Bessel-Like Beams Based on Optical Fiber Polymer Microtips

Jingyu Tan, Ruowei Yu, and Limin Xiao

Bessel-like beams possess unique light intensity distribution and self-healing propagation property have been widely used in various fields such as imaging [1], particle guiding [2], and microfabrication [3]. Generation of them with optical fibers allows a compact device without alignment and stability issues compared with bulky optical systems. Microaxicons at the fiber ends were fabricated to produce a Bessel-like beam [4, 5]; however, the fabrication process is generally time-consuming and complicated. Besides, multimode fibers were spliced to single mode fibers (SMFs) with fiber lens or SMFs with long period gratings to demonstrate the generation of Bessel-like beam[6, 7].

Bachelot et al. introduced a method to fabricate a microtip on the top end of optical fibers based on free radical photopolymerization [8]. Our approach relies on the growth of such a polymer microtip fabricated at the facet of a SMF. In this letter, we will show the optimization of length and shape of microtips to generate Bessel-like beams and the investigation of far-field patterns and the self-healing property.

The photopolymerizable reagent is made up of 0.5% in weight of eosin Y, 8% in weight of methyldiethanolamine, and 91.5% in weight of pentaerythritol triacrylate [8]. A drop of photopolymerizable reagent was deposited on the end of SMF-28 from Corning. Generally, the droplet length on the facet is around 30 μm because of

J. Tan · R. Yu · L. Xiao (✉)
Advanced Fiber Devices and Systems Group, Key Laboratory of Micro and Nano Photonic Structures (MoE), Department of Optical Science and Engineering, Fudan University, Shanghai, China
e-mail: liminxiao@fudan.edu.cn

L. Xiao
Key Laboratory for Information Science of Electromagnetic Waves (MoE), Fudan University, Shanghai, China

Shanghai Engineering Research Center of Ultra-Precision Optical Manufacturing, Fudan University, Shanghai, China

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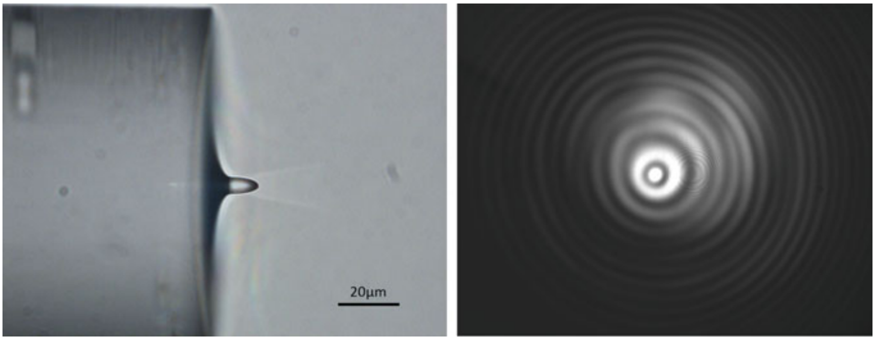

Fig. 1 **a** 100× microscopic image of a photopolymer microtip at the end of a SMF fabricated with green laser. **b** Bessel-like beam pattern from behind the fabricated microtip, measured by a CCD camera

liquid surface tension. However, we find shorter microtips are favorable for Bessel-like beams generation, so we use a dose reduction method to fabricate short microtips. The length of droplet can be reduced to around 10–20 μm after one operation. Then green laser emerging from the SMF selectively solidified external photosensitive material and therefore formed a polymer microtip.

In addition to the length, the achievement of Bessel-like beams highly depends on the shape of the microtip, which is mainly affected by photopolymer parameters, such as laser exposure time, green laser power, and oxygen diffusion concentration. After a suitable height droplet was deposited, a green laser with the wavelength of 532 nm was coupled into the SMF through a mode filter to ensure that only the fundamental mode was excited. The laser illuminated the center part of the liquid, and at this moment the far-field pattern behind the tip showed nearly a single mode. As shown in Fig. 1, after rinsed off the unreacted liquid with a few drops of ethanol, a firm microtip appeared, and the far-field pattern became Bessel-like. A tip with a base diameter of around 6.1 μm and a length of 17.4 μm could grow after the polymer droplet was exposed to the laser with the power of 1 μw for 60 s.

In the experiments, the end facet of our microtip is not round but is quite sharp similar to a polished microlens, acting as a specific microaxicon. Figure 2 shows that the Gaussian beam propagated from the SMF can be reshaped with the interference of wave vectors from different positions at the microtip end and thereby directly forming a Bessel-like beam.

In order to study the working wavelength range and the mode properties of the microtip, we directly placed the screen behind the microtip to observe the far-field patterns at different wavelengths. As shown in Fig. 3, four far-field patterns at different wavelengths were captured. High-quality Bessel-like beams of light in the wavelength range from 406 to 660 nm that covered the full visible light spectral region can be produced by our microtips, with more than 30 concentric rings. In the near-infrared spectral region, it also functions well. However, it is difficult to capture

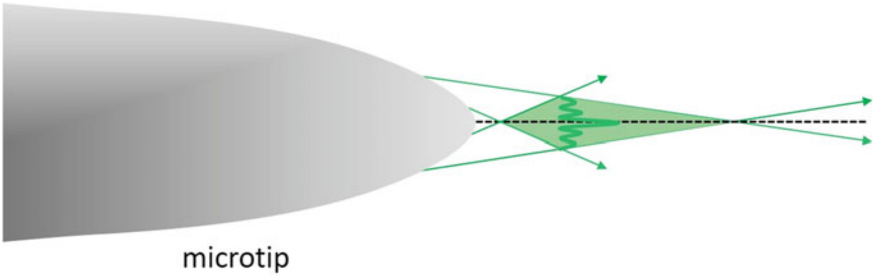

Fig. 2 Formation principle of a Bessel-like beam from the microtip illuminated by a Gaussian beam

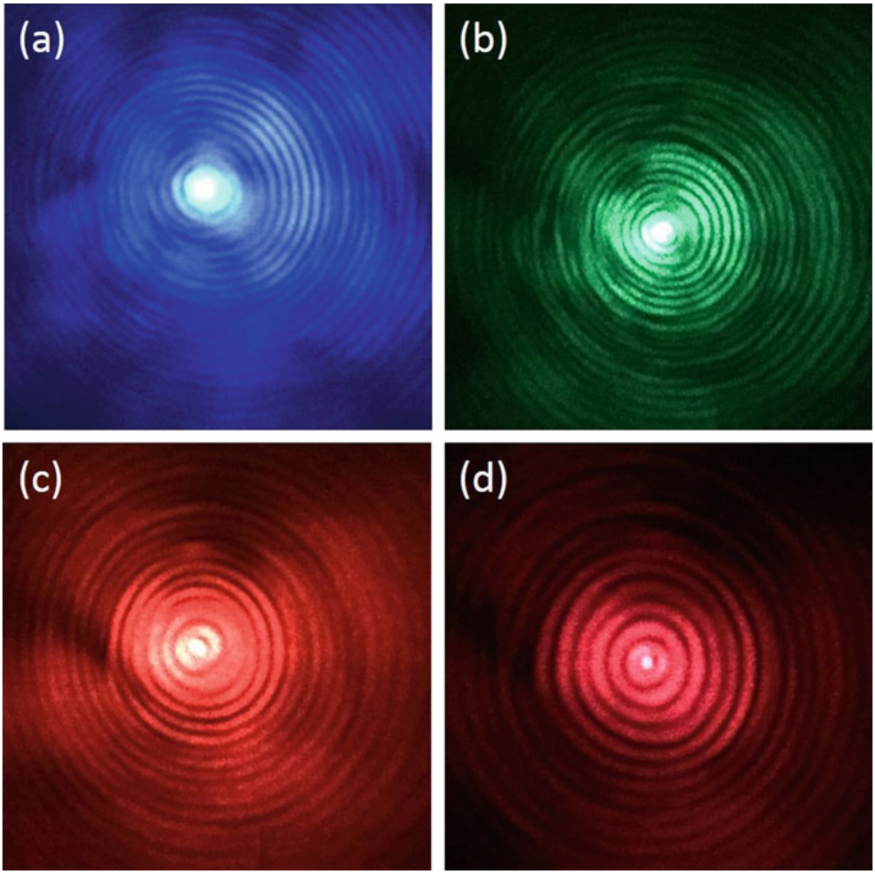

Fig. 3 Far-field patterns at four different wavelengths behind the microtips: **a** 406 nm; **b** 520 nm; **c** 638 nm; **d** 660 nm

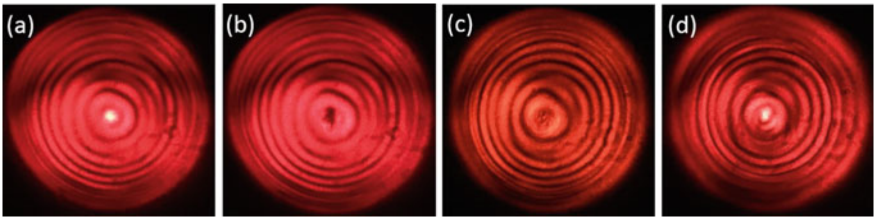

Fig. 4 **a** Light pattern without an obstacle. **b** Light pattern with an obstacle, $z = 0$ mm. **c** Light pattern after moving the unit 5.5 cm to the right, $z = 55$ mm. **d** Light pattern with the recovered central bright spot after moving the unit 10 cm further to the right, $z = 155$ mm

the entire far-field patterns because in the near-infrared CCD, we used possessed a limited photo-surface area compared with the larger screen.

We also verified the self-healing property of the Bessel-like beam. The experimental setup consists of a 40× objective lens, a glass slide with obstacle, a 10× objective lens, a camera, and a screen. The 10× objective lens, screen, and camera were placed as a unit along an axis, i.e., along the z position. As shown in Fig. 4a, we can see that the pattern on the screen was out of obstacles. When the center bright point was completely blocked, the position of the unit on the axis is used as the initial position of our measurement [Fig. 4b]. When the device was moved 5.5 cm to the right, the central point started to recover to some extent [Fig. 4c]. When the device was moved another 10 cm, the bright center has recovered [Fig. 4d].

In conclusion, we introduce an ultra-compact, convenient, low-cost, and effective approach of Bessel-like beams generation through self-growing polymer microtips. The droplet height and polymerization parameters are essential for achieving high-quality Bessel-like beam conversion. Our microtips can function in a wide spectral region with up to more than 30 concentric rings. Besides, the self-healing property of Bessel beams has been verified.

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