Narrow polymer fibers obtained as a combination of photopolymerization and non-diffracting beams

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ABSTRACT

The photopolymerization in focused laser light is a modern way how to create three-dimensional microstructures with even sub-micron details. We present how this method can be utilized even in very narrow non-diffracting beams. Combination of the self-healing property of these beams and the narrow core of the non-diffracting beam enables the generation of a very uniform fiber of diameter less than 2 micrometers and lengths of several millimeters. Manufacturing conditions and dimensions of the generated fibers are studied.

CONCLUSION

In this paper we presented a method how a non-diffractive laser beam (Bessel beam) can be used to create photopolymerized fibers 2 μm wide and at least 1 cm long. Using environmental scanning electron microscope we found that the fiber surface and width are uniform. The fiber diameter depends on the width of the Bessel beam core and on the power of the laser. Higher illumination laser power created longer fibers and increased speed of the fiber creation. We proved the presence of the self-writing mechanism that considerably prolongs the length of the manufactured fiber which exceeded the length of the illuminated region of the nondiffracting beam.

THEORY OF BESSEL BEAM

In real circumstances it is not possible to obtain a beam that does not change its lateral properties over infinity range of propagation. In the case of the Gausian beam (GB) incident on an axicon the following scalar form of the spatial light intensity distribution in the Bessel beam (BB) passing through the telescope (see experimental setup) can be used:

$$I(r',z') = \frac{4PTk\sin\theta'}{w'}\frac{z'}{z'_{max}}J_0^2(kr'\sin\theta')\exp\left\{-\frac{2z'^2}{z'^2_{max}}\right\}. \qquad (1)$$

The parameters of the BB are transformed by telescope as:

$$\sin\theta' = \frac{\sin\theta}{M},\; w' = Mw,\; z'_{max} = w'\frac{\cos\theta'}{\sin\theta'}, \qquad (2)$$

where θ is the polar angle between propagation axis of the BB and the plane waves wave-vectors forming the BB behind the axicon :

$$\theta \approx \left(\frac{\pi}{2}-\frac{\alpha}{2}\right)\left(\frac{n_a}{n_m}-1\right), \qquad (3)$$

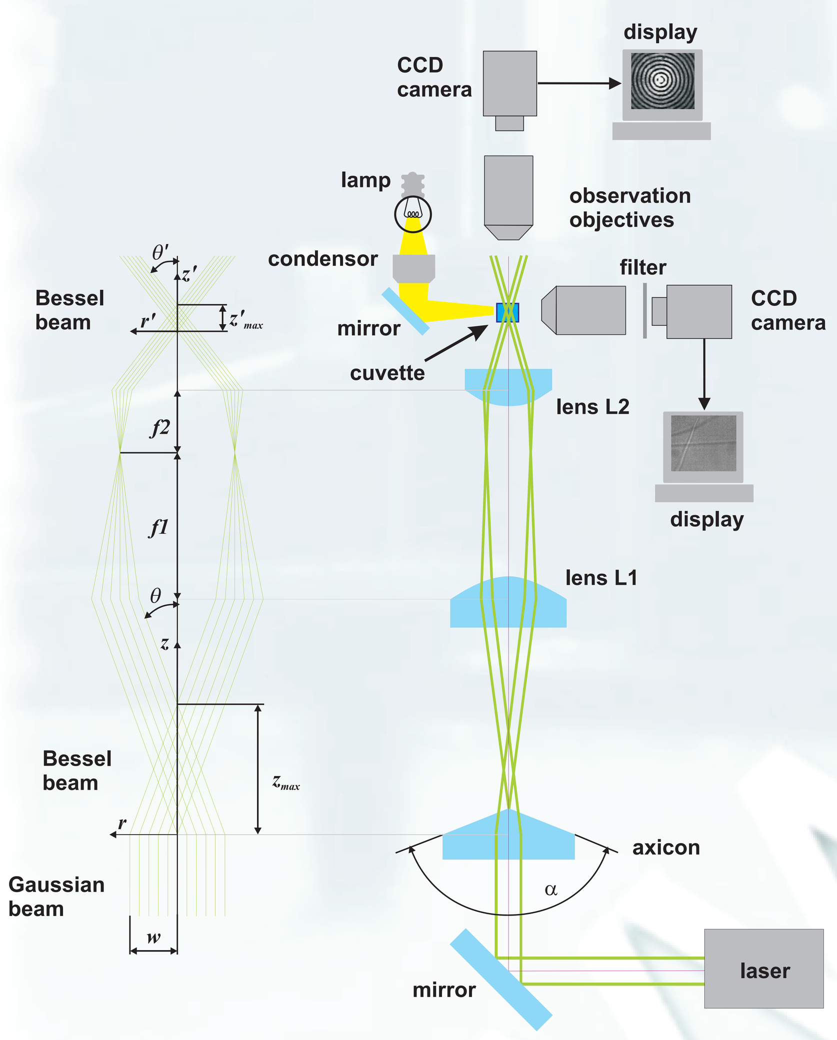
where α is the apex angle of the axicon, n_a is the refractive index of the axicon and n_m is the refractive index of the surroundings medium, k is the wavenumber of the beam in the medium, P is the power of the GB incident on the axicon, $M=f2/f1$ is the magnification of the telescope and $f1$ or $f2$ is the focal length of the lens L1 or L2, respectively, T is the transmissivity of the telescope, w is the half-width of the GB at the axicon, and z'_{max} is the maximum propagation distance expressing the axial range where the BB exists.
In the lateral plane the highest light intensity is at the centre of the BB. Let us define the radius of the BB core (RBBC) as the radial distance from the beam centre to the first intensity minimum done by:

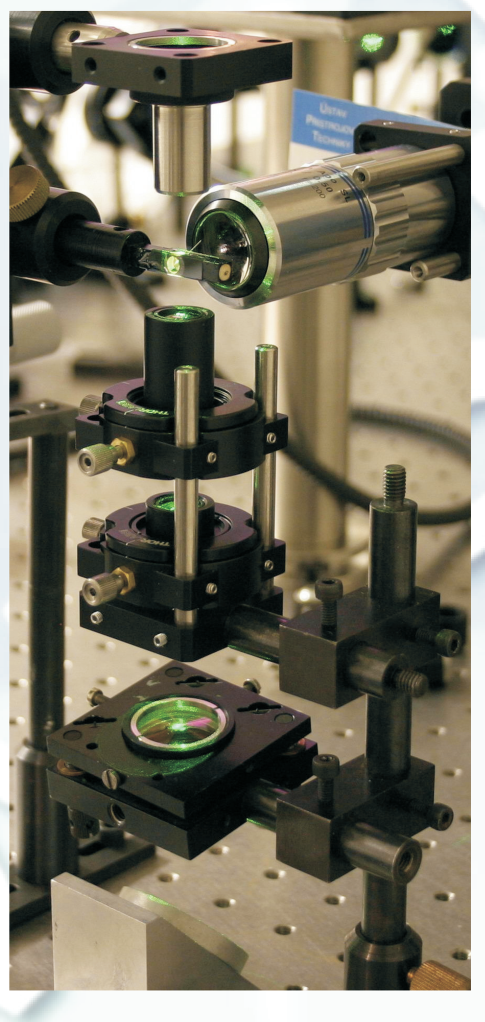
$$r'_B = Mr_B = M\frac{2.4048}{k\sin\theta}. \qquad (4)$$

The narrow BB is formed inside a cuvette filled with a fluid of refractive index n_p. The previous results assumed the beam propagates in the air, therefore using the Snell's law for refraction into the fluid $\sin\theta'_p=\sin\theta'/n_p$ the following form of BB maximal propagation distance should be considered in the fluid:

$$z'_{max\,p} = w'\frac{\cos\theta_p'}{\sin\theta_p'} \cong n_p z'_{max}. \qquad (5)$$

EXPERIMENTAL SETUP





In all experiments we used a Gaussian beam coming from the CW laser (Verdi V5, Coherent, wavelength 532 nm, maximal power 5.5 W, w = 1.125 mm). This beam was transformed by an axicon into a Bessel beam (BB) and further decreased by a telescope formed from lenses L1 and L2. The apex angle α of the axicon and the focal lengths f1, f2 of the lenses were chosen according to the actual experimental demands and their values are specified below for each experiment. Quality and diameter of the BB was observed by objective (Mitutoyo M Plan Apo SL 80X) and CCD camera (CCD camera Kampro KC-381CG). The transformed BB propagated vertically up through a cuvette filled with a solution of UV light indurate optical glue (Norland NOA 63, n_p=1.52). Polymer fiber grows in the central core of the BB if the monomer is exposed by a BB. The created polymer structures were observed by the long-working-distance microscope objective (Mitutoyo M Plan Apo SL 50X) and a CCD camera (Kampro KC-381CG or IDT X-StreamVISION XS-3).We developed a technique how to extract the fibers out from the solution and carry them to a different medium or place. Optical fiber was placed on monomer solution across the central part of BB. Created fiber was stuck on optical fiber on front or lateral side and mechanically pulled out of the solution, washed by acetone and transferred.

RESULTS

We study a diameter of the created fiber depending on properties of telescope lenses (L1 and L2). We used axicon (Eksma 130-0270) with cone angle α = 170° and refractive index n_a = 1.52 and a few different telescopes (see Fig 1.). Theoretical results are calculated by Eqs. (2, 4 and 5). The differences between theoretical and experimental results follow from the insufficient incident laser power to initiate polymerization in the whole area of the central core. The length of the created fiber (L_{fiber}) was determined from the side-view of the CCD camera but for wider BBs (**B** and **C** columns in Fig. 1) the length of the fiber was limited by the dimensions of the used cuvette. Measurement of diameter of the fiber was provided by the environmental scanning electron microscope Aquasem-Vega (ESEM, operator Ing. V. Neděla) under the high pressure conditions and without metallic coating.

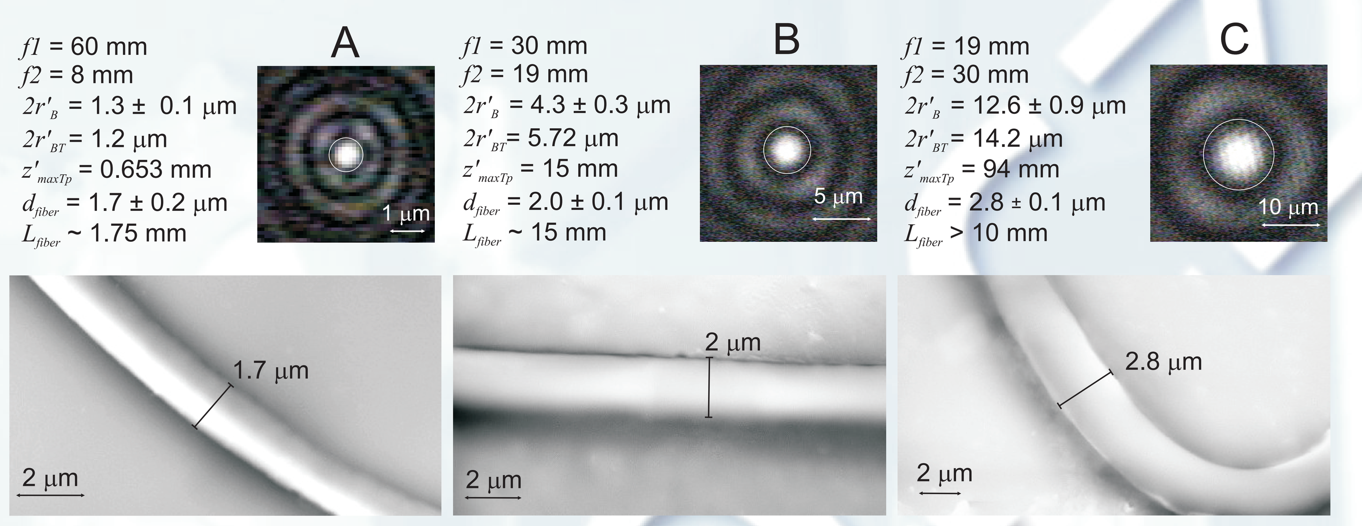


Figure 1. *Top row:* Lateral intensity profiles of three types of generated BBs with different diameters of the BB cores ($2r'_B$). Corresponding parameters of the set-up, created fiber diameter (d_{fiber}), and its length (L_{fiber}). *Bottom row:* ESEM image of the polymer fibers. In all three cases we used the same output laser power 3 W giving laser power 1.5 W in the cuvette.

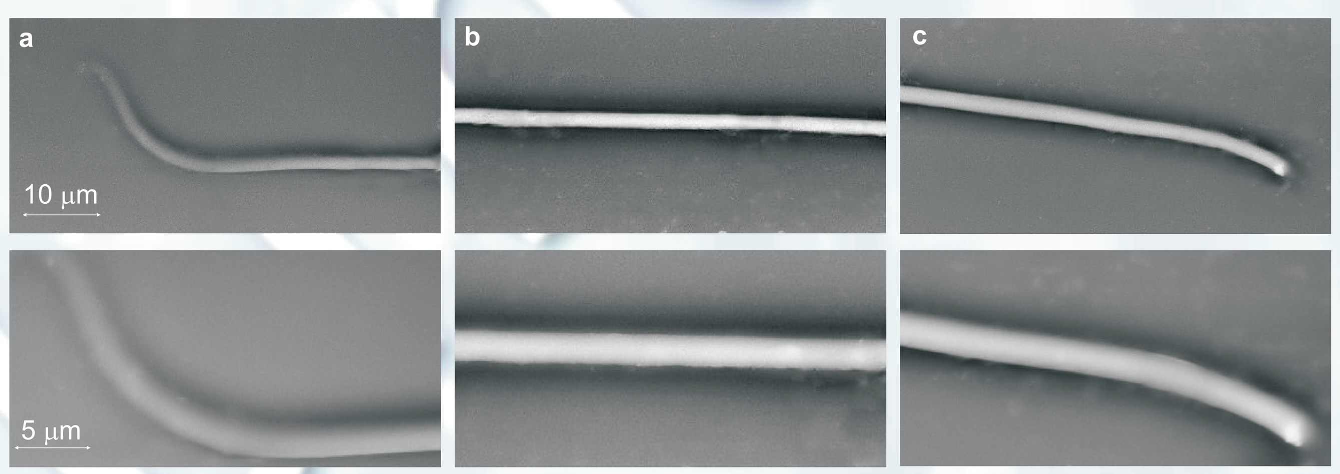


Figure 2. ESEM images of the left (a), middle (b) and right (c) part of one fiber long 15 mm (see the column **B** in Fig. 1.). Each of the image rows keeps the same scale but uses different magnifications to demonstrate the fiber homogeneity.

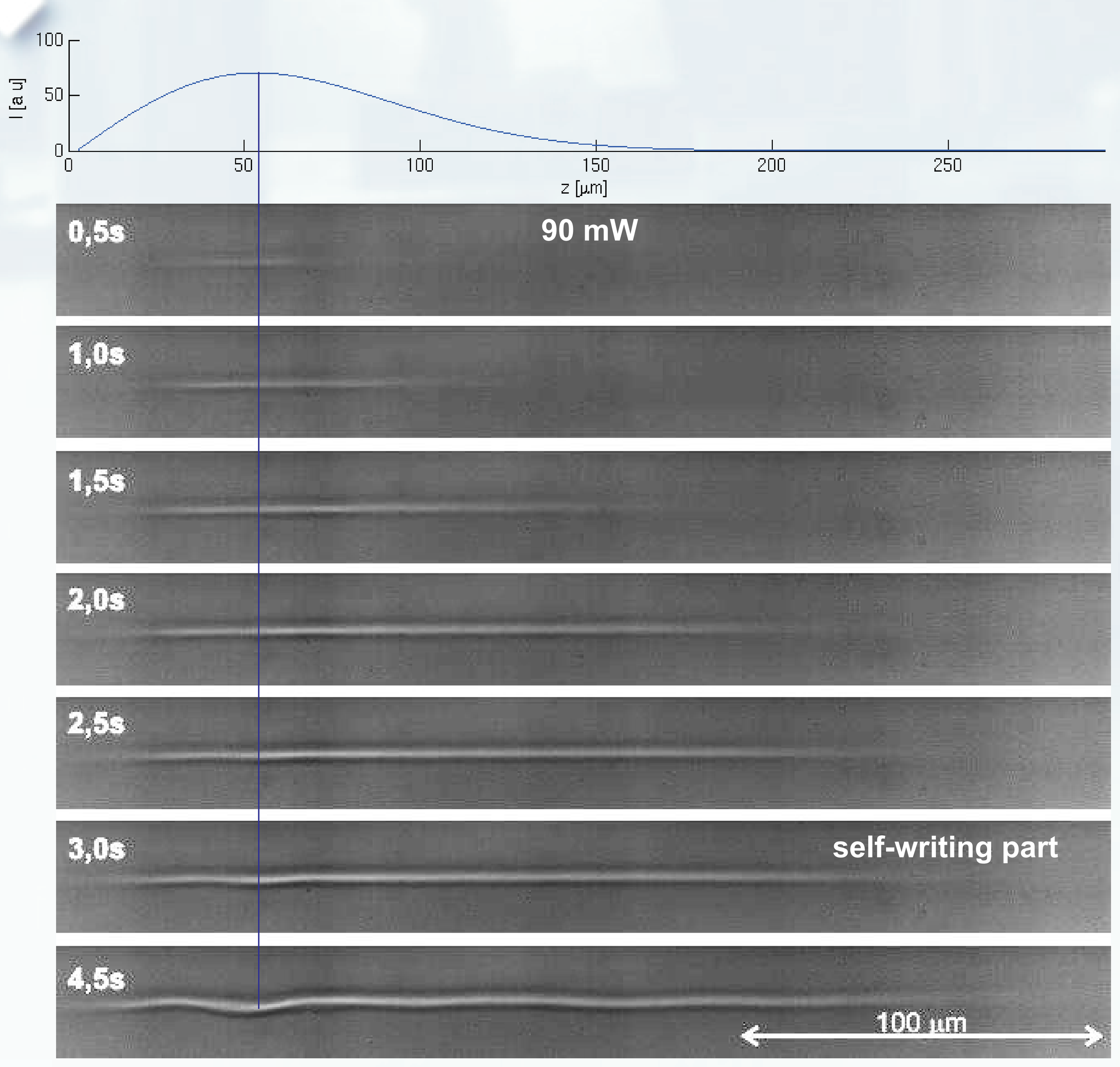


Figure 3. Formation of the polymer fiber in the short BB. The BB core radius was 0.8 μm and the maximum propagation distance of the BB was about 100 μm. The laser power in the cuvette was 90 mW. The top plot shows the calculated on-axis intensity profile of the BB for the parameters used in the experiment.

We used a different setup where the BB z'_{maxTp} was short enough to observe both - the whole BB and the manufactured fiber by the CCD from a side. The setup consisted of the axicon with the apex angle α = 179.065° and a combination of lenses with focal lengths $f1$ = 500 mm and $f2$ = 8 mm. The generated BB had the following parameters: $2r'_B$ ~ 1.5 μm and z'_{maxTp} ~100 μm. The top plot in Fig. 3 shows the calculated on-axis intensity profile in the BB using Eq. 1 and the images bellow show the side view of the created fiber if the image background at zero time was subtracted. Obviously the fiber grew asymmetrically with respect to the high intensity part of the BB. This also proves that the self-writing mechanism prolongs the fiber in the direction of the BB propagation.

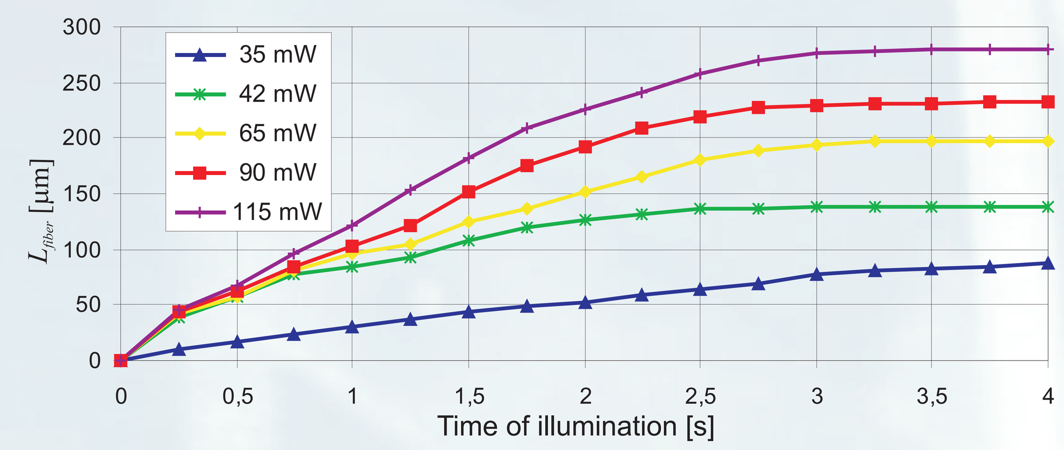


Figure 4. Time evolution of the length of the fiber formed by different laser powers in the cuvette. The BB has the same parameters as in the previous case in Fig. 3.

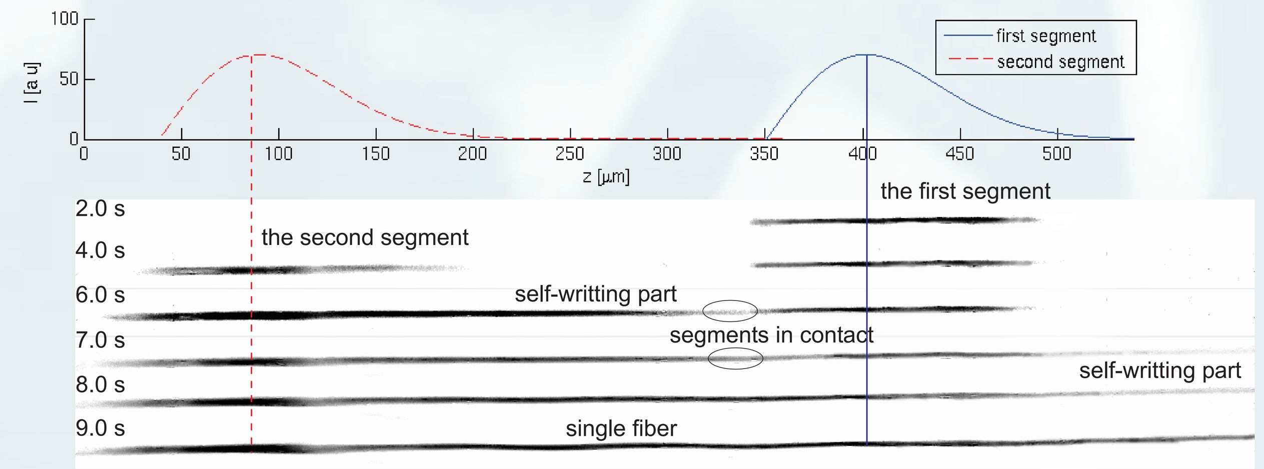


Figure 5. Top plots show the calculated on-axis intensity distribution for the used experimental parameters. The first image shows on the right a short fiber segment created after 2 s of illumination. The beam was blocked and the cuvette was shifted along the beam propagation. Unblocked beam created on the left side the second segment after 2 s of illumination (2nd row). This segment gradually grew till it reached the first segment on the right (3rd row). Both segments interconnected (4th row) and immediately the first fiber segment continued in its growth on the right (4th-6th rows). Laser power in the cuvette equaled to 130 mW.

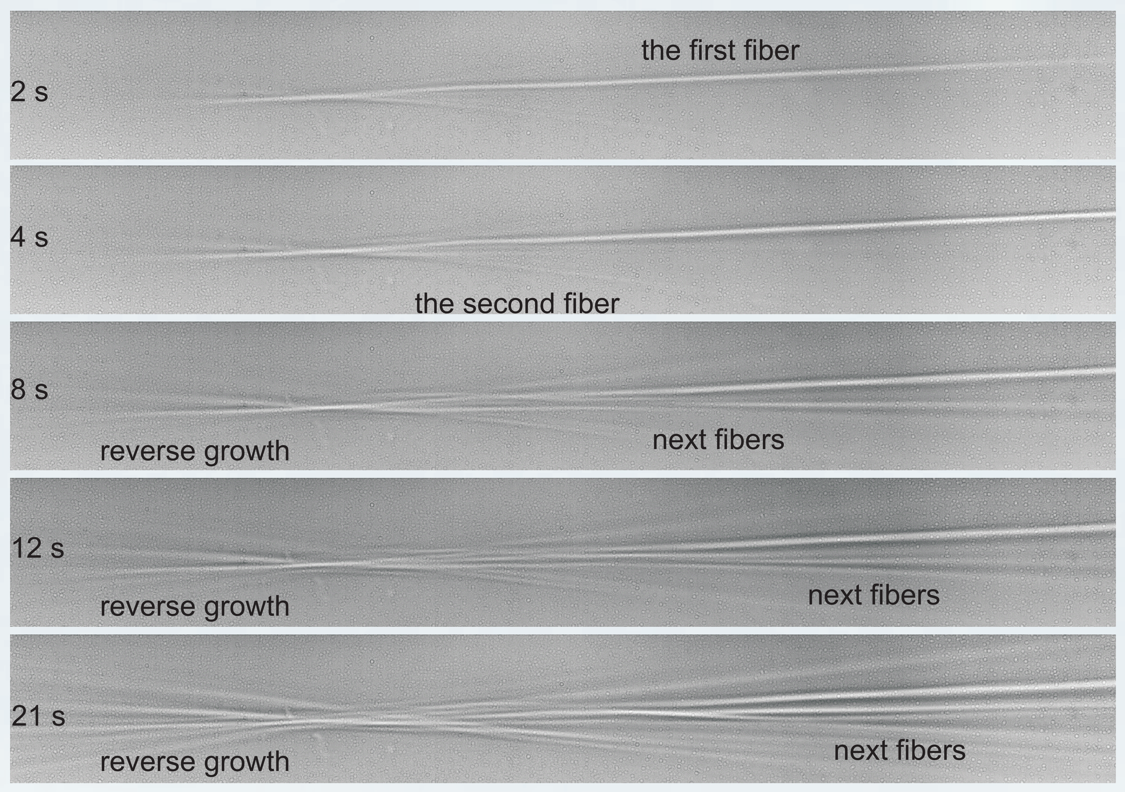


Figure 6. Chaotic growth of the polymer fibers. Single fiber is formed if the illumination is shorter than 2 s. Later on more fibers started to grow especially at the ripples of the older fiber where the leakage of the light from the fiber is probably higher. The light is backscattered in the formed structures and via the self-written waveguide mechanism initiated a reverse growth. Laser power in the cuvette equaled 400 mW.

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