Micro-Lensed Single-Mode Fiber Tip as a High-NA Objective

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High-NA objectives play essential roles in various optical experiments. Namely, in biomedical confocal microscopy [1], they are necessary to achieve high-resolution imaging. Also they assure high-photon collection efficiency in quantum optics experiments demonstrating single photon sources with nano-emitters [2]. However, such high-NA objectives in general consist of multiple lens systems, and cause experimental complexity in particular when the systems are used in ultra-low cryogenic temperature or ultra-high vacuum condition.

Here, we report on micro-lensed single-mode optical fibers as high-NA lenses connected to low-loss optical transmission lines. Standard single-mode optical fibers are tapered to diameters of the order of the wavelength and are terminated with a spherically/hemispherically shaped tips [Fig. 1(a) and (b)]. We show that the micro-lensed fiber tips can focus the output beam to sub-wavelength waists with finite working distances [Fig 1(c) and (d)], in contrast to the relatively large size of lensed fiber tips in previous works. In addition, we experimentally demonstrated confocal microscopy with a precisely fabricated fiber tip used as a high-NA objective [Fig 1(e)]. The obtained image was consistent with the numerical simulation.

A significant advantage of the micro-lensed fibers is direct coupling of collected photons into a standard single-mode fiber. These fibers enable one to perform efficient spatial filtering and low-loss long-distance transmission of the collected photons. The monolithic simple design of the micro-lensed tips compared to the conventional compound lens system enables us to reduce the complexity and enhance the stability of the experiments in the extreme condition, and these fibers can be easily integrated into fiber optical systems.

![Figure 1](image_url)

Figure 1: Schematics of fibers with (a) the hemispherical and (b) the spherical tips. $d$ and $D$ are the diameters of the stem fiber and the tip sphere, respectively ($d = D$ for the hemisphere case). Numerically calculated intensity distribution of the output beam from (c) the hemispherical and (d) the spherical tips. (e) SEM image of the hemispherical fiber tip. The scale bar corresponds to 3 $\mu$m.