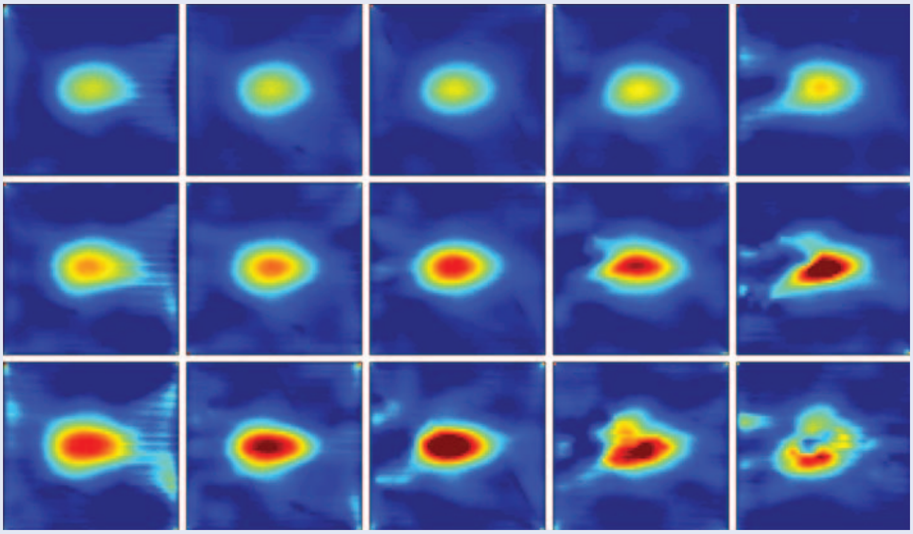
TOMOGRAPHY

## Movies of evolving objects from a single laser shot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Tomography is typically associated with the generation of cross-sectional images of a stationary object by measuring the absorption of radiation beams incident at various angles on the object. Now, Zhengyan Li and co-workers at the University of Texas in Austin, USA, report an adaption of tomography that uses a single laser pulse to generate movies of evolving 'light-velocity objects' — transient perturbations in the refractive index induced by pulses of light or high-velocity particles (*Nature Commun.* **5,** 3085; 2014). These tomographic movies, the frames of which are essentially slices in both space and time, reveal the spatiotemporal evolution of the object and can be used to examine phenomena as diverse as rogue waves, plasma wakefield acceleration and filament formation in gases.

Previously developed techniques can generate pseudo-movies of such objects by stacking snapshots obtained using different pulses in a time sequence. However, they are based on the assumption that each pulse evolves identically — something that does not hold for objects that evolve stochastically, propagate in turbulent media or fluctuate from shot to shot.

In contrast, the approach introduced by Li *et al.*, which they call frequency-domain tomography, employs a combination of four-wave mixing, second-harmonic generation and chirping in a nonlinear-crystal sandwich (HZF4 glass/β-barium oxide/HZF4 glass) to generate multiple probe pulses at various angles of incidence in a single step. As these pulses propagate through the medium they interact with the evolving object, and are imprinted with a 'phase streak' via cross-phase modulation in the process. The pulses are then simultaneously detected by a charged-coupled device detector in a spectrometer. Finally, a modified tomography algorithm is used to generate movie frames of the object moving through the medium.

The researchers demonstrated the effectiveness of the technique by using it to produce movies of a laser pulse propagating through a transparent Kerr medium. The movies revealed diffraction, self-focusing and filamentation of the pulse and were in good agreement with simulations based on the nonlinear Schrödinger equation.

The group leader, Michael Downer, told *Nature Photonics* that the team is currently investigating using the technique "to visualize plasma wakefield accelerator structures driven by petawatt laser pulses and charged particle bunches." He anticipates that "tomographic movies will open these structures to direct, immediate view in the laboratory and facilitate understanding, optimization and scaling of table-top accelerators and the future X-ray free-electron lasers that they will drive."

SIMON PLEASANTS

OPTICAL PHYSICS

# Extending filamentation

The introduction of a dressing beam to extend the reach of filaments promises a wealth of new applications that extend beyond the laboratory scale.

Günter Steinmeyer and Carsten Brée

Femtosecond filamentation is an appealing self-organization phenomenon in optical physics that has been awaiting practical applications for a long time. First described some 20 years ago[1], the collapse of the spatial beam profile of a femtosecond laser beam may lead to the formation of metre-long plasma channels in atmospheric air. These plasma channels resemble those generated by electric discharges but are absolutely straight, without any bends or turns. Despite the undisputed beauty of this phenomenon, femtosecond filamentation has led to only a limited number of applications to date (for example, pulse self-compression[2]). One critical issue hindering the development of many other attractive applications is the restricted length of single filaments.

Writing in *Nature Photonics*, Maik Scheller and colleagues describe the use of dressing laser beams as a promising new approach for generating extended single filaments[3]. With an experimentally demonstrated range of 2.2 m, the generated plasma strings are nearly an order of magnitude longer than filaments produced without a dressing beam. Moreover, numerical simulations predict that further scaling up to nearly 50-m-long single filaments will be possible.

Let us approach the underlying limitation from a physical perspective. If the power in an optical beam exceeds a certain critical value inside an optical medium, nonlinear optical self-focusing effects will kick in and initiate catastrophic collapse of the beam profile. These self-focusing effects may appear similar to the gravitational pull of a black hole that sucks in all matter once a certain critical mass is exceeded. Nevertheless, in contrast to a black hole, the collapse of an optical beam is expected to terminate at the scale of the wavelength, which is much smaller than the 100–200 μm diameter filaments observed in atmospheric air. For near-infrared wavelengths, it is generally agreed that plasma formation and the resulting defocusing play a decisive role in halting the collapse. The resulting dynamic balance of self-focusing and plasma defocusing may then give rise to guiding of a laser beam in a self-induced transient waveguide structure. In atmospheric gases, single filaments may reach lengths of a few tens of centimetres or even metres. Although it is easy to beat the few-centimetre Rayleigh range of a linear laser focus with this nonlinear self-confinement, single filaments cannot be extended to arbitrary propagation lengths.

To understand this limitation, it is important to analyse the two physical mechanisms responsible for the rather quick death of undressed filaments; these mechanisms are collectively known as dissipation. The first loss mechanism is based on the strong dependence of filamentation on plasma formation, namely the generation of free electrons via multiphoton absorption. However, the loss due to this process accounts for only a certain percentage of the total loss. The second and probably more important loss mechanism arises from the fact that self-guiding effects can support only a part of the temporal profile of a femtosecond pulse. Both loss mechanisms lead to continuous outward bleeding of the filament core (Fig. 1). It may seem straightforward to overcome these losses by simply increasing the input power, but this simplistic idea also faces immediate limitations. Exceeding the critical power by an order of magnitude will quickly lead to multifilamentation — a highly dynamic process that is unstable in both space and time[4].

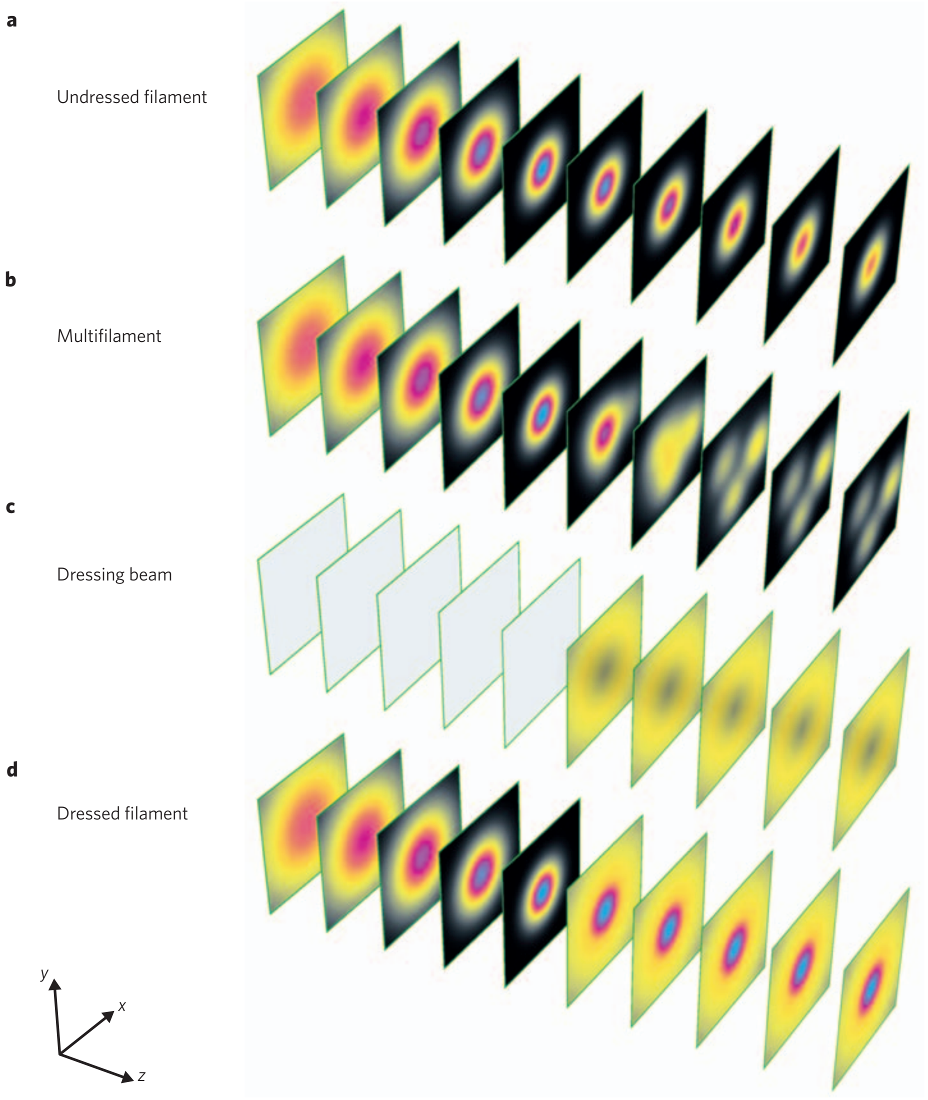

**Figure 1 |** Comparison of undressed and dressed filamentation. **a**, Propagating along the *z* axis, an unaccompanied Gaussian beam undergoes catastrophic collapse, which is halted by plasma formation. Dissipative processes quickly deplete the filament. **b**, On increasing the input energy, the regime of multifilamentation is reached, with each subfilament bleeding out at a similar rate as the single filament. **c**,**d** Suitable addition of an annular dressing beam (**c**) after initial filament formation may serve to compensate dissipative effects, resulting in a much longer extension of a dressed filament (**d**).

The seminal idea to overcome this dilemma is the use of a specifically shaped input beam, for example a Bessel-like beam, which has an annular structure. By its very nature, a Bessel beam possesses an inward energy flux towards its optical axis and is therefore ideally suited to serve as a dressing beam to replenish the filament core. Beams with suitable annular beam characteristics can be generated by axicon lenses or mirrors, and they display more favourable diffraction characteristics than Gaussian beams. By directly using such a beam for filament generation, one can in fact obtain a moderate improvement in the single filament length[5].

Scheller *et al.* have now gone one radical step further and combined a high-energy annular dressing beam with a low-energy Gaussian filament seed beam. In their scheme, the Bessel beam is expanded to a diameter that prevents filamentation of the isolated dressing beam. In contrast, the Gaussian beam is launched at a much higher intensity, such that it undergoes filamentation by itself. Without the dressing beam, this filament quickly dies out (Fig. 1). However, when both beams are employed, the Bessel dressing beam serves as an energy reservoir to replenish the filament on propagation, and the filament length is increased by more than a factor of ten compared with that realized by unaccompanied propagation. In contrast, launching the total available laser pulse energy in a single Gaussian beam produces far shorter filaments than this clever combination of seed and dressing beams. These experiments revive the photon-bath picture of filaments, according to which filaments quickly die out if the surrounding low-intensity region of the beam profile is clipped by a suitable aperture. Consequently, a filament can survive only if it is surrounded by a low-intensity reservoir of photons that can suitably replenish the unavoidable dissipative losses of the filament core. In fact, the experiments by Scheller and co-workers seem to constitute a beautiful confirmation of the photon-bath concept. Rather than relying on only incidental formation of a photon bath, it apparently pays to actively replenish this bath by an annular beam. This concept will almost certainly undergo further optimization, as it is not clear that Bessel-like beams are the ultimate answer for optimum replenishment.

Although the current work can certainly be considered a major breakthrough, further optimization seems necessary to scale the dressing concept towards atmospheric distances. For example, filaments have been considered as a means for triggering discharges and other weather phenomena on an atmospheric scale[6,7]. Other applications rely on the remote transfer of electrical energy through air. All these methods have been demonstrated on the few-metre laboratory scale, but it currently seems impossible to scale them to the hundred-metre scale — let alone ranges of kilometres. Therefore, despite the many beautiful laboratory demonstrations, only a few real-world applications of filaments have been realized so far. The demonstrated refuelling of filaments in mid-air may prove an important first step towards removing this restriction from the laboratory. With filament lengths of a few tens of metres within reach, it becomes possible to write plasma channels into air for triggering long-range discharges and to guide microwaves or optical radiation over extended distances through air. In fact, for the latter, there are also other highly promising new concepts[8], which, in combination with the current work of Scheller *et al.*, may help to solve this long-standing dilemma of filamentation. In any case, applications can greatly benefit from improved spatial confinement and strongly reduced dynamic instabilities relative to those obtained using multiple filaments. In other words, filaments may finally have come of age. ❐

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### QUANTUM PLASMONICS

# Two-plasmon interference

A new experiment demonstrates the first unequivocally quantum two-particle interference with surface plasmons. Subwavelength optical quantum information processing may be just around the corner.

Michael Steel

Even casual readers of *Nature Photonics* will have observed that plasmonics and integrated quantum photonics are two of the most active and rapidly developing fields in optics, being regularly featured in these pages. Although the general field of quantum plasmonics is also very active (for example, see Tame *et al.*[1] for a recent review), the particular field of the quantum behaviour of integrated surface plasmons is only beginning to take off.

In this issue, James Fakonas and colleagues from the Kavli Nanoscience Institute and the T. J. Watson Laboratory at Caltech in California, USA, report the first observation of two-plasmon interference that is unambiguously in the quantum regime[2].

A surface-plasmon platform for quantum optics offers the potential to realize subwavelength quantum devices, albeit at the cost of the significant losses that usually accompany plasmonics. Both the subwavelength scale and the losses make quantum plasmonics experiments challenging and exciting. The few experiments that have been performed in this area can be divided into several classes. The first class, performed around a decade ago, demonstrated the preservation of entangled states on propagation through plasmonic channels[3,4]. Akimov *et al.*[5] subsequently demonstrated the excitation and guidance of single quanta of plasmon modes by coupling to single-quantum emitters using a CdSe quantum dot coupled to a silver nanorod. Single-particle statistics were soon after observed in a similar system involving nanodiamond nitrogen–vacancy centres[6]. These were highly significant experiments because plasmonic waveguides and antennae are a natural means to interface atom-like qubits and optical quantum states, as many true single-quantum systems are strongly submicrometre in scale.

The present study by Fakonas *et al.*[2] addresses the quantum interference of two integrated plasmons (each a single quantum), which was first examined last year by Heeres *et al.*[7] (working in another Kavli Institute at Delft University of Technology). This is a notable step because two-photon quantum interference (here, two-plasmon interference) has become the *de facto* first test for an optical effect to be considered truly quantum. Higher complexity tests of quantum behaviour, such as Bell inequality violations with entangled states, typically follow this first confirmation of two-particle interference.

The result sought in such experiments is a Hong–Ou–Mandel (HOM) second-order interference curve, universally known as a 'HOM dip'[8]. This test relies on a curious cancellation phenomenon predicted by basic quantum mechanics. In its simplest form (see Box 1 and Fig. 1), two nominally identical (or 'indistinguishable') single