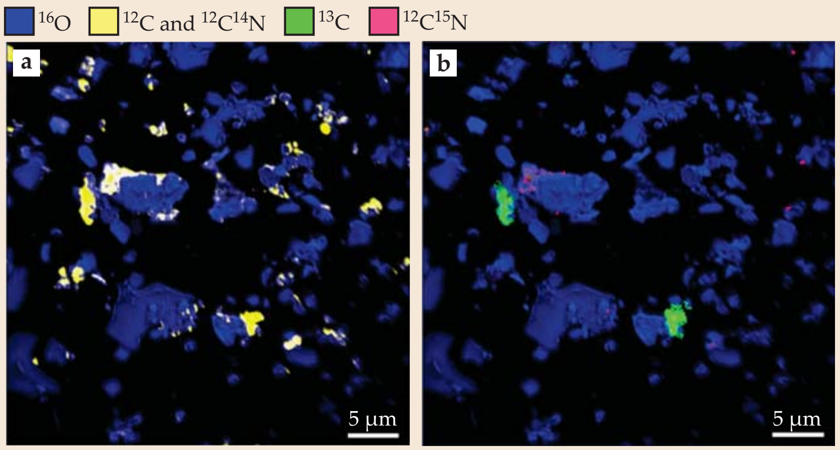

Figure 2. Nanoscale secondary-ion mass spectrometry images of clay-sized soil particles after three weeks of incubation with isotopically labeled plant litter. The oxygen-16 signal in both images shows the outlines of the mineral particles. **(a)** Organic matter, indicated by ^{12}C and ^{12}C^{14}N signals, covers about 20% of the total mineral surface. That fraction remained roughly constant over the course of the six-week experiment. **(b)** Newly incorporated organic matter, indicated by enrichment in ^{13}C and ^{15}N, covers a smaller but growing fraction of the area. (Adapted from ref. 4.)

for regions with unusually high fractions of ^{13}C or ^{12}C^{15}N, as shown in figure 2b. (The mass spectrometer is sensitive enough to distinguish between ^{12}C^{15}N and ^{13}C^{14}N.)

Images taken at different times necessarily showed different mineral surfaces. Even if nanoSIMS were a nondestructive technique, it would be impossible to retrieve the same clay particles from the incubator more than once. So tracking the labeled litter's progress in binding to the clay had to be done statistically. For each nanoSIMS image, the researchers determined the fraction of the total mineral area that contained ^{12}C and the fraction of the organic area enriched in ^{13}C. The former fraction did not change over the course of the six weeks, but the latter increased: At two hours, one-third of the organic area was isotopically enriched; at six weeks, more than half of it was. Clearly, the new organic matter was attaching to the clay, but it wasn't seeking out new mineral surfaces to bind to.

What makes rough mineral surfaces more hospitable to organic matter than smooth ones, and what makes some rough surfaces better than others? Kögel-Knabner and colleagues attribute the difference to microbial activity. The submicron nooks and crannies of mineral clusters make good homes for single-celled organisms, but not every suitable surface is populated by microbes.

So far, the researchers' nanoSIMS work has focused on just one type of soil—a topsoil taken from near their home in Germany and typical of soils in central Europe, the US, and parts of Australia and Asia. As a next step, they plan to extend their analysis to other types of soil and to study the effect of the soil particles' composition in addition to their size and shape. They hope that that work will paint a clearer picture of how much carbon soil can hold and how best to exploit that capacity.

Johanna Miller

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A long-lived optical waveguide made out of thin air

Sound and heat in the wake of a femtosecond laser pulse can produce a refractive-index gradient that channels subsequent higher-power pulses.

It isn't easy to deliver the concentrated power of a laser beam through air to a distant target—whether to disarm some military threat, say, or to remotely detect hazardous materials. The light diffracts, can be scattered and absorbed, and may experience phase-distorting turbulence and temperature fluctuations that blur its focus. Worse, a high-powered beam can suffer what's known as thermal blooming, in which the beam heats the air it passes through and spreads much faster than it normally would by diffraction.

If a beam is intense enough, though, it focuses itself—no lens required—thanks to the slight dependence of the index of refraction on light intensity. Brighter in the center than on its edges, a femtosecond pulse with peak power of a few gigawatts generates its own refractive-index gradient that causes the wavefront to collapse about the center and form a tighter focus. Positive feedback drives the self-focusing until the energy density grows so high that it ionizes nearby atoms. The resulting plasma, whose refractive index is lower than air's, defocuses the pulse until the intensity falls below the ionization threshold. That dynamic interplay between focusing and defocusing creates what's known as a filament, a pulse that acts as its own waveguide (see PHYSICS TODAY, August 2001, page 17).

Such filaments can cover nearly a kilometer without diffracting and will propagate through clouds and fog. Applications abound but suffer from a persistent limitation: Single filaments cannot deliver more than a few watts of average power. Self-focusing tends to amplify the noise in the beam profile such that any pulse loaded with more than a millijoule of energy splinters into multiple filaments from random hot spots across the profile. "The beam quickly becomes a mess," says Howard Milchberg of the University of Maryland.

Milchberg and his colleagues have now found a clever way to use an array of single filaments, each of low enough energy to remain stable, as impulsive heat sources that guide subsequent laser beams of much higher average power. As proof of principle, the researchers have demonstrated the waveguiding effect on energetic nanosecond laser pulses shot into the structured pattern of hot air in the wake of a square filament array.[1]

Theirs isn't the first filament-based

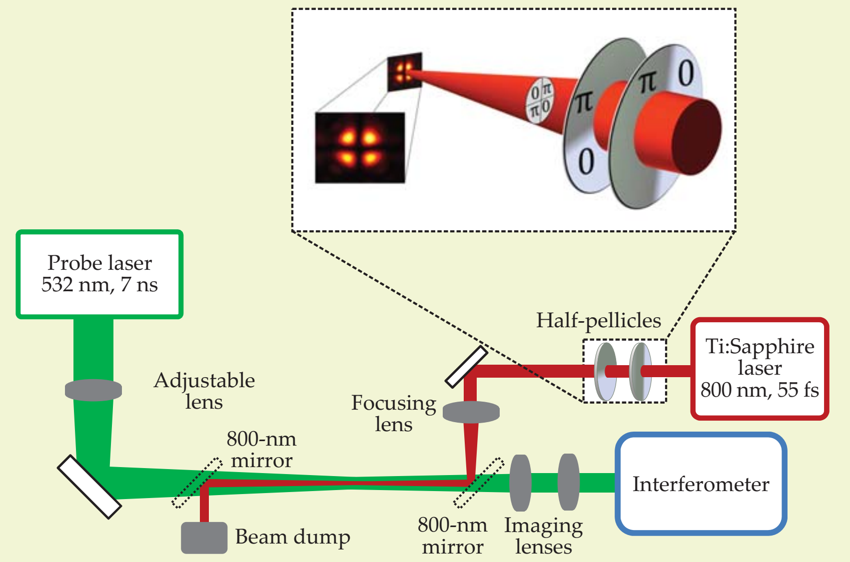

Figure 1. Optical setup. Near-IR 55-fs light from a titanium:sapphire laser is passed through two phase-shifting "half-pellicles" to generate an optical mode (inset) whose four lobes are focused down to intensities high enough to nucleate four parallel-propagating filaments. Pulses of green light from a 7-ns laser counterpropagate through the filaments and are imaged either directly onto a CCD camera (not shown) for waveguiding experiments or through an interferometer to measure the phase shift and thus the air's index of refraction. (Adapted from ref. 1.)

waveguide. Prior groups have sent microwaves through a cylindrical array of them.[2] Those schemes rely on using the filaments like conducting wires in a Faraday cage and depend on the presence of a plasma to work. But the filament's plasma survives just a few nanoseconds, which severely limits the waveguide's lifetime and utility. By contrast, the University of Maryland scheme relies not on the optical response of the plasma but on what happens long afterward, in the hydrodynamic response of the gas. And that response can last up to milliseconds—plenty of time to channel a stream of high-powered pulses.

Density holes

In late 2012 Milchberg's group wasn't thinking about waveguides but puzzling over the fundamentals of filament formation. A Swiss–French collaboration had argued that defocusing was caused not by the presence of plasma but by neutral atoms so perturbed by the high electric fields that their polarizabilities somehow shifted negative.[3] The controversy prompted Milchberg and company to use femtosecond laser pulses to measure absolute ionization yields in a variety of gases. Strangely, the yield turned out to depend on the laser's repetition rate: A 1-kHz pulse rate ionized fewer atoms per pulse than a laser run at 10 Hz. It became clear in the kilohertz version of the experiment that the laser light was interacting with a gas at lower-than-ambient density because the gas didn't have enough time to recover between pulses. Each filament had left behind a long-lived depression in gas density. What's more, the density hole deepened as the pulses accumulated.[4]

The group's hydrodynamic simulations bore out the same result. Hot electrons in the plasma quickly recombine with ionized atoms to re-form a neutral gas. Thanks to the gas's finite thermal conductivity, the absorbed pulse energy remains localized in the filament's roughly 100-µm diameter, where it becomes distributed among translational and rotational degrees of freedom. The result is a high-pressure region that launches a radial sound wave tens of nanoseconds after the filament passes. By a microsecond or so, the gas reaches pressure equilibrium with an elevated temperature and reduced density where the filament had previously been.

A gas density hole is equivalent to a drop in refractive index. And shortly after the researchers finished their experiments and simulations on single filaments, they were able to describe how a beam can be steered as its kilohertz-rate pulses interact with the gas.[5] But with its beam-defocusing hole, a single filament, according to their results, can only produce a diverging lens.

The group immediately began planning and setting up experiments to make ring-shaped holes with an internal density bump that might act as a focusing element. Thus it was confusing—and,

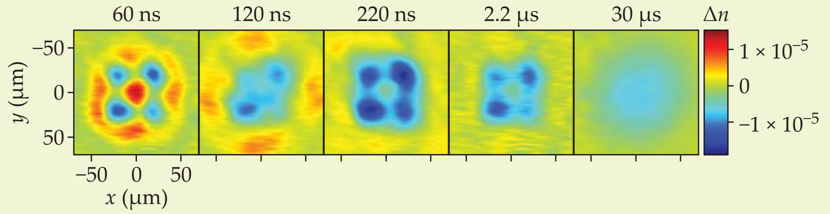

Figure 2. The structured pattern of air density. After a square array of filaments is produced by a femtosecond pulse ($t = 0$), spikes in air pressure at each lobe launch acoustic waves that constructively interfere in the array's center, positively shift the air's refractive index n there, and form a waveguide. After 100 ns or so, the acoustic waves have fled, but they leave behind density depressions in the corners. After a few hundred nanoseconds, the center's air density remains higher than its surroundings; the depressions slowly fill in by thermal diffusion. (Adapted from ref. 1.)

says Milchberg, depressing—when in July of last year he was handed a paper that his colleague Jared Wahlstrand had noticed on the arXiv eprint server. Researchers led by Oren Cohen at the Technion–Israel Institute of Technology had claimed just the opposite—that there exists a central positive-index enhancement in the wake of a single filament, and that they'd observed a waveguiding effect through it that lasts about a microsecond.[6]

Thinking he'd been scooped, Milchberg "moped around the lab, put my head in the sand, and didn't read the paper for days," as he puts it. When he finally read the paper, he was convinced the Technion group had to be seeing an artifact. Index changes can be directly inferred from monitoring phase changes in a separate, time-delayed probe beam that propagates through the filament to an interferometer. But it's key, he says, that the experiment be set up so that the filament and probe interact over just a short length—no more than a couple of millimeters. "Otherwise, the probe beam distorts in a way that's unrecoverable." Emboldened after verifying their earlier hydrodynamic simulations,[7] Milchberg and his group dropped everything and went on a "crash program" to finish the job they'd started. (Cohen and his group, meanwhile, stand by their own account.)

Thinking waveguides

The Maryland researchers' trick to building a long-lived waveguide was to use several filaments whose combined effect on the air's refractive-index profile mimicked that of an optical fiber: a higher-index core bordered by lower-index cladding. They tested the idea with a square array of four filaments propagating parallel to each other. One might think the most straightforward path to making such a structure would be to shine a pulse through four holes drilled in a plate and then focus the light down. "We tried that; it didn't work," confided Milchberg's graduate student Nihal Jhajj. "What's essential here is to provide not geometric shaping but phase shaping," which allows the beam to hang together as a single optical mode while propagating.

Jhajj, Wahlstrand, and two other students on the project, Eric Rosenthal and Reuven Birnbaum, instead prepared a four-lobed optical mode by appropriately modifying the phase of the electric field. Placing two strips of nitrocellulose—thin cellophane film, basically—in front of half the beam, as shown in figure 1, turned out to do the job. And fortuitously, the phase structure of the mode at low intensity was preserved at the extremely high intensities needed to seed four filaments from the four lobes.

The researchers formed a 2-mm-long filament array out of a 55-fs, 800-nm pulse from a titanium:sapphire laser and then used a series of counterpropagating 7-ns, 532-nm laser pulses to probe it. That arrangement allowed them to interferometrically measure the phase shift in the transverse direction and thus the refractive-index shift encountered by the probe beam as a function of time.

The air-density profiles shown in figure 2 encapsulate the group's central result: A short-duration acoustic regime begins as soon as 50 ns after the filaments form, when sound waves launched from the corners superpose in the array's geometric center and enhance the density there. Tens of microseconds later, a much longer-lasting and more stable thermal regime begins in which the higher-density center is surrounded by a moat of slowly thermalizing lower-density air.

Although the gas evolution outlined in figure 2 ends after tens of microseconds, the lifetime of the waveguide in the thermal regime can be several milliseconds in cases where the spacing between lobes is made larger. Milchberg and company injected a 110-mJ, green, 7-ns laser pulse through a 70-cm-long, 300-μm-wide filament waveguide, and they estimate that such waveguides can easily channel average powers on the megawatt scale, either as a single millisecond burst or a stream of pulses.

On the horizon

It doesn't require much heating to generate the required refractive-index gradient for a robust waveguide. Although the free electrons in the plasma are extremely hot (about 2 eV, or 23 000 K), the plasma density is just 0.1% of atmospheric density at sea level and raises the air temperature by only a few hundred kelvin.

But a femtosecond pulse may heat a gas more effectively without making plasma at all. Ultrashort pulses can induce a polarization in oxygen and nitrogen molecules and set them spinning like kicked rigid rotors.[8] Says Milchberg, "We think we can goose this effect to really high gas temperatures." The greater temperature gradient will, no doubt, boost a waveguide's lifespan and average power-carrying capacity. The latter is ultimately limited by gas heating as the guided laser beam flattens that initial gradient, after which thermal blooming takes over.

The researchers' method to make the waveguides is also scalable. They have built one out of an octagonal array of filaments—the greater the number of lobes, the larger the array can be, and the greater the power that can efficiently pass through it.[7] Because filaments can be initiated remotely, Milchberg and his students envision that their method's relevance can go beyond directed-energy applications. One scheme, for instance, would be to use the air waveguide as a remote collection lens to collimate distant optical signals that would otherwise radiate away isotropically. In that scheme, the locally launched waveguide reaches the distant source, captures its signal, and then channels it back to a local detector.

Other groups are paying attention. "The work is really nice," commented Princeton University's Richard Miles. "We're running around kicking ourselves for not having the same idea here."

Mark Wilson

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