Ultrathin Optical Fibers for Particle Trapping and Manipulation

Aili Maimaiti[1,2], Viet Giang Truong[1], and Síle Nic Chormaic[1]
[1]Light-Matter Interactions Unit, Okinawa Institute of Science and Technology Graduate University, Onna, Okinawa 904-0495, Japan
[2]Physics Department, University College Cork, Cork, Ireland
Author e-mail address:sile.nicchormaic@oist.jp

Abstract: We present experimental and theoretical results on chains of microparticles optically bound in the evanescent field of ultrathin optical fibers that can support the fundamental, LP_{01}, and first group, LP_{11}, of higher order fiber modes.
OCIS codes: (230.3990) Micro-optical devices; (350.4855) Optical tweezers or optical trapping

1. Introduction

Ultrathin optical fibers [1], pulled from commercial step-index fiber using a heat-and-pull technique [2,3], have a waist comparable to or smaller than the fiber-guided wavelength. Such fibers can have a significant portion of the guided light external to the fiber itself in the form of an evanescent field. By placing particles on or near the optical fiber surface, interactions between the field and the surrounding system can be studied. These fibers have distinct advantages over tightly focused free-space beams: the restriction on interaction length arising from the Rayleigh range is eliminated, very high intensities can be reached in the evanescent field for very low powers due to the tight radial confinement, and the fibers themselves can have flexible geometries facilitating the manipulation of particles along curved paths. Such ultrathin fibers have also been used to study nonlinear effects, such as electromagnetic induced transparency (EIT), in laser-cooled alkali atoms [4,5] and to generate ring resonators for nonlinear atom-cavity response in rudidium vapor [6].

Most work on ultrathin optical fibers has focused on the evanescent field associated with the fundamental guided mode (FM) due to the difficulty of achieving low loss, higher order mode (HOM) propagation. However, there have been several theoretical works that have illustrated the advantages of using HOMs in relation to atom manipulation next to nanofibers and one early experimental demonstration exists [7]. Aside from the interesting features - such as the fact that HOMs can extend further into the environment (see Fig. 1) and can provide modal interference trapping potentials - it is also known that specific HOMs may carry orbital angular momentum (OAM) and, if such modes could be propagated through ultrathin fibers, then it should provide an ideal system for studying the transfer of OAM to particles or spin-orbit coupling.

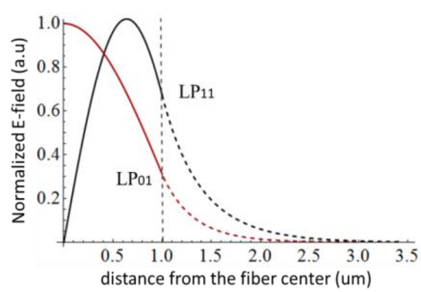

Fig. 1. Normalized electric field distribution of the fundamental, LP_{01}, and the first order, LP_{11}, modes of an ultrathin optical fiber with a diameter of 2 μm. The horizontal dashed line represents the fiber boundary.

Here, we present our work on engineering ultrathin optical fibers to carry the first group of higher order modes, namely TE_{01}, TM_{01} and $HE_{21e,o}$ [8]. We will discuss our early work on HOM manipulation of microbeads [9] and make the comparison between particle chain dynamics under fundamental mode versus HOM influence. When considering the evanescent field of HOMs, it is important to note that azimuthal symmetry is broken, but the greater penetration depth and the stronger field intensities lead to stronger light scattering fields for particle manipulation. We present a theoretical model and experimental results to show that HOMs can provide stable multiparticle trapping sites and allow us to control the position of individual trapped objects within particle chains better than for fundamental mode propagation alone [10].

2. Experimental Details

An ultrathin optical fiber from two-mode fiber (Thorlabs, SM1250G80) was prepared using a H:O heat-and-pull rig [3]. A double linear taper was used to make a fiber with a waist diameter of 2 μm, yielding 80% transmission of the higher order modes and 95% transmission of the fundamental mode. The experimental setup is shown in Fig. 2. A spatial light modulator (SLM) was used to generate a donut-shaped, LG_{01}, beam to excite the higher order modes in the microfiber at 1064 nm.

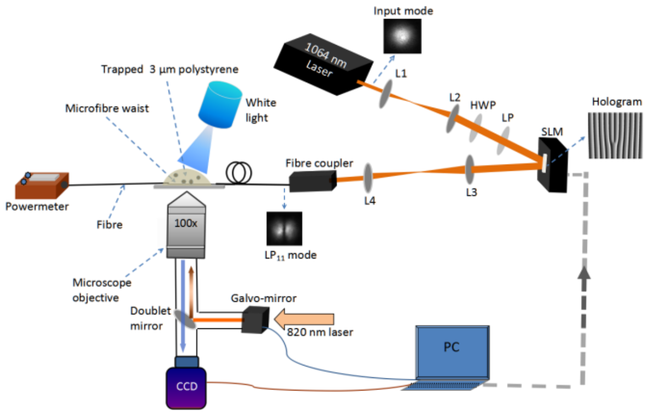

Fig. 2. Schematic of the experimental setup.

3. Results

Using the setup illustrated in Fig. 2 (sometimes with minor modifications, depending on the exact experiment), we studied particle propulsion and trapping along an optical microfiber for both FM and HOM cases. We note that the propulsion speeds for single particles under HOM influence are an order of magnitude higher than for the FM case [9]. We have also studied this behavior for chains of up to five particles and see that the interparticle distance is largest for only two particles and decreases as more particles are added. Theory supports this self-adjustment observation. We note that scattered light fields from the particles in the chains strongly influence the particle separation and the system can be modelled using a tritter scattering-matrix approach [10].

4. Conclusion

In conclusion, we can engineer ultrathin optical fibers to support both the fundamental and first group of higher order modes for 1064 nm propagating light and a waist of 2 μm. This allows us to study particle dynamics in the resultant evanescent fields and determine stable trapping configurations in a 1D geometry along the fiber waist region. The experimental data is supported by analytical and numerical analyses. This work is a precursor to studying the transfer of OAM from light to particles in the evanescent field region and distinguishing between spin and orbital angular moment influences on microbead dynamics. Further work related to cold atom trapping is also being investigated.

5. Acknowledgments

The authors wish to thank D. Holzmann and H. Ritsch for their contributions to this work. This work was funded by Okinawa Institute of Science and Technology Graduate University.

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