Characterization of optical nonlinearity and formation of Self-Collimated Beams in nanocolloids

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Abstract: We demonstrate the propagation up to 1cm length of Self-Collimated Beams in suspensions of dielectric nanoparticles with positive polarizability, which is much longer than reported before. Detailed experimental characterization is compared with numerical simulations.

OCIS codes: (190.0190) Nonlinear optics; (190.5940) Self-action effects; (190.6135) Spatial Solitons.

The nonlinear optical properties of colloidal suspensions of nanoparticles in water were discovered in the 1980's [1]. Since then, several theoretical and experimental works aimed at elucidating the kind of nonlinearity produced by the nanosuspensions have been carried out. In general, the nonlinear optical response for these media is attributed to the gradient optical forces acting on the particles. Depending on their polarizability (α), the nanoparticles will experience attractive effects (α>0) towards the regions with highest optical intensity or repulsive effects (α<0) from those regions [2]. In both cases, the redistribution of particles induces a gradient in the effective refractive index of the medium, which produces a self-focusing effect. Previous work has shown that a bright optical spatial soliton (OSS) can be formed in such media by a CW laser, for optical powers above a critical value, and with propagation lengths of a few hundred microns for the case of particles with positive polarizability [3]. Recent experimental works have used specially tailored particles with negative polarizability [4] or metallic particles [5], leading to soliton propagation distances of a few millimeters. It is unexpected, however, that such long propagation distances of OSS can be reached when α>0, due to scattering losses of light intensity along propagation [4]. Theoretically, the description of the formation and propagation of OSS in (2+1)D is given by the nonlinear paraxial wave equation. In the case of colloidal media, different considerations and assumptions have been made in order to describe the nonlinearity, which is found to be an exponential function of the intensity, but may also include, for instance, effects such as nonlinear Rayleigh losses [6], hard sphere potential particle interactions [7], or Coulomb repulsion forces [8]. These effects tend to stabilize the propagation of OSS, which would collapse otherwise.

In this work, we demonstrate the formation and propagation of self-collimated beams over distances in excess of 1cm through a colloidal medium with nanoparticles having positive polarizability. We use the term self-collimated beams (SCB) to describe a kind of beams, which propagate in nanocolloids reducing significantly their natural divergence angle due to the self-focusing effect, but, in contrast with OSS, the natural diffraction is not compensated completely to form a self-trapped mode. We present a detailed experimental characterization of the SCB as a function of different control parameters. And finally, our experimental results are explained and compared with numerical simulations based on a modified version of the theoretical model described in reference [7], but considering also scattering losses.

The experiments are performed using a nanocolloidal suspension formed with polystyrene nanoparticles of 57 nm diameter immersed in distilled water. The experimental setup, shown in Fig. 1, includes a green laser beam (532 nm wavelength) focused by an objective lens into the sample cell, which is mounted on a motorized stage, since we noticed that the distance D between the lens and the sample is an important parameter in the formation of the SCB. The transverse profile of the SCB is observed with a second objective lens coupled to a CCD camera. Another camera (top view camera) is used to observe the propagation of the SCB and the acquired images are subsequently analyzed using processing software.

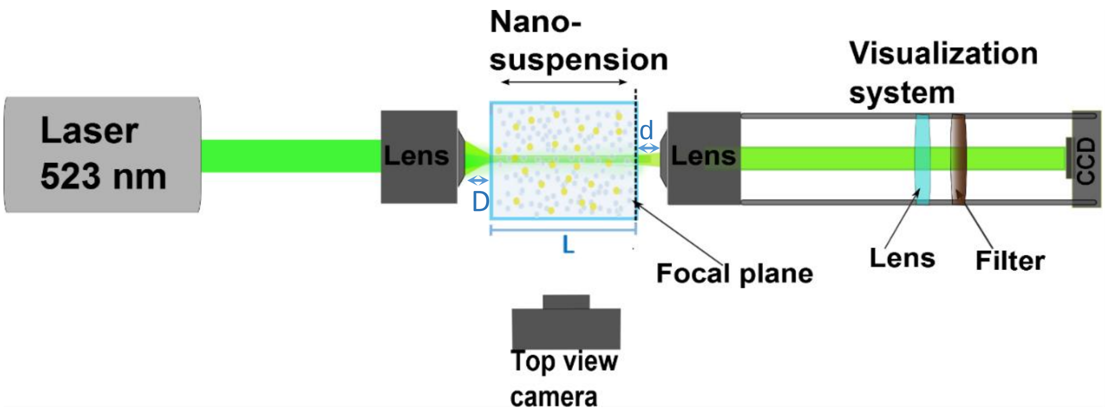

Figure 1: Experimental set-up

Figure 2 shows an example of the registered changes in the width of the SCB as a function of the input power. These were measured at the output of the sample, using glass cells of different lengths. The resulting curves show a proportional dependence between the glass cuvette length L and the width of the SCB, proving that these are not OSS.

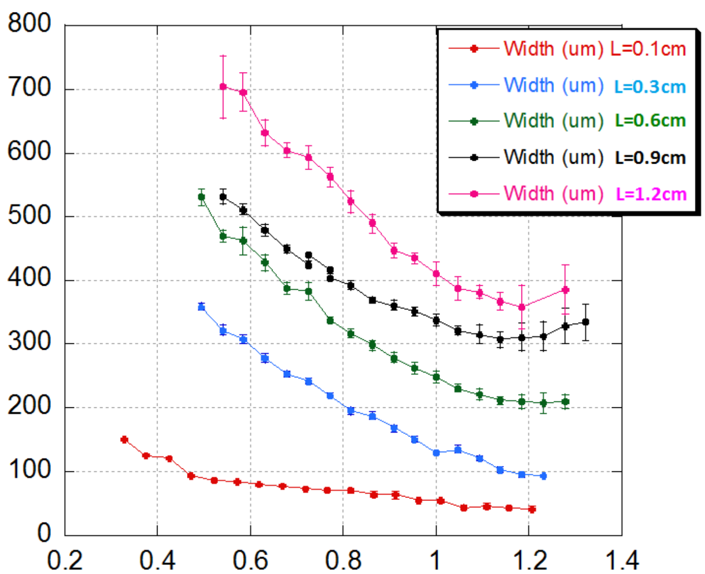

Figure 2: Cross-section of the SCB as a function of optical power for different lengths of the glass cell.

As another example of the experimental characterization, the response time of the nanosuspension for different input powers is shown in Fig. 3. This is defined as the time at which the width of the beam reaches the minimum size for a constant optical power. In this case, an inverse relation between the input power and the width of the beam is obtained. The response time for the tested samples is approximately 1 second, which can be considered slow when compared to other materials showing self-focusing effects [9].

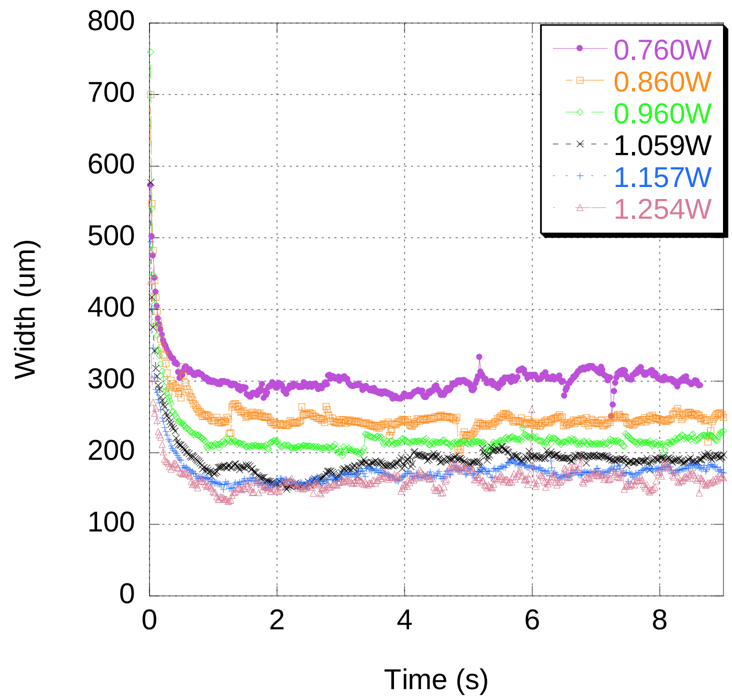

Figure 3: Response time of the colloidal suspension for different optical powers.

As will be shown, the behavior of the SCB can be well described by the theoretical model we use. We will discuss the interesting features exhibited by SCB in contrast with OSS, as well as their similarities, like for instance, the possibility of using SCB to waveguide a weaker probe beam [10], and how this can be used also to characterize the waveguide itself.

References

[1] A. Ashkin, et al. “Continuous-wave self-focusing and self-trapping of light in artificial Kerr media,”Opt. Lett. **7**, 276 (1982).
[2] P. W. Smith, et al. Opt. Lett. **6**, 284 (1981); P. W. Smith, et al. Opt. Lett. **7**, 347 (1982).
[3] P. W. Smith, et al. Opt. Lett. **9**, 131 (1984).
[4] W. Man., Z. Zhang., J. Prakash., M. Lau., P. Zhang., M. Heinrich., D.N. Christodoulides and Z. Chen., Phys. Rev. Lett. **111**, 218302 (2013).
[5] S. Fardad., A. Salandrino., M. Heinrich., P. Zhang., Z. Chen., and D.N. Christodoulides., Nano Letters **14**, 2498-2504 (2014).
[6] R. El-Ganainy, et al. Opt. Express **15**, 10207 (2007).
[7] M. Matuszewski, et al., Opt. Express **16**, 1371-1376 (2008).
[8] R. El-Ganainy, Phys. Rev. A **80**, 053805 (2009).
[9] B. E. A. Saleh., M. C. Teich., A John Wiley & Sons, Inc., Publication, 2nd ed, U.S.A., ISBN: 978-0-471-35832-9, (2007).
[10] R. A. Terborg, et al., Opt. Lett. **38**, 5284 (2013).