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Application of Bessel beams for ultrafast laser volume structuring of non transparent media

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Abstract

The use of ultrashort laser pulses has been shown to be an attractive option for high quality micromachining. In these applications low energy laser pulses are tightly focused to achieve high light intensities. While this approach has been demonstrated to be successful, its application is challenged by the short Rayleigh range of a tightly focused laser beam. Precise positioning of material samples becomes crucial imposing extra requirements on sample flatness, tilt, and irregularities. To overcome some of these limitations an application of non-diffractive Bessel beams for laser material processing has been attempted recently. The non-diffractive focus of Bessel beams can have the depth of field significantly longer than the Rayleigh range of a Gaussian beam of a comparable diameter. With sub mJ laser pulse energy the light intensity along the line focus can reach and exceed the required threshold levels making laser Bessel beams suitable for material processing. Preliminary numerical simulations show that truncated by a micron size aperture Bessel beam still has the propagation depth sufficiently long to be suitable for volumetric micro structuring of non transparent media. The paper aims to demonstrate feasibility of ultrafast laser structuring of non transparent media using Bessel beam focusing geometry.

Keywords: ultrafast material processing; micro structuring; Bessel laser beams

1. Introduction

Application of ultrafast lasers for material surface and volume micro- and nano- structuring has been an active area of research due to the variety of promising applications. With the recent development of reliable, compact, and easy to operate laser sources this technology becomes a serious competitor for conventional micro processing techniques. Femtosecond and picosecond lasers are used to process a broad variety of materials such as metals, glass, semiconductors, biological samples, etc. with very high degree of precision and reproducibility, and with minimized laser induced damage[1]. Although the physics of ultrafast ablation is quite complex, its characteristic feature is the presence of a well defined laser fluence threshold below which no ablation is observed[2]. Also the threshold effect is significant because it allows structuring over characteristic dimensions smaller than focusing spot

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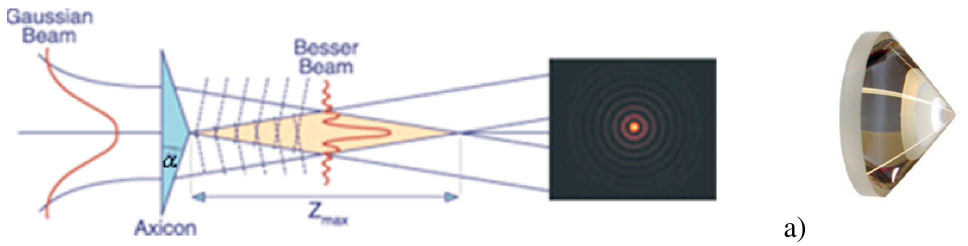
size[3]. While the laser ablation threshold depends on the processed material, its value typically lays in the range 1-10 J/cm^2. For a characteristic laser focal spot size of 1 μm, the required laser pulse energy is quite modest < 1 μJ and can be easily achieved / exceeded by modern ultrafast lasers. In this situation one of the major difficulties associated with the further development of micro- and especially nano- structuring technologies is precise laser beam - sample alignment. For the laser focal spot size of 1 μm the corresponding Rayleigh range of an ideal Gaussian beam will be only around 3 μm for λ = 1 μm. Small alignment tolerance imposes severe limits on sample tilt, flatness, and irregularities, especially for large (> 1 cm x 1 cm) samples and may require complicates positioning and monitoring setups. To overcome these limitations an application of "non-diffractive" or Bessel type beams for laser material processing has been attempted recently. The non-diffractive focus of a Bessel beam can have the depth of field significantly longer than the Rayleigh range of a Gaussian beam - up to tens of mm[4], potentially allowing significant relaxation of sample alignment and positioning tolerances.

The ideal zero order Bessel beams constitute a class of solutions to the Helmholtz wave equation with rotational symmetry and are invariant along the propagation direction[5]. Such idealized non-diffractive beams have infinite transverse extent and carry infinite amount of energy and, therefore, cannot be realized experimentally. However, over a limited spatial range, an approximation to such idealized beams can be obtained. These quasi-Bessel beams are shape invariant only for finite spatial extents and contain finite amount of energy. For such quasi-Bessel beams the transverse extent is limited by the finite input beam aperture, except for the case of ultrashort pulse where the diffraction free beam diameter is limited by the finite pulse duration. Commonly the quasi-Bessel beams are realized using Gaussian beams and therefore called Bessel-Gauss (BG) waves[6]. Experimentally Bessel-Gauss beams have been realized using a narrow circular slit illuminated with collimated light[7], reflective or refractive axicon conical lenses[8,9], and a spatial beam modulator[10].

An axicon is a conical lens used to create a non-diffractive Bessel-Gauss beam. A sample focusing setup using a refractive axicon is shown in Fig. 1.



a) b)

Fig. 1. a) Simplified ray tracing of a refractive axicon lens; b) an axicon lens can be completely characterized by the substrate material index of refraction, base angle α, lens diameter, and base thickness. The extent of the diffraction free zone is linearly proportional to the input laser beam diameter

In the most simple but very important case of axicon focusing of a non diverging Gaussian beam, the intensity profile of the generated Bessel-Gauss beam is given by

$$I(r,z) = 2\pi k(\tan^2\alpha)(n-1)^2 z I_0 e^{-2((n-1)z\tan\alpha/w_0)^2} J_0^2(k(n-1)r\tan\alpha) \qquad (1)$$

Where r and z are the radial and longitudinal coordinates respectively, I_0 is the incident on-axis intensity, w_0 is the incident beam waist, $k = 2\pi/\lambda$, n is the glass refractive index[11]. The FWHM length of the axicon diffraction free zone L and the radial position r_0 of the first zero of the transverse field distribution are given by the following equations:

$$L \approx \frac{0.8w_0}{(n-1)\tan\alpha} \qquad (2)$$

$$r_0 = 2.4048/(k(n-1)\tan\alpha) \qquad (3)$$

Several conclusions can be immediately derived from these equations:

- Axicon generates diffraction free line focus of finite extent with on-axis maximum;

- The length of axicon diffraction free zone can be substantially longer than the confocal parameter (doubled Rayleigh range) of a Gaussian beam;
- The transverse dimension of on-axis intensity peak can be comparable to λ;

Another interesting property of an axicon generated Bessel-Gauss beam is the following: if the peak of on-axis laser intensity of a BG beam is kept at a constant value than the relationship between the length of the diffraction free zone and the laser pulse energy will be linear, allowing simple process scaling. For example, to achieve characteristic on-axis peak laser fluence of $30J/cm^2 \approx \frac{1\mu J}{\pi(1\mu m_{FWHM})^2}$ and 10X elongation of the Rayleigh range over a 1 µm FWHM Gaussian beam, the laser pulse energy should be approximately 5 µJ (for 20X elongation the pulse energy should be 10 µJ) for 25° axicon. While the relative increase of the required laser energy is quite substantial, the absolute laser pulse energies are easily achievable by modern ultrafast lasers at repetition rates suitable for industrial micromachining applications.

In micromachining, the application of BG beams has been relatively limited so far. Femtosecond Bessel-Gauss laser beams have been used to write low loss 1 cm long waveguides within bulk SiO_2 and BK7 glasses via direct modification of the refractive index[12] and to nano structure glass surfaces[13]. In the later work almost identical surface structures have been produced while the sample is longitudinally translated over 20 microns. The working distance for the corresponding Gaussian beam is estimated to be only 2.35 µm. It is important to note that the secondary maxima of Bessel beams can also interact with a sample, especially in linear regime. For ultrafast laser processing, when samples are structured in nonlinear mode, the undesirable structuring due to the secondary maxima can be negated if the intensity of diffraction rings is kept under the ablations threshold.

While Bessel-Gauss beams have been successfully used for micromachining of glasses, it is conventionally assumed that their application for volumetric structuring of non transparent media is limited due to their interferometric nature. However, Kohno *et al*[14] reported through drilling of 100 µm non transparent austenitic stainless steel (SUS304) plates using the second harmonic of 10 ns Nd:YAG laser. Diameter of the almost straight hole was approximately 5 µm giving the remarkably high aspect ratio of 20:1. Also blind drilling of silicon wafers was demonstrated by the same research group. The paper aims to investigate the feasibility of ultrafast laser drilling / deep structuring of various media using Bessel-Gauss beams.

2. Propagation model and results of simulations

As a first step to study feasibility of ultrafast laser drilling using Bessel-Gauss laser beams we have developed an EM model to simulate propagation of a BG beam obstructed by a 3D object using RF module of COMSOL simulation software. The model solves electro-magnetic Maxwell equations for a specified spatial geometry and boundary conditions. In this model, a continuous wave Gaussian laser beam is spatially reshaped using a refractive axicon lens to form Bessel-Gauss beam (Fig. 2a) and the central maximum of the beam is directed into a preformed hole. The hole, made in the material of interest such as glass, metal, and semiconductor, has the transverse radius matching the first zero of the BG beam intensity distribution (1.5 µm) and its depth is considered to be infinite. The laser wavelength is 1.064 µm and the laser beam intensity is kept at a low level to make any nonlinear propagation effects negligible. Also, laser matter interaction processes are omitted. For comparison, similar simulations are performed using conventional focusing geometry of Gaussian beams (Fig. 2b), the focal spot size is 0.8 µm 1/*e* radius. To reduce the calculation time the simulations are performed in 2D geometry assuming cylindrical symmetry in the beam propagation, the computational mesh size of 0.1 µm is sufficiently small to sample sinus wave. The overall spatial dimensions of the mesh are limited by the available computational power.

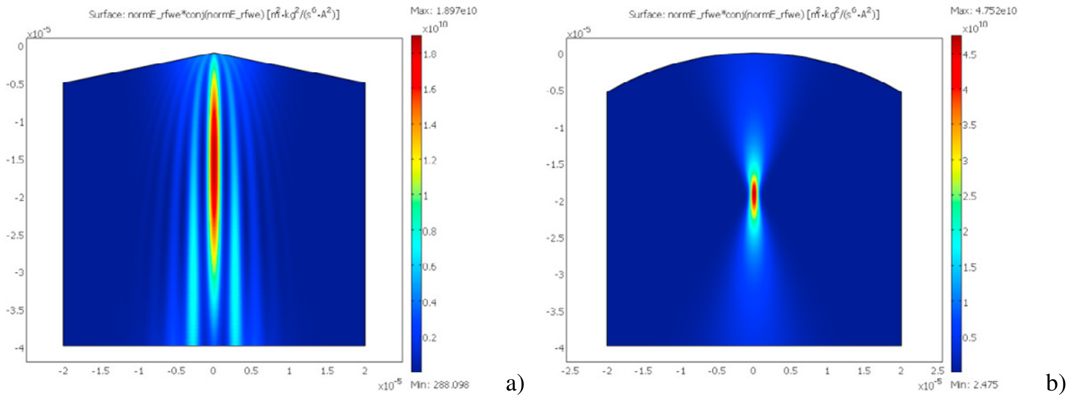


Fig. 2. EM simulations of stationary unobstructed Bessel-Gauss a) and Gaussian b) laser beam intensity distributions

The proposed model attempts to mimics propagation of a Bessel-Gauss laser beam in a self-drilled hole in bulk material. While the presented model is definitely an oversimplification of the ultrafast laser drilling process and does not take into account numerous important issues such as nonlinear interaction processes, nonlinear propagation effects, and temporal propagation dynamics it can address the important question of Bessel-Gauss laser beam penetration depth and can provide comparison with the penetration depth of a conventional Gaussian beam of similar transverse extents. The results of simulations for Bessel-Gauss and Gaussian laser beams propagating inside predrilled hole in bulk aluminum (complex index of refraction n_{Al} = 1.37+10.2i), silicon (n_{Si} = 3.56+0.009i), and fused silica (n_{FS} = 1.45) are presented in Fig. 3. The absolute values of the refractive indices are taken from[15].

It should be noted that the clearly observable interference pattern in the Bessel-Gauss laser beam stationary intensity distribution (Fig.3) above the sample surface is due to the back reflection of the laser radiation. The modulation depth (*md*) of the intensity oscillations approaches 0.8 for the highly reflective aluminum surface and correspondingly reduces in the case of less reflective silicon (*md* ~ 0.5) and transparent glass (*md* ~ 0.15). In the case of femtosecond laser micromachining with the typical laser pulse duration of τ ~ 150 fs the interference effects should be diminished due to the strong spatial confinement of the laser pulse $c\times\tau$ ~ 45 µm, where c is the speed of light.

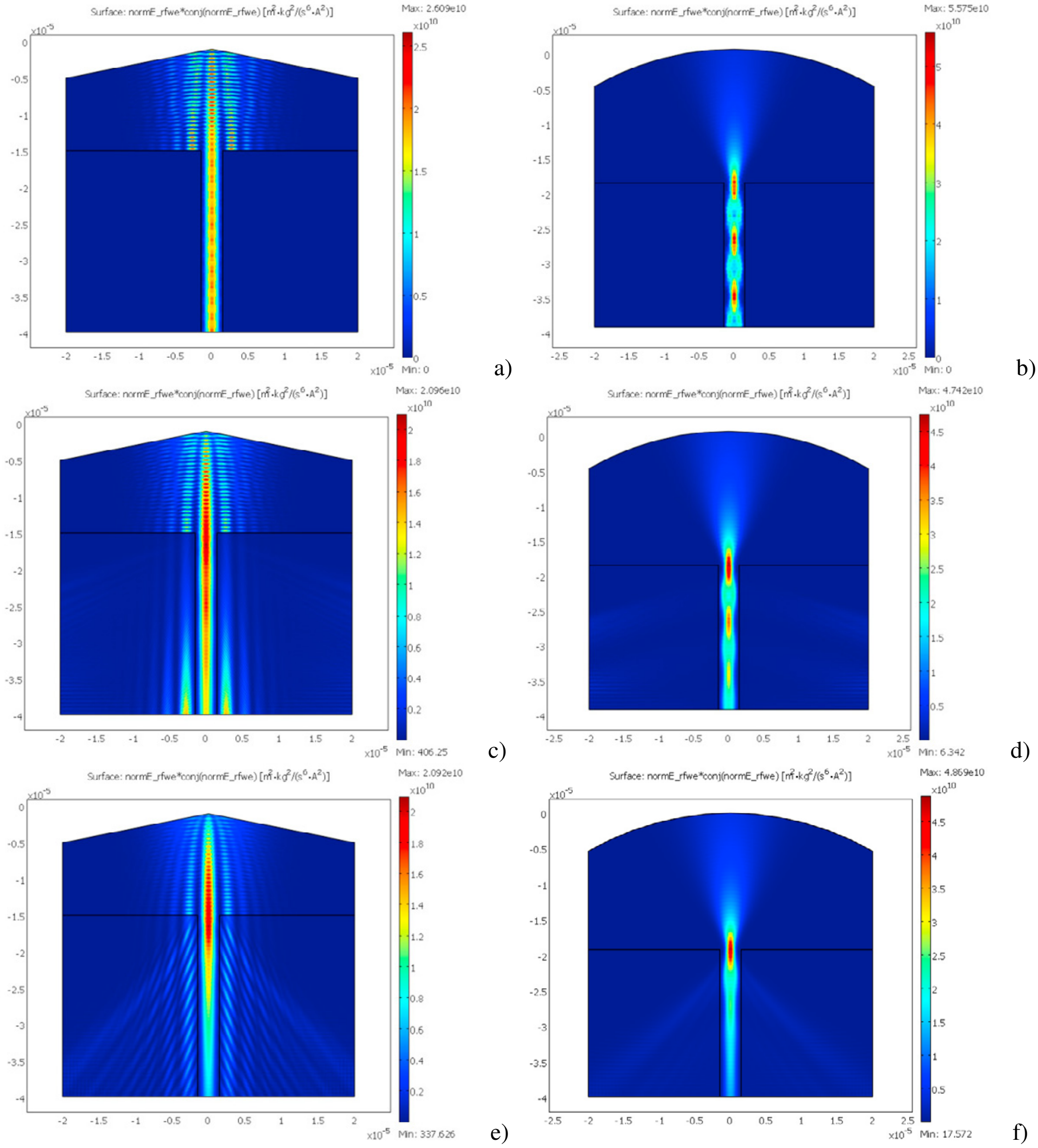


Fig. 3. The simulation results for Bessel-Gauss (left column) and Gaussian (right column) stationary laser beams propagation inside predrilled hole in bulk aluminum (upper row), silicon (middle row), and fused silica (bottom row). The laser wavelength $\lambda = 1.064$ µm, the hole diameter is 3 µm

Several important conclusions can be drawn from the presented simulations.

First, the penetration depth of the Bessel-Gauss beam inside the prefabricated infinite holes is substantially longer than can be predicted from geometrical optics analysis. In the later case, the penetration depth is determined only by the hole radius and the ray approaching angle. For the considered geometry, the geometrical penetration depth is estimated to be only 6 µm or only twice longer than the hole diameter, while the wave propagation model predicts the penetration depth of the Bessel-Gauss beam to be noticeably more than the doubled hole diameter with the exact elongation factor being dependent on the ambient medium. The mismatch between the geometrical optics results and the results produced by the EM model cannot be considered unexpected since the characteristic problem dimensions are comparable to the laser wavelength and correspondingly the wave effects cannot be ignored and must be accurately taken into consideration.

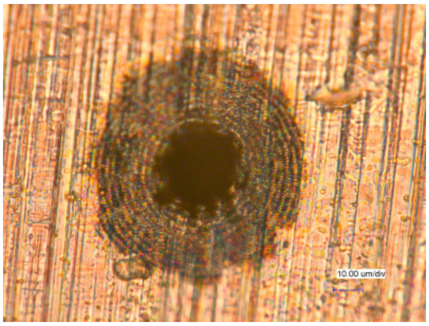
Second, the laser beam propagation cannot be considered independently from the ambient medium. Metal and semiconductor materials clearly demonstrate important guiding effect that strongly influences the penetration depth of the laser beam. Hollow metal waveguides are extensively used for guiding microwaves but apparently they can also enhance laser beam propagation as it can be seen from Fig. 3 (a, b,). It should be noted that the guiding effect itself is the property of ambient material not the laser beam focusing geometry. At the same time the exact mode distribution within the waveguide is the combinational effect of the surrounding medium, waveguide geometry, and the input laser beam mode.

Third, the propagation behavior of the Gauss and Bessel-Gauss beams inside the hollow waveguide structure is completely different as it can be seen from the simulations and this difference is especially apparent in Fig. 3a and 3b. According to the simulation results, the Gaussian beam goes through periodic focusing and defocusing inside the preformed hole (Fig. 3b) with the corresponding increase and decreased in the on-axis laser beam intensity. For the given example, the difference between on-axis maxima and minima is approximately a factor of 5. This oscillatory behavior of the laser beam on-axis intensity inside metallic structure cannot be observed experimentally during ultrafast laser drilling process because the first defocusing of the laser beam will lead to significant drop of the peak laser intensity, corresponding arrest of the ablation, and effectively termination of the drilling process since the laser beam cannot propagate further. In the case of Bessel-Gauss laser beam propagation inside preformed hole in bulk metal (Fig. 3a), the oscillatory behavior is also noticeable but the amplitude of the intensity variation is substantially smaller - on the level of 10 % or less. This allows maintaining almost constant on-axis laser beam intensity (as well as laser beam transverse profile) along the propagation direction independently on the penetration depth assuming no laser beam absorption occurs. This beam propagation mode is advantageous for the ultrafast laser drilling since it should preserve uniform laser beam intensity even inside the processed hole. We believe that numerically observed "guided non-diffractive" propagation of laser Bessel-Gauss beam inside preformed circular hole can explain the experimental results reported by Kohno *et al* for high aspect ratio drilling of 100 µm thick steel foil with the opening orifice diameter of only 5 µm. The observed experimental results are in good qualitative agreement with the presented simulations.

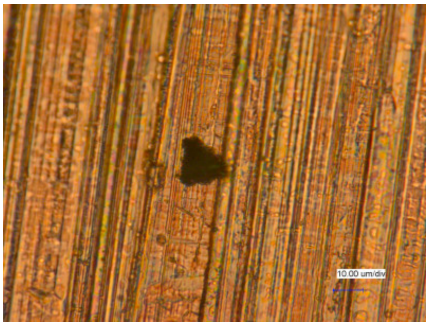
The Bessel-Gauss laser beam also demonstrates much deeper penetration depth and less oscillatory behavior in the case of semiconductor substrate (Fig. 3c), compared to the conventional Gaussian beam behavior (Fig. 3d). For the dielectric material (glass) elongation of the penetration depth for Bessel-Gauss beam is less drastic but still quite noticeable.

3. Experimental results

Prove of principle ultrafast laser drilling using axicon lens has been demonstrated using commercial diode pumped solid state laser with pulse duration 10 ps, laser wavelength 1064 nm, 50 kHz repetition rate, and 170 µJ pulse energy (Duetto laser, Time Bandwidth Products, Switzerland). The input Gaussian beam (M^2 < 1.25) is reshaped to Bessel-Gauss beam using 130^o base angle 1 inch OD axicon lens (Altechna Co., Lithuania) similar to one shown in Fig. 1a. In this focusing geometry the diameter of the first zero intensity ring is calculated to be 3.9 µm, the radial separation of the sequential zero intensity rings is calculated to be approximately 3.1 µm, and the geometrical extent of the diffraction free zone is estimated to be on the order of 5 mm. 100 µm thick copper foil has been position within the diffraction free zone 3 +/- 1 mm away from the axicon apex. Fig. 4 shows sample images of laser drilled penetration hole.



a)



b)

Fig. 4. Optical microscope images of entrance (a) and exit (b) holes drilled in 100 μ m thick copper plate using 10 ps laser pulses and axicon focusing lens. The entrance hole diameter is under 20 μm, the exit hole characteristic dimensions are on the order of 15 μm

The entrance orifice appears to be quite round with relatively good edge quality and the corresponding average diameter of 20 μm. The shape of the exit orifice normally deviates from circular, as it can be seen in Fig. 4b. Also its characteristic size is slightly smaller with the typical characteristic dimension being on the order of 15 μm indicating that the produced hole is slightly tapered. On average, we estimate the aspect ratio of the laser drilled penetration hole to be better than 1:5.

It should be noted that sample structuring with higher order intensity peaks is quite apparent. This fact explicitly indicates that the laser beam intensity is above the ablation threshold not only for the central lobe but also for several secondary intensity maxima and should be decreased to reduce the affected area. Apparently the laser drilling has been performed not only by the central lobe but also by several most central secondary rings (two or three central rings) resulting in larger than expected hole diameter. By reducing the laser pulse energy much smaller diameter (6-7 μm) blind holes have been drilled in the same copper foil and silicon wafers with only single secondary maximum apparent.

4. Conclusion

In conclusion, we have numerically demonstrated that the penetration depth of a Bessel-Gauss laser beam propagating inside a hole in bulk material cab be substantially longer than the penetration depth achievable by a conventional Gaussian beam of comparable transverse dimensions. This effect is observed for different type of ambient materials such as metal, semiconductor, and glass. The laser beam confinement is especially obvious in the case of metal substrate and can be potentially utilized for ultrafast laser drilling.

High aspect ratio penetration holes have been produced with ultrafast high intensity Bessel-Gauss beam experimentally verifying feasibility of the proposed structuring method. Further theoretical and experimental research work is required in order to improve structuring quality, aspect ratio of drilling, and to establish method's applicability for other materials.

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