Filamentation of Femtosecond Self-Bending Airy Beams

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Abstract: We report experimental observation of laser filaments generated by intense, femtosecond, self-bending Airy beams in air and water. The generated curved filaments act as streak cameras for the forward-emitted broadband conical radiation.

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Propagation of high-intensity ultrashort laser pulses in transparent dielectrics is a rich and interdisciplinary field of modern physics with a multitude of potential applications ranging from generation of extreme wavelengths to remote sensing to lightning control [1, 2]. During propagation of a high-intensity pulse in a Kerr medium, the self-focusing collapse of the beam is stopped (or arrested) by the onset of a defocusing process, the nature of which depends on the medium parameters and on the intensities involved. In gases, the collapse is stopped by the defocusing action of plasma generated on the beam axis via multi-photon ionization. In condensed media, the arrest mechanism typically involves pulse compression and breakup by the group-velocity dispersion (GVD). In either case, a sub-diffractive propagation of the beam results, and the hot core of the beam, that propagates over extended distances, is referred to as the filament.

High optical intensities inside filaments facilitate efficient nonlinear wavelength-conversion processes, resulting in forward emission of a broadband radiation (supercontinuum). Analysis of the angularly resolved spectra of this emission yields insights into pulse evolution and dynamics [3, 4]. In early studies of laser filamentation, laser beams with axially symmetric beam profiles were used, resulting in the creation of straight filaments [5–7]. Forward emissions from different sections of a straight filament overlap in the far field, complicating the analysis of this emission significantly.

Recently, a new class of optical beams has been discovered. These beams have transverse amplitude profiles described by a two-dimensional Airy function, and the main intensity features of these non-axially-symmetric beams have been shown to self-deflect on propagation, in the absence of any refractive index gradients [8]. Airy beams can be straightforwardly generated from ordinary Gaussian beams by passing the beam though a cubic phase mask, followed by focusing with a lens.

In a recent publication, the filamentation of ultra-intense Airy beams in air has been reported [9]. Pulse energies used in these studies were about 10 mJ, and the transverse beam dimensions were of the order of 1 centimeter. Beam deflections of about five millimeters were observed, and plasma channels generated by self-bending Airy beams were found to follow the curved beam trajectories. Forward emission by curved filaments was angularly resolved in the far field, thus enabling a detailed study of this emission along the optical path (Fig. 1). The experimental observations were in good agreement with numerical simulations.

Here we report filamentation of femtosecond Airy beams in a condensed medium (water). In this case, the GVD, which was negligible in the case of filamentation in air, is the major player in the propagation of the pulse. The

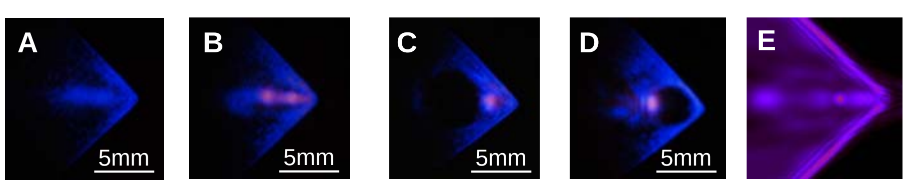

Fig. 1. Photographs of the far-field patterns of the forward emission by an Airy filament in air. The beam self-bends in the horizontal plane from left to right. A: Complete emission pattern at low pulse energy (5 mJ); B: Complete emission pattern at higher pulse energy (10 mJ); C,D: Emission patterns with the tip of the beam blocked at different locations along the propagation direction; E: Computer simulation of the complete emission pattern at 10 mJ pulse energy.

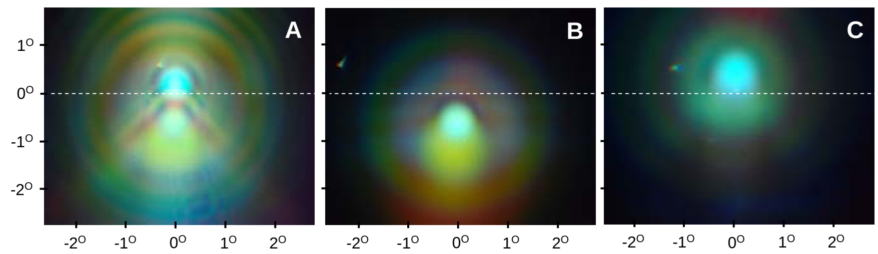

Fig. 2. Single-shot images of the forward emission patterns from a curved Airy filament in water. The beam self-bends in the vertical plane upwards. A: Complete pattern; B: Emission from the beginning section of the filament; C: Emission from the end section.

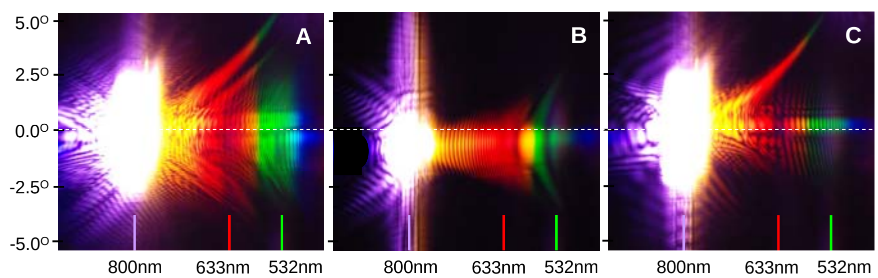

Fig. 3. θ - λ spectral maps of the forward emission corresponding to the direct emission patterns shown in Figures 3(A,B,C). Different X-wave patters are indicative of the changing character of the pulse evolution and splitting, along the beam path.

pulse evolution becomes excessively complex, and the streak-camera feature of the bent filament provides detailed information about this evolution. As in the earlier experiments in air, we started with 35 fs-long pulses with a Gaussian beam profile and transformed the beam into a 2D-Airy beam by using a combination of a cubic phase mask and a focusing lens. Pulse energy was fixed at 20μJ. The total propagation length in water was 6.5 cm, and the estimated beam deflection from a straight line was 85μm. We found that the forward emission was not uniformly distributed along the optical path, but was dominated by two partially overlapping bright spots. By inserting aperture and edge obstructions into the beam, we were able to selectively block either spot, while allowing the rest of the emission to pass through unobstructed (Fig. 2).

Angularly resolved spectral maps of the forward emission (the so-called θ - λ spectra [10]), in case of filamentation of ultrafast self-bending Airy beams in water, revealed how pulse evolution and splitting changed along the beam path. The spectrum of emission from the beginning section of the filament (Fig. 3B) has pronounced X-features at both long- and short-wavelength sides. According to earlier studies [3], this emission pattern suggests that the fully compressed 35 fs pulse underwent pulse splitting immediately after entering the water cell, and that the pulse waveform after splitting was dominated by the trailing daughter pulse. The spectrum of emission from the end-section of the filament (Fig. 3C) reveals a different pulse-evolution scenario. This pattern has a pronounced X-feature at the short-wavelength side, which is indicative of the strong leading-edge daughter pulse. The sharpness of the X-feature suggests that the daughter pulse survived over a long propagation distance of the order of several millimeters. This type of a diagnostic would be impossible with axially-symmetric beams (producing straight filaments). Thus filamentation with self-bending Airy beams provides the basis for a diagnostics tool that yields new insights into the complex evolution of ultrashort laser pulses in nonlinear media.

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