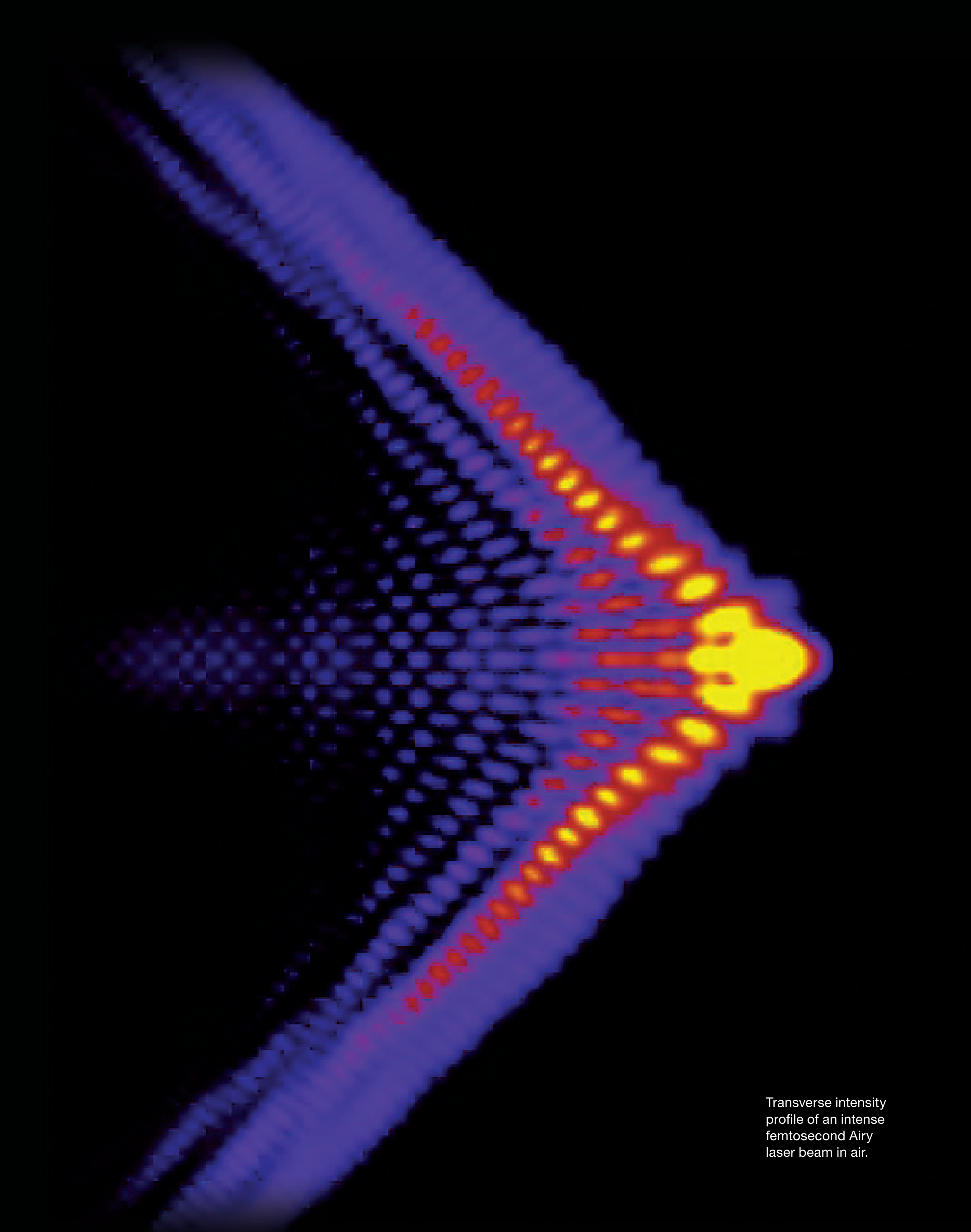

Transverse intensity profile of an intense femtosecond Airy laser beam in air.

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Extreme Nonlinear Optics with Ultra-Intense Self-Bending Airy Beams

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Recent research in nonlinear optics with ultra-intense and ultra-short laser pulses has opened the door to applications in remote spectroscopy, communications and atmospheric science. Smart beam engineering introduces a new degree of freedom into the already complex pulse-propagation scenario. This article reviews studies into the propagation of ultra-intense self-bending Airy beams in transparent dielectric media.

Over the past decade, physicists have made remarkable progress in developing ultra-high intensity, short-pulse laser systems. For example, multi-terawatt-class tabletop laser systems are now becoming commonplace in research laboratories around the world. These lasers typically operate in the near-infrared spectral range and generate very short optical pulses with repetition rates ranging from several hertz to several kilohertz. Remarkably, the peak power of these pulses equals or exceeds the total power generated by all electric power plants in the world combined.

Such multi-terawatt peak-power levels only last for a short while—the ultra-short pulsewidth—which is on the order of tens of femtoseconds. Yet this is long enough to enable very unusual regimes of interaction between laser fields and various media. The forces that such fields exert on electrons within atoms are comparable to or exceed the attractive forces between the electrons and the atomic nuclei. In this regime, the effect of the laser field on the bound electrons can no longer be treated as a small perturbation, which is the case in conventional nonlinear optics. The interaction of these ultra-intense and ultra-short laser pulses with matter falls into the domain of "extreme" nonlinear optics.

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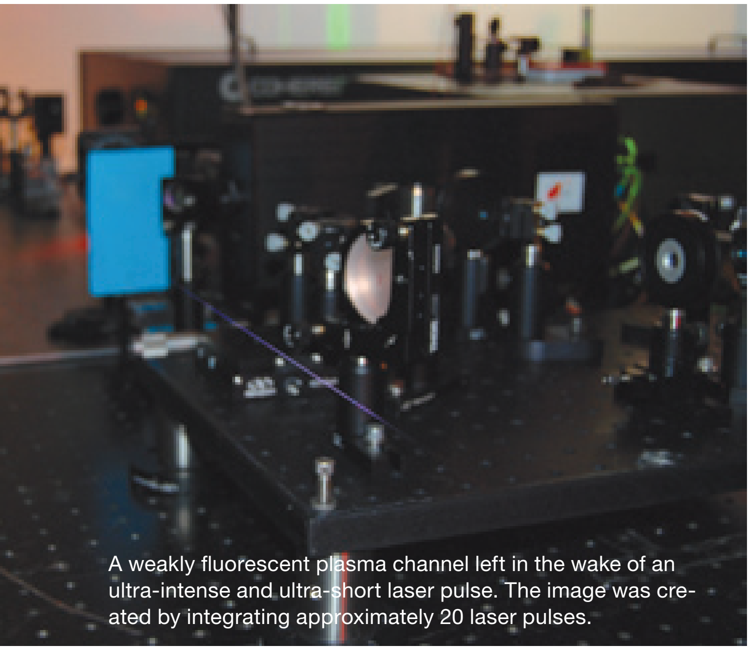


A weakly fluorescent plasma channel left in the wake of an ultra-intense and ultra-short laser pulse. The image was created by integrating approximately 20 laser pulses.

Laser filaments

Extreme nonlinear optics of gaseous media is of particular interest because of its potential applications in communications, remote sensing and atmospheric science. When an ultra-intense and ultra-short laser pulse propagates in a gas such as ambient air, the most practically relevant propagation environment, the beam tends to contract in the transverse plane due to self-focusing effects.

In principle, the self-focusing process can be perfectly balanced by diffraction for a certain beam diameter. However, this equilibrium state is known to be highly unstable. In such a case, mathematical analysis predicts that small fluctuations in the beam diameter or local intensity would lead to a catastrophic collapse and the beam will form a singularity—which is not physically possible. In reality, this collapse is prevented by the defocusing effect of the plasma generated by the ultra-intense laser field on the beam axis.

The dynamic interplay among these three effects—self-focusing, diffraction and plasma de-focusing—results in the apparent self-guiding of the laser wavefront. The intense beam core, which is about 100 μm in diameter, exhibits quasi-stable propagation over distances much larger than the corresponding diffraction length. Recently, it has been suggested that a fourth effect—the sign reversal of the Kerr effect—may also play a major role in this dynamic balancing act.

The peculiar object that is composed of the high-intensity laser field and the generated plasma and that exhibits the extended propagation is commonly referred to as a laser filament. Filaments have been shown to propagate over kilometers in ambient air. As the image above shows, the beam propagates from the left upper corner to the bottom right. The beam itself is infrared and hence not visible. On the other hand, what is clearly visible in the photo is the purple fluorescence of the ionized air molecules that are left in the wake of the propagating intense laser pulse.

Thus far, several studies have indicated that laser filaments are relatively immune to scattering and turbulence effects and that they are electrically conductive. Furthermore, the ultra-high intensity of light in the filament core coupled with the extended propagation distances facilitates efficient nonlinear conversion processes and results in the generation of a forward-emitted radiation that spans a broad spectral range, from terahertz to ultraviolet.

The unusual properties of laser filaments make them potentially useful for applications such as remote sensing and the detection of super-saturated water vapor in the atmosphere; guiding electricity and channeling lightning; generating extreme wavelengths; and tabletop charged-particle acceleration. Yet, in spite of more than a decade of intense research activity in this field and several high-profile demonstrations, harnessing the potential of laser filaments thus far remains elusive. There are many reasons for this—which become apparent when we examine the filamentation process more closely. As we will see, however, some of these obstacles can be effectively overcome by appropriately engineering the properties of the source field itself.

The aim of this article is to review recent filamentation experiments using ultraintense laser pulses with pre-engineered intensity profiles. As it turns out, patterning the transverse profile of a laser beam can profoundly modify the filamentation process and potentially offer the means for controlling and manipulating this complex phenomenon.

Airy beams

Virtually all prior studies of laser filamentation used intense laser pulses with Gaussian or flat-top beam profiles. Such beams are simpler to generate experimentally than more sophisticated beam shapes, and they are more straightforward to model and analyze. Due to the axial symmetry of such beams, the plasma strings generated through filamentation are always straight.

Very recently, a new type of beam has been introduced in the context of linear optics. The transverse electric-field profile of this new beam can be described in terms of a one- or two-dimensional Airy function. Accordingly, the beam is termed an Airy beam. A surface plot of the transverse intensity distribution of an ideal 2-D Airy beam is shown in the bottom left part of the figure on p. 41. Evidently, the beam profile lacks axial symmetry.

The spatial Airy wavepacket has been shown to constitute an invariant solution of the paraxial wave equation in free space; thus, the beam propagates seemingly without experiencing diffractive spreading. This behavior is analogous to that of the much-better-known Bessel beam. However, the most unusual property of an Airy beam is its ability to self-bend on propagation, when the entire beam pattern shifts sideways and traverses a parabolic trajectory. In analogy with a

Recently, researchers have realized Airy beams in the realm of ultra-intense femtosecond nonlinear optics.

mechanical free-fall, such self-bending is sometimes referred to as beam acceleration.

Note that this beam acceleration can occur even in free space or in a perfectly linear medium in the absence of any refractive index gradients. In fact, it results entirely from linear diffraction effects that constantly reshape the transverse beam profile. This reshaping entails constant elimination of some parts of the beam while re-creating them elsewhere. The net result is a beam whose intensity profile tends to continuously shift sideways. Given that the Airy function itself is not square integrable, the only practical realization of such beams requires that they are truncated or apodized.

Experimentally realizable truncated Airy beams still retain the propagation invariance and self-bending property of their ideal counterparts—but only for a finite propagation distance. For such truncated versions of Airy beams, the properly defined center of mass of the transverse beam pattern propagates along a straight line in accordance with the general principles of linear optics.

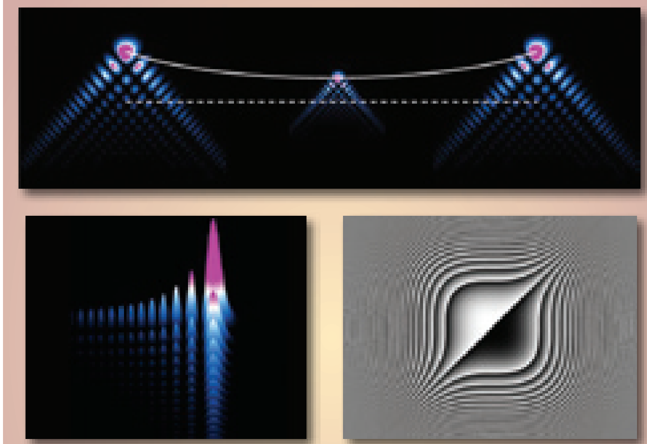
Contrary to what one may desire, light beams (in any shape or form) cannot be linearly curved around a corner or tied into a knot. For Airy beams, the maximum attainable beam deflection from a straight line is always limited by their total transverse extent. However, even with such curvature limitations, Airy beams bring new and exciting possibilities to optics, in both linear and nonlinear regimes.

How does one create Airy beams in a laboratory? It so happens that an Airy function $\mathrm{Ai}(x/x_0)$ and an exponential of a cubic phase factor $\exp\left[i(\beta K)^3/3\right]$ form a Fourier-transform pair. Thus, Airy beams can be generated from plane waves by imposing a pure phase transformation—by means of a cubic phase mask, for example—followed by a Fourier transformation. The latter can be achieved by either propagating the beam into the far-field, or by focusing the beam with a lens.

Recently, scientists have reported several exciting experiments that use the self-healing and self-bending properties of Airy beams. In one application, the self-bending property of these spatial wavepackets was applied to sorting microparticles. In another, a temporal analogue of the Airy beam was realized. This temporal Airy waveform propagated in a dispersive medium without spreading.

Such a wavepacket offers an alternative to solitons that also remain non-dispersing upon propagation. The difference is that the Airy pulse does so in a linear medium, while the soliton propagation involves a balance between dispersion and nonlinearity; it also requires high optical power. The dominant sub-pulse in the temporal Airy wavepacket propagates with a speed that is different from the group velocity of light in the medium and accelerates upon propagation.

[Airy beam: A new type of beam in linear optics]



(Top) Propagation of a finite-energy Airy beam in free space. The dominant intensity feature of the beam follows a parabolic trajectory, while the center of mass of the beam propagates along a straight line. (Bottom left) Simulated transverse intensity profile of an Airy beam. The sharp intensity spikes, including the dominant intensity feature in the corner of the beam pattern, propagate along curved trajectories. (Bottom right) Cubic phase mask used for the generation of Airy beam patterns. The grayscale image represents the phase-distribution modulo 2π.

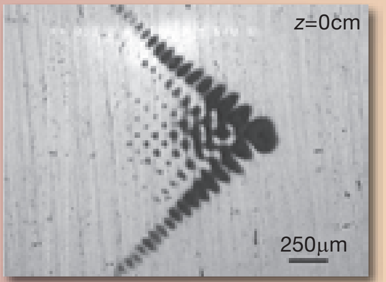
Extreme nonlinear optics with self-bending Airy beams

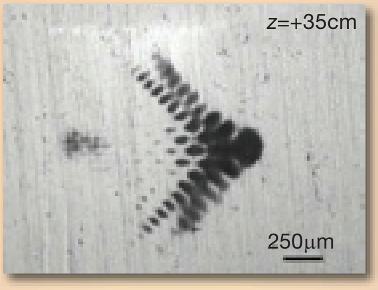
Recently, researchers have realized Airy beams in the realm of ultra-intense femtosecond nonlinear optics. In these experiments, 35-fs-long pulses with multi-mJ pulse energy and a Gaussian beam profile were transformed into femtosecond Airy beams by using a transmissive cubic phase mask and lens focusing. The self-bending propagation of these ultraintense Airy beams took place within about a 1-m-long air path.

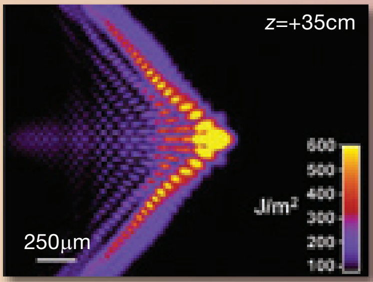
Only the dominant intensity feature in the corner of the beam pattern was intense enough to ionize the air in which the pulses propagated and to create a laser filament. Spatially resolved measurements revealed that the plasma channels that were left in the wake of the pulses followed the parabolic beam trajectory. The total length of the plasma channels was about 1 m, and the total beam deflection from a straight line was about 5 mm.

The numerical modeling of filamentation with Airy beams revealed that, at low pulse energies, the generated plasma channels were continuous. As the pulse energy was increased beyond approximately 10 mJ, the plasma channels developed the split-off secondary channels and bifurcated at several

[Airy beam self-bending and reshaping]

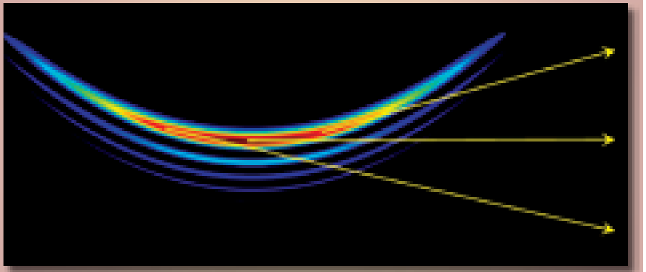






(Left) Burn pattern produced by an ultra-intense self-bending Airy beam on aluminum foil inserted into the beam path shortly after the Airy beam pattern is formed. (Center) Same after about 35 cm of propagation. In addition to the beam self-bending, the pattern exhibits a complex nonlinear reshaping on propagation. (Right) A numerical simulation accurately reproduces the major features of the beam reshaping.

[Angularly resolved forward emission by a curved filament]



The exact origin of the emission along the beam path can be determined from the location at which the emission is detected in the observation plane.

locations along the beam path. Furthermore, the transverse beam profile exhibited a strong nonlinear reshaping. The evolution of the beam profile was visualized by photographing burn patterns produced by the beam at several locations along the propagation direction. Numerical modeling accurately reproduced this behavior.

As pointed out above, perhaps the most practically relevant property of laser filaments in gases is their ability to emit broadband forward-propagating radiation. This allows them to be used as bright, directional light sources in various remote-spectroscopy applications, including laser-induced breakdown spectroscopy. In the case of conventional straight filaments generated by axially symmetric beams, the forward emission that emanates from different longitudinal sections of the filament overlaps in the far-field, rendering the interpretation of the resulting emission patterns difficult.

In the case of the curved filaments produced by self-bending Airy beams, the emissions coming from different points propagate along angularly resolved trajectories. As a consequence, the origins of these emissions in the observational plane can, in principle, be traced back to the particular locations along the beam path. This property can potentially add longitudinal resolution to remote spectroscopy applications of laser filaments.

Filamentation of self-bending Airy beams in condensed media

In order to demonstrate the power of the longitudinal resolution that was brought about by curved laser filaments, we conducted a follow-up study on the propagation of femtosecond Airy beams in a condensed medium (water). The nonlinearity in a condensed medium is three orders of magnitude higher compared to that in a gas. In addition, the group-velocity dispersion, which is very weak in gases, becomes an additional key effect that contributes to the pulse evolution. The propagation dynamics become excessively complex, and the curved nature of Airy beams allows for the detailed analysis of the pulse evolution along the beam path.

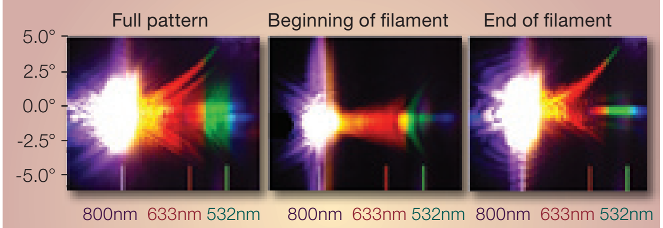
Because of the high nonlinearity of water compared to air, microjoule-level pulse energies are sufficient for the observation of highly nonlinear propagation regimes, including a rapid self-focusing. The experimental setup is essentially identical to that used in the experiments in air, but scaled down to the centimeter range. The self-bending beam propagation occurs in a 6.5-cm-long cuvette filled with water. The beam curves upwards as it propagates, and the total beam deflection from a straight line is estimated at 85 μm.

The curved filament's angularly resolved forward emission generated by the intense self-bending Airy beam in water is composed of stacked-up, partially overlapping patterns that originate from different locations along the beam path. By placing edge and aperture obstructions into the beam, the emission patterns emanating from the beginning and end sections of the filament can be isolated from the rest of the emission produced by the filament.

To gain a quantitative insight into the pulse evolution, we applied a versatile technique in which the emission patterns produced by the filaments are analyzed with the aid of an imaging spectrometer. In this approach, the emitted radiation

Researchers have recently introduced various other beam shapes in linear optics that can enable novel physics in the context of laser filamentation, such as parabolic beams and spiraling beams.

[Angularly resolved spectra of emission by a curved laser filament in water]



(Left) The complete emission pattern is composed of stacked-up and vertically shifted individual patterns originating from different points along the beam path. (Center) Emission pattern originating from the beginning section of the filament. This pattern indicates that a pulse-splitting event has occurred in which the trailing sub-pulse is the dominant one. (Right) Emission pattern originating from the end section of the filament. This pattern is representative of a pulse-splitting event in which the leading sub-pulse is the strongest.

is mapped onto a 2-D plot, in which the wavelengths of the emission are resolved along the horizontal axis while the emission angles are resolved along the vertical one. The resulting graph, the so-called θ–λ spectrum of the forward emission, conveys important information about pulse evolution inside the filament. Obtaining this type of information in any other way is virtually impossible, because light intensities inside laser filaments are extremely high, and any direct measurement apparatus would be damaged.

Photographs of the θ–λ spectra for the case of filamentation of a self-bending Airy beam in water are shown in the figure above. The left most image is the complete emission pattern. It is composed of multiple stacked-up patterns that originate from the emission events at different longitudinal positions along the filament. By inserting edge and aperture obstructions into the beam, it is possible to isolate the emission events that occurred in the beginning and in the end sections of the beam path.

The analysis of these patterns reveals a complex pulse-evolution scenario. As the pulse first entered the water cell, it almost immediately split into two sub-pulses, and the majority of the pulse energy was carried by the trailing sub-pulse. As this dual-pulse waveform propagated further, it dissipated; however, an intense single pulse was re-formed shortly afterward.

Finally, this intense pulse again split into two sub-pulses, but this time it was the leading sub-pulse that was dominant. This type of a diagnostic would be impossible in the case of an axially symmetric beam, since in that case the filament would be straight and the emission patterns emanating from different sections along the beam path would overlap in the observation plane.

Applications and future perspectives

These examples demonstrate that smart-beam engineering introduces an additional degree of control over the very complex propagation dynamics of ultra-intense and ultra-short laser pulses in transparent nonlinear media. In particular, using self-bending Airy beams results in unusual propagation regimes in which the linear self-bending property of the wavepacket competes against nonlinear self-channeling effects. Potential applications of these generated curved filaments include remote spectroscopy with added longitudinal resolution, table-top acceleration of charged particles along curved trajectories, and writing bent waveguides in glasses.

Moreover, researchers have recently introduced various other beam shapes in linear optics that can enable novel physics in the context of laser filamentation, such as parabolic beams and spiraling beams. The field of extreme nonlinear optics continues to evolve, and using exotic beam profiles for the generation of laser filaments in transparent media may enable exciting and unexpected applications.

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