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Generation of ultrafast Bessel micro-beams and applications to laser surface nanoprocessing

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ABSTRACT

The novel propagation characteristics of Bessel beams have been widely applied to optical manipulation and harmonic generation, and have provided new perspectives on fundamentals of ultrashort laser pulse propagation in nonlinear media. Fully exploiting their many unique properties, however, requires the development of techniques for the generation of high quality Bessel beams with flexible adjustment of the beam parameters. Moreover, long working distances are needed to produce Bessel beams inside bulk samples. In this paper, we report on the development of a novel spatial light modulator based setup that combines the properties of parameter flexibility, long working distance, high throughput and operation on micron-scale. We report both on the general characterization of the beam properties as well as a specific application in surface nanoprocessing.

Keywords: Bessel beams, nondiffracting beams, ultrafast laser material processing, nano-ablation

1. INTRODUCTION

Non-diffracting beams have recently attracted much research interest. They have the exceptional property to resist to diffraction over long distances. Nondiffracting beams are solutions to the Helmholtz equation that can propagate without modification of their transverse profile [1]. Non-diffracting beams allow for the production of "flying images" that propagate without deformation [2] .

Non-diffracting beams, such as Bessel beams have been mainly applied to optical manipulation of particles and atoms or nonlinear generation of harmonics [3]. Bessel beams have also been used for laser material high aspect ratio microstructuring [4][5].

In nonlinear media, nondiffracting beams have recently attracted a much interest, since these beams sustain a nonlinear light/matter interaction over distances larger than the Rayleigh length by orders of magnitude. Pulsed Bessel beams are a class of attractors to the filamentation regime[6]. Their specific noncollinear energy flow allows for controlling plasma generation on long distances [7].The self-healing properties of nondiffracting beams are also of prior importance for applications to propagation in turbulent media [3].

Therefore, for applications to materials micro/nano-structuring and for fundamental studies of Bessel beam nonlinear propagation, a perfect control of the Bessel beam production is required.

Experimentally, the simplest way to produce zeroth-order Bessel beams is to place an axicon lens in the optical path. In this case, however, modifying the conical angle becomes more complex since the alignement of the axicon tip is critical. The quality of the tip is also an important factor [8]. Following Durnin's approach of Bessel beams [1], illuminating a ring aperture has been demonstrated to produce Bessel beams on µm scales [9] but the energy throughput is too low for applications to nonlinear optics and laser material processing. Spatial light modulators (SLM) allow for more flexibility, high energy throughput eventually multiplexing [2] [10][11]. Here, we demonstrate the experimental development of a setup that allows for the flexible producing of the whole class of Bessel beams. We present the application to surface laser nano-processing with noncritical sample positioning.

2. EXPERIMENTAL SETUP

The experimental setup for the producing of micro-Bessel beams was designed such as to give spot sizes on the sub-5 µm range, allowing a flexible modification of the conical angle of the Bessel beam and maintain a long-working distance.

To answer these objectives, the femtosecond Bessel beam was produced by a spatial light modulator associated with a telescope arrangement, whose second lens is a microscope objective. A scheme of the setup is depicted on figure 1.

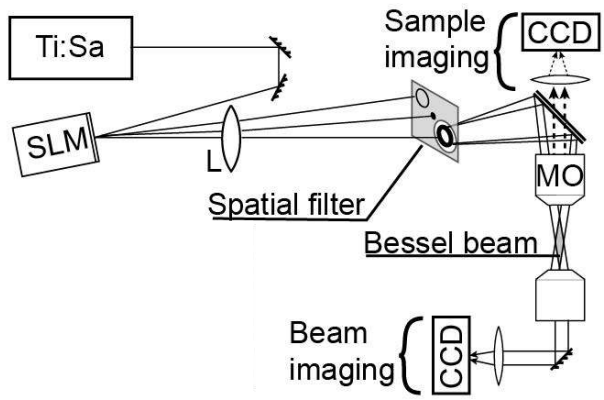

Figure 1 Experimental setup.

The amplified laser source emits 100 fs laser pulses with a central wavelength of 800 nm at 5 kHz repetition rate. An independant Pockels cell system with a thin film polarizer plays the role of an optical shutter. A non-pixelated spatial light modulator (SLM, Hamamatsu PAL-SLM), enables to imprint a linear phase with rotational symmetry to the wavefront, in a similar way as an axicon does We add moreover a phase term of a tilted plane wave to spatially separate the different orders of diffraction.

The first lens is of focal distance f=1m and is associated to an infinitely-corrected microscope objective (MO) x20 or x50 to realize a telescope of magnification $M=9.1\times10^{-3}$ or $M=3.6\times10^{-3}$ respectively. This telescope therefore allows for reducing the spot size of the Bessel beam produced by the SLM in the first diffraction order down to 1.5 µm or 0.6 µm FWHM. Moreover, in the Fourier plane of the lens, an iris plays the role of a spatial filter to eliminate all orders of diffraction except +1. In this plane, the Fourier transform of the Bessel beam appears as a thin circle [11].

The evolution of the produced Bessel beam profile along the propagation axis was recorded by translating a x40 infinitely corrected microscope objective with NA=0.6 along the beam. The collected light was then imaged onto a CMOS camera by a lens with f=200 mm.

3. RESULTS

Figure 2 shows the experimental measurement for a beam with conical half angle 10° and demonstrates the high quality of the beam. The central spot diameter is 1.5 µm, and extends over more than 150 µm.

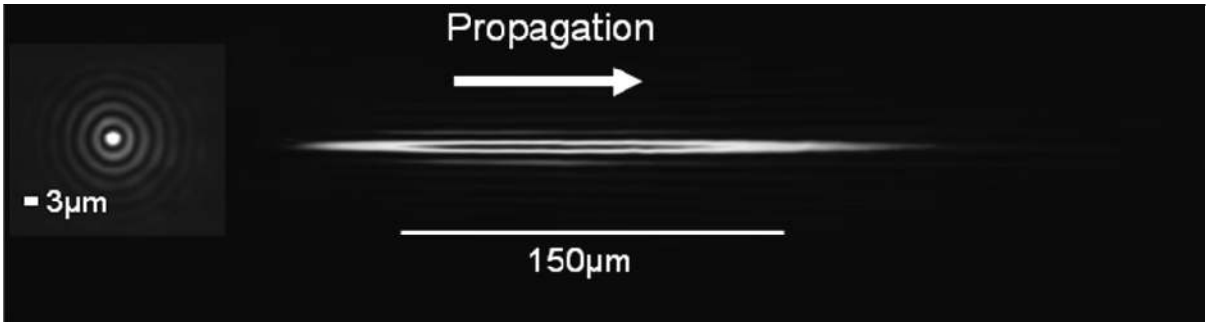

Figure 2 Experimental image of the beam in the (r-z) section. (inset) Corresponding beam profile image. This profile is saturated to enhance the peripheral lobes readability.

We have thus produced a Bessel beam with micron-scale central spot size that can be easily tuned by changing the phase pattern of the SLM. For applications to microstructuring, an important benefit is that the working distance is the one of the microscope objective that is 3 mm for our x20 microscope objective. The energy throughput is >35%.

4. APPLICATIONS TO SURFACE NANOPROCESSING

Femtosecond laser ablation is a powerful tool for the structural modification of many different materials, with particular success in surface nanostructuration [12]. Due to the extremely short light-matter interaction time with femtosecond pulses, the ablation process is quasi-deterministic allowing a high degree of precision and reproducibility [14] Many different physical processes are involved in the ultrafast laser ablation process and it is the precisely defined ablation threshold that allows the structuration to sub-spot and even to sub-wavelength characteristic dimensions [12]

However, both laser nanopatterning and sample imaging requires strong focusing by high numerical aperture optics, generally down to the wavelength, which leads to a nearly identical depth of focus due to diffraction laws. The precise positioning of the sample to be laser micro- or nano-machined with respect to the waist of the laser beam then becomes critical, especially in the case of fluences close to the ablation threshold with few laser shots per pulse train.Therefore, fast patterning of large samples (up to a few cm^2) requires very high flatness of the sample and a precise compensation of the remaining tilts.

To overcome the criticity of sample positioning, the need is to increase the length of the waist while maintaining a small spot size. In this frame, the fact that Bessel beams remain collimated over long distances offer a novel opportunity for laser nanostructuring [15].

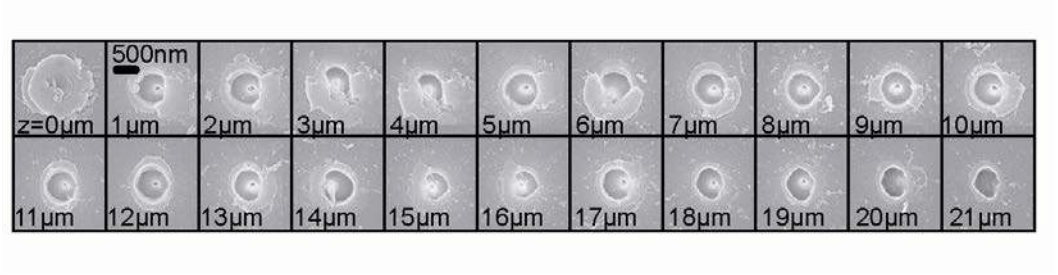

Figure 3. Sequence of SEM images of the craters obtained by single shot ablation with the fs Bessel beam for different longitudinal positions z in the beam. The mentioned distance is relative.

To assess the non-critical positioning when nanomachining with Bessel beams, single-shot near threshold ablation of Corning 0211 glass was performed. We used a Bessel beam with a depth of focus at half-maximum of 18 µm and a diameter of 620 nm.
The sample surface was illuminated by individual shots of the Bessel beam and displaced by 1 µm steps on longitudinal axis between each laser shot. After metallization, the glass sample was examined with high resolution Scanning Electron beam Microscopy (SEM).

A representative example series of laser damages is shown on Figure 3. The damage is clearly identical whatever the longitudinal position over a distance of more than 18µm between z=1 to z=19µm. In this range, the crater radius remains constant at 500 nm with a standard deviation of 9.6%. For comparison, in the case of a gaussian beam focused by the same microscope objective, the accessible range to ensure repeatability is less than 4µm. Therefore, the longitudinal range for nanomachining with the Bessel beam is larger than the usual values of TTV of wafers and enables a tilt up to 2 mrad for patterning over 1 centimeter. This demonstrates that the use of Bessel beams renders sample positioning far less critical than with usual Gaussian beams focusing, without compromising the size of the laser induced damage. The constraint imposed by the use of Bessel beams is that the fluence needs to stay below the limit of 3 times the fluence threshold to avoid the machining by the lateral lobes. However, nanopatterning by femtosecond lasers is mostly performed near the threshold, far below this limit.

5. CONCLUSION

As a conclusion, we have reported a novel setup allowing a flexible synthesis of micro-Bessel beams with a central spot diameter down to 0.6µm. This approach renders fast laser nanoprocessing more reliable and largely diminishes the constraints on sample positioning. We anticipate that this approach will lead to a more widespread application of fast laser processing for patterning nanometric-scale surface features over large samples in nanophotonics.

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