# Combination of photopolymerization and optical micromanipulation techniques

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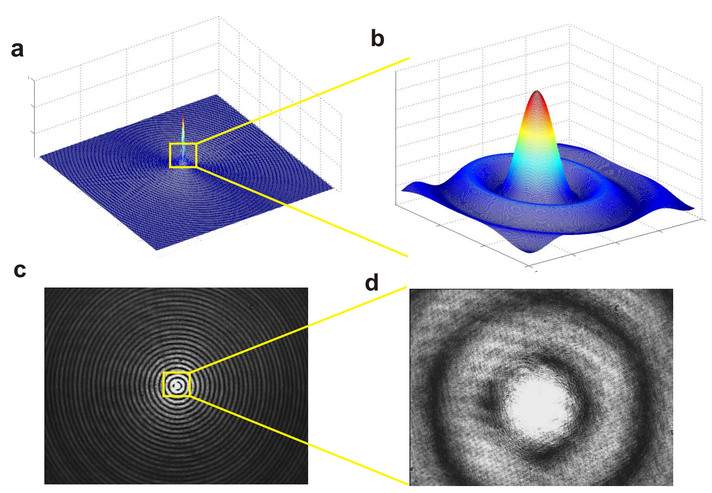
## ABSTRACT

The polymerization by a focused laser light is a modern way how to create easily three-dimensional microstructures with even sub-micron details. We present how this method can be combined with non-classical laser beams to get a unique tool for generation of long and narrow polymer fiber.

## Theory of Bessel beam

The uniqueness of non-difraction (Bessel) beam is that its width does not spread during propagation and can even possess orbital angular momentum (optical vortex). The non-diffractive vector Bessel beams are described as both the solution to the vector Helmholtz wave equation and the superposition of vector components of the angular spectrum .These beams can be generated with the use of an axicon, an annular aperture placed at the focal plane of a lens, or a hologram and their radial intensity profile is in ideal case described by Bessel or Mathieu functions.



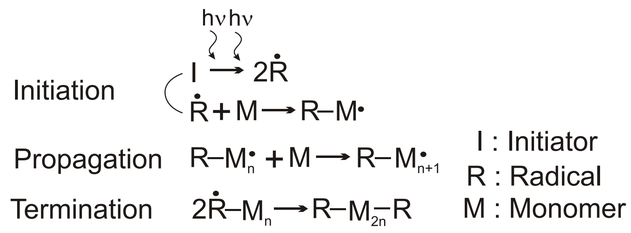

Profiles of Bessel beam in radial plane. **a** and **b** are calculated profiles, **c** and **d** profiles are imaged by CCD camera. **b** and **d** details denoted in the central area of pictures **a** and **c**.

## CONCLUSION

In this paper we presented a method how the non-diffractive laser beam (Bessel beam) can be used for photopolymerization of fibers 2 μm wide and at least 1 mm long. By environmental scanning electron microscope Aquasem-Vega (ESEM) we found that the fiber surface and width is uniform. This diameter depends on the width of the Bessel beam core and on the power of the laser. Lenght of fiber may be modifyed by exposition time of monomer by laser beam and speed of creation may be changed by laser power.

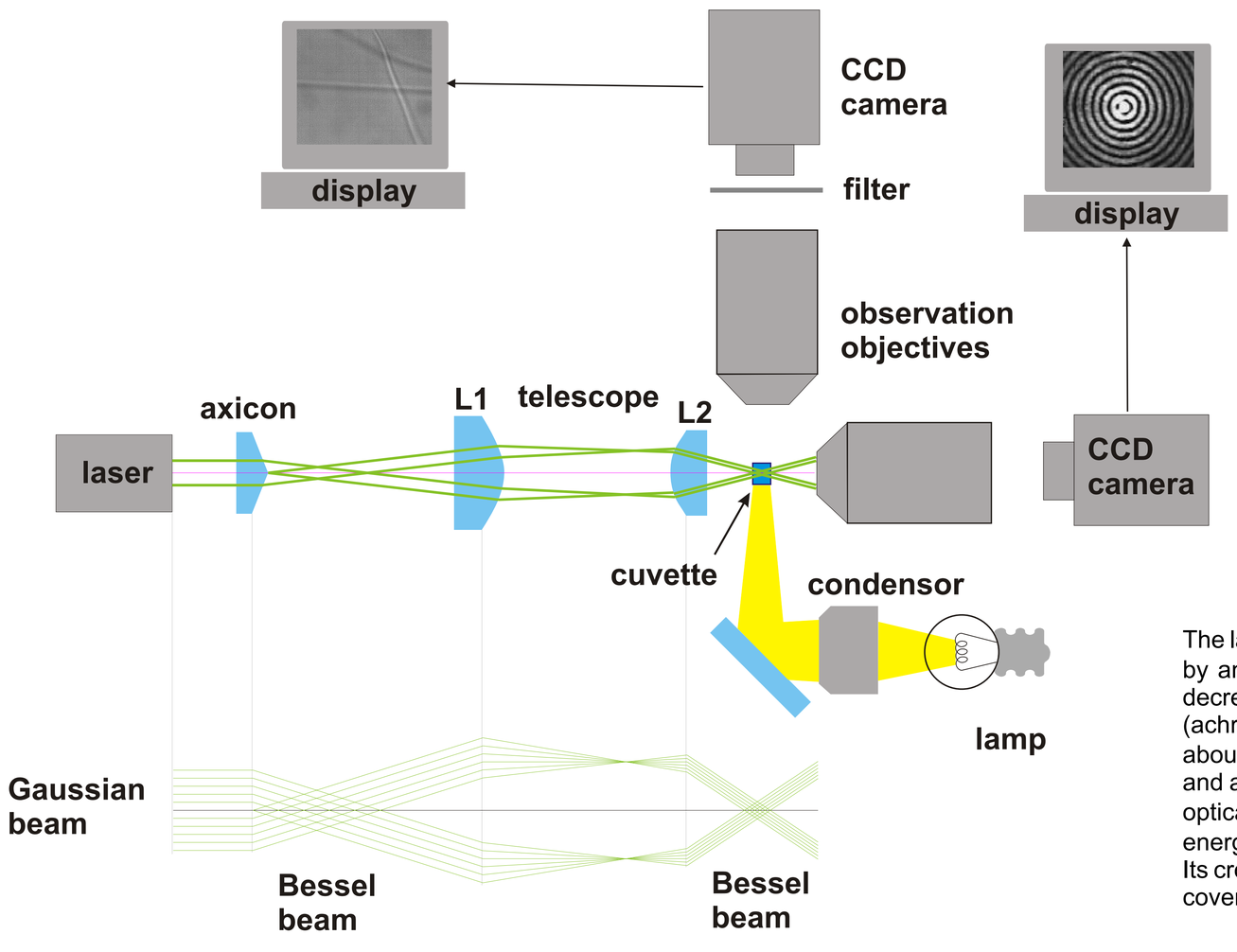
## Photopolymerization

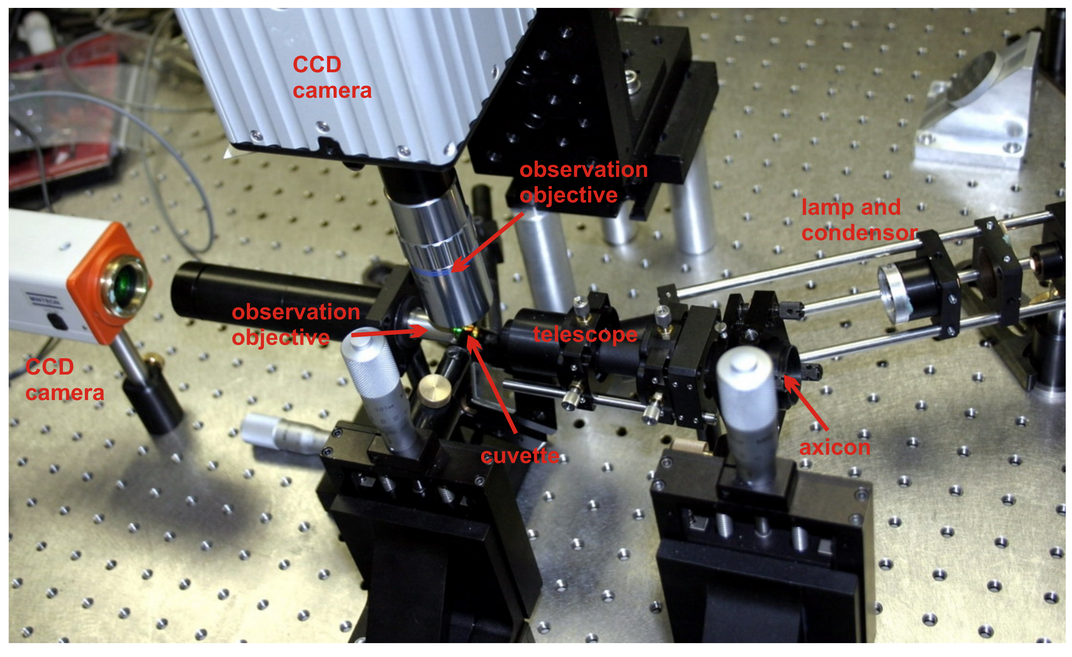
Commercially available resin, consisting of monomers and oligomers as well as photoinitiators, is transparent to near-infrared wavelengths and allows them to penetrate deeply. When a resin absorbs a photon of proper wavelength (usually from UV region of spectra), the resultant radicals cut the double bonds of carbons in the acrylic groups in the monomers and oligomers and successively create new radicals at the ends of the monomers and oligomers. The radical combines with another monomer and the process becomes a chain reaction until the chained radical meets another chained radical.




The same chain reaction can be initiated if two visible photons, instead of one UV photon, are absorbed (so called two-photon absorption). Two-photon initiated laser polymerization has been shown to provide the means for two- and three-dimensional micro-fabrication with a much higher spatial resolution than conventional one-photon polymerization, because the process depends quadratically on the laser pulse energy

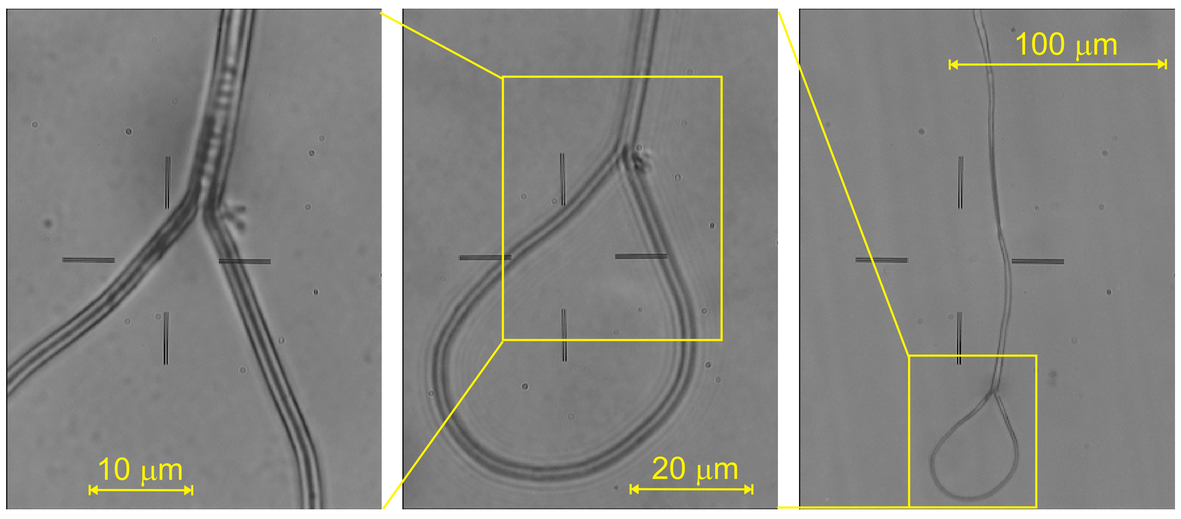
## EXPERIMENTAL SETUP AND RESULTS



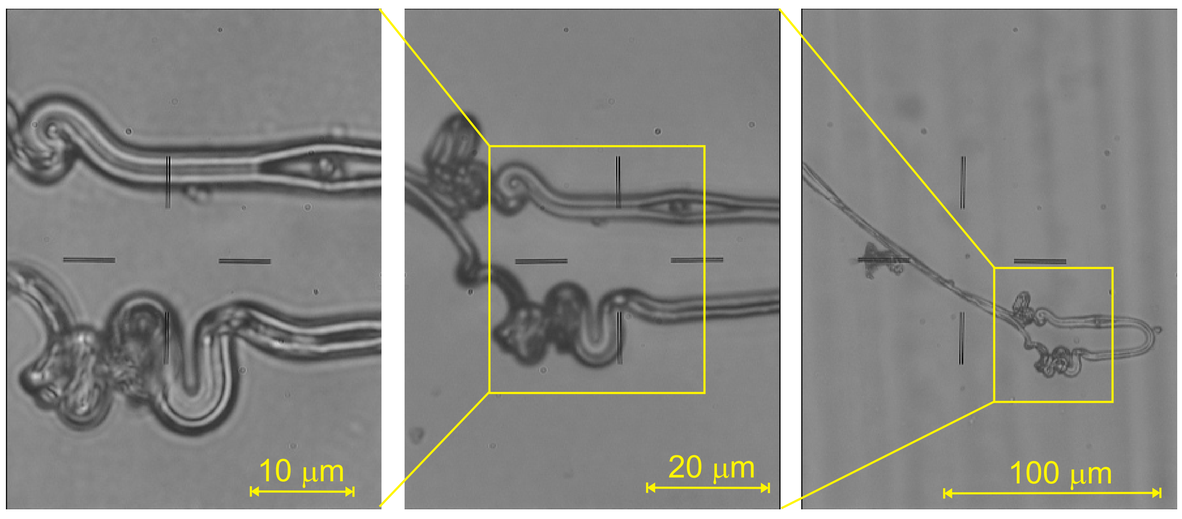




The laser beam from CW laser (Verdi 5W, Coherent, λ = 532 nm, maximal power 5.5 W) was transformed by an axicon (cone angle τ = 170°, Eksma) into a Bessel beam. The core of this Bessel beam was decreased by a telescope formed by lens L1 (achromatic doublet lens f = 30 mm, Thorlabs) and lens L2 (achromatic doublet lens f = 19 mm, Thorlabs). The final diameter of the core of the Bessel beam was about 3 μm. Quality of the Bessel beam was observed by an objective (aspheric lens f = 8 mm, Thorlabs) and a CCD camera (CCD camera Kampro KC-381CG). Solution of monomer NOA 63 (UV light indurate optical glue Norland NOA 63, index of reflection 1.56, maximal absorption for λ < 340 nm, minimum energy for indurate 4.5 $Jcm^{-2}$ = 0.045 $\mu Jm^{-2}$) is placed in cuvette. The cuvette was made from duralumin. Its cross-section was a square (side 5 mm) with two perpendicular circular open holes. These holes were covered by a microscope cover glass. The cuvette is mounted on 3D micro-positioning stage.

**Polymer fiber loop observed by optical microscopy (magnification 100x, 60x and 20x).**




**Polymer double-fiber viewed by optical microscopy (magnification 100x, 60x and 20x).**




We were able to create fibers about 1 mm long within 5 second of laser exposition. We used output laser power equal to 2 W. The fibers were taken out from the monomer solution by mechanical micromanipulator (TransferMan NK, Eppendorf) and glass micropipette. The extracted fiber was cleared in acetone and placed on a microscope slide. If the loops were created, different parts of the fiber were glued together and micromanipulation in acetone was needed to get a single untwisted fiber. The fiber diameter was measured by an optical microscope (Olympus IX70) and verified by ESEM. Its value was 2 μm and stays unchanged along the fiber length.

## ACKNOWLEDGEMENTS

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