductor Lasers and Light-Emitting Diodes," Tech. Phys. Lett. 38, 402-404 (2012).

[12] Sokolovskii, G. S., Melissinaki, V., Dudelev, V. V., Losev, S. N., Soboleva, K. K., Kolykhalova, E. D., Deryagin, A. G., Kuchinskii, V. I., Viktorov, E. A., Farsari, M., Sibbett, W., Rafailov, E. U., "Superfocusing of high-M^2 semiconductor laser beams: experimental demonstration," Proc. SPIE 9134 9134 1N, DOI: 10.1117/12.2052483 (2014).

[13] Sokolovskii, G.S., Dyudelev, V.V., Losev, S.N., Zolotovskaya, S.A., Deryagin, A.G., Kuchinskii, V.I., Rafailov, E.U., Sibbett, W., "Generation of propagation-invariant light beams from semiconductor light sources," Tech. Phys. Lett. 34, 1075-1077 (2008).

[14] Sokolovskii, G.S., Dudelev, V.V., Losev, S.N., Deryagin, A.G., Vinokurov, D.A., Lyutetskii, A.V., Pikhtin, N.A., Slipchenko, S.O., Tarasov, I.S., Zolotovskaya, S.A., Rafailov, E.U., Kuchinskii, V.I., Sibbett, W., "Study of non diffracting light beams from broad stripe edge emitting semiconductor lasers," Tech. Phys. Lett. 36, 9-12 (2010).

[15] Sokolovskii, G.S., Zolotovskaya, S.A., Losev, S.N., Dudelev, V.V., Deryagin, A.G., Kuchinskii, V.I., Sibbett, W., Rafailov, E.U., "High power Bessel beams from EP-VECSELs," Proc. SPIE 7919, 79190J, DOI:10.1117/12.877066 (2011).

[16] Sokolovskii, G.S., Butkus, M., Losev, S.N., Dudelev, V.V., Deryagin, A.G., Kuchinskii, V.I., Sibbett, W., Rafailov, E.U., "Non-diffracting beams from surface-emitting lasers" Proc. SPIE 8242, 82420T, DOI: 10.1117/12.907913 (2012).

[17] Durnin, J., "Exact solutions for nondiffracting beams. I. The scalar theory" J. Opt. Soc. Am. A 4, 651-654 (1987).

[18] Zel'dovich, B.Ya., Pilipetskii, N.F., "Pole lazernogo izlucheniya, sfocussirovanoe realnymi sistemami (in Russian)" Izvestia VUZov Radiophysics 9, 95-101 (1966).

[19] McLeod, J. H., "The Axicon: A New Type of Optical Element," Journal of Opt. Soc. Am. 44, 592-597 (1954).

[20] Sokolovskii, G. S., Dudelev, V. V., Losev, S. N., Soboleva, K. K., Deryagin, A. G., Fedorova, K. A., Kuchinskii, V. I., Sibbett, W., Rafailov, E. U., "Bessel beams from semiconductor light sources," Progress in Quantum Electronics, 38(4), 157-188 (2014).

[21] Sokolovskii, G. S., Losev, S. N., Soboleva, K. K., Dudelev, V. V., Deryagin, A. G., Sibbett, W.,Kuchinskii, V. I., Rafailov, E. U., "Manipulation of microparticles using bessel beams from semiconductor lasers," Tech. Phys. Lett. 40(6),495-498 (2014).

[22] Sokolovskii, G. S., Dudelev, V. V., Losev, S. N., Soboleva, K. K., Deryagin, A. G.,Kuchinskii, V. I., Sibbett, W., Rafailov, E. U., "Optical trapping with Bessel beams generated from semiconductor lasers," Journal of Physics: Conference Series 572, 012039 DOI:10.1088/1742-6596/572/1/012039 (2014).

[23] Brzobohaty, O., Cizmar, T., Zemanek, P., "High quality quasi-Bessel beam generated by round-tip axicon," Optics Express 16, 12688-12700 (2008).

[24] Sokolovskii, G. S., Dudelev, V. V., Losev, S. N., Butkus, M., Soboleva, K. K., Sobolev, A. I.,Deryagin, A. G., Kuchinskii, V. I., Sibbett, W., Rafailov, E. U., "Influence of the axicon characteristics and beam quality parameter M^2 on the formation of Bessel beams from semiconductor lasers," Quantum Electronics 43, 423-427 (2013).

[25] Malinauskas, M., Farsari, M., Piskarskas, A., Juodkazis, S., "Ultrafast laser nanostructuring of photopolymers: A decade of advances," Physics Reports 533, 1-31 (2013).

[26] Malinauskas, M., Zukauskas, A., Purlys, V., Gaidukeviciute, A., Balevicius, Z., Piskarskas, A., Fotakis, C., Pissadakis, S., Gray, D., Gadonas, R., Vamvakaki, M., Farsari, M., "3D microoptical elements formed in a photostructurable germanium silicate by direct laser writing," Optics and Lasers in Engineering 50, 1785-1788 (2012).

[27] Ovsianikov, A., Viertl, J., Chichkov, B., Oubaha, M., MacCraith, B., Sakellari, I., Giakoumaki, A., Gray, D., Vamvakaki, M., Farsari, M., Fotakis, C., "Ultra-Low Shrinkage Hybrid Photosensitive Material for Two-Photon Polymerization Microfabrication," ACS Nano 2, 2257-2262 (2008).