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Viewpoint

A Waveguide Made of Hot Air

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The thermal wake left in air by a bundle of intense laser pulses can act as a channel for sending subsequent laser light over long distances.

Subject Areas: **Optics**

A Viewpoint on:
Demonstration of Long-Lived High-Power Optical Waveguides in Air
N. Jhajj, E. W. Rosenthal, R. Birnbaum, J. K. Wahlstrand, and H. M. Milchberg
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During the cold war, politicians spoke of weapon technologies that seemed to come from science fiction [1], including high-power laser beams for fighting remote battles in the sky. The ability to transmit a powerful laser beam through the atmosphere to a distant location—albeit for friendlier purposes—may become reality thanks to the latest discovery by Howard Milchberg and his colleagues at the University of Maryland in College Park. In *Physical Review X*, they demonstrate that a laser beam can be efficiently channeled through a gas and arrive at its destination with a much higher average power than was previously thought possible [2]. Their trick is to use a square-shaped bundle of four intense filaments of light that leave behind a trail of hot gas: The four hot air columns expand and create a central zone of higher-density air that serves as a waveguide for subsequent pulses of light. The researcher's method could be used to direct laser energy to remote locations, providing a new way to, for instance, nudge space debris out of Earth's orbit. Other applications include the remote detection of radioactive or hazardous materials and atmospheric laser communications.

To channel optical beams, researchers and engineers typically rely on waveguides like optical fibers. These fibers are made of a dielectric core with a high index of refraction surrounded by a "cladding" material with a lower refractive index. Light entering the fiber experiences total internal reflection and can thus be channeled over long distances (Fig. 1, top left). But conventional waveguides have two critical limitations. One is that fibers can be damaged by high-energy or high-power optical pulses. (A typical fiber—with core diameter ∼ 100 micrometers—can tolerate no more than 1 joule per square centimeter in a short, 100-femtosecond (fs) pulse and even less for longer pulses.) Another limitation is the impracticality of laying and controlling a physical optical fiber over an extremely long distance, especially if, as in the atmosphere, the fiber has no structural support.

Milchberg and co-workers have demonstrated a method for making a "transient" waveguide in air that tackles both challenges and opens up the possibility to guide optical beams with an average power of a few megawatts (MW)—roughly the same average power delivered by a small nuclear power plant. Their approach takes advantage of the changes to the optical density of air (or other gases) that occur in the vicinity of an intense filament of light [3]. When it propagates in air, a sufficiently powerful ultrashort laser pulse transforms into a narrow string of light, called a filament. These filaments form because the refraction index of air increases in the more intense central part of the beam, which then acts as a focusing lens that prevents light from spreading by diffraction.

Filaments are intense enough to ionize air molecules and can convey high intensities of light up to a kilometer away from the laser source [4]. But the average power they can carry is limited to roughly one watt (W), far below the megawatt levels needed for many proposed technologies. The reason is that most pulses powerful enough to cause filamentation are generated by solid-state lasers. Each pulse carries a high peak power of 1–10 gigawatts but the pulses are produced at the rate of 1000 pulses per second and each one only lasts for 100 fs, which means

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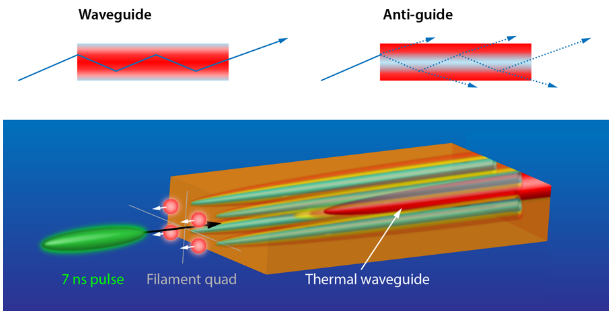

FIG. 1: (Top left) An optical fiber consists of a high-refractive index core (red) surrounded by a "cladding" (light blue) with lower index of refraction. The fiber can pipe light because the gradient in the refractive index causes total internal reflection of the light. (Top right) If the core of the guide has a lower refractive index as in the plasma wake of an intense filament of light, an optical beam injected in the pipe will leak instead of being efficiently guided. (Bottom) To create a transient waveguide in air, Milchberg and his colleagues generated a quadruplet of femtosecond pulses that generated expanding hot air in their wakes. The superposition of these hot air waves in the center of the quadruplet (red) has a higher refractive index than the surrounding air and can create a waveguiding effect for subsequent pulses of light for up to several milliseconds. (APS/Alan Stonebraker)

the average power is about a factor of ten billion times lower than the peak power—or less than a watt. Increasing the peak power of the pulse doesn't result in a higher throughput because the beam simply breaks up into multiple filaments. Each filament still only carries roughly 1 millijoule (mJ), and much of this energy is lost to heating the surrounding air.

Researchers speculated that the wake of a filament could be used as a waveguide for a subsequent, longer pulse that would deliver a greater average power. But it turns out that the dynamics of the gas in the wake of filaments aren't favorable. The dilute electron plasma at the trail of the filament pulse leaves a lower than average refractive index that defocuses light (i.e., an antiwaveguide, Fig. 1, top right) for any pulse launched less than 10 nanoseconds behind the femtosecond pulse. Once the plasma recombines, the laser energy given to the electrons is transferred to the air molecules, creating a hot air string that begins expanding in the radial direction [5]. In simple terms, this expanding air is a propagating sound wave that leaves behind lower-density air that acts as an antiwaveguide lasting for several microseconds.

What is clever about Milchberg and co-workers' approach is that they find a way to turn the long-lasting gas dynamics in the filament wake into an advantage. Instead of a single filament, the researchers generate four laser beams arranged in a square using a femtosecond laser. They prepare the quadruplet with a well-controlled phase difference between two neighboring beams (Fig. 1, bottom), which prevents the beams from fusing into a single central filament and keeps the quadruplet stable. The wake of air behind each individual filament still acts as a weak defocusing lens for any subsequent beam. But the center of the quadruplet turns out to be a "sweet spot" for guiding laser energy. The reason is that sound waves emitted by each column of hot air interfere and produce an overpressure of high-density air at the quadruplet's center that lasts for a few microseconds. During this time, this central column of air can act as a waveguide. Once the air pressure reaches equilibrium and thermal diffusion dominates the motion of the hot gas molecules, the gas profile evens out while preserving a hot, dense core of air surrounded by a moat of lower density air that lasts for up to a millisecond. Milchberg's team shows this thermal waveguide can efficiently channel a 110-mJ pulse of green light through 70 centimeters of air. In principle, if longer laser pulses can carry the same power without disrupting the thermal column, the technique could channel light carrying tens of joules of energy.

Guiding light energy or collecting light over distances of a few meters are both immediate applications of Milchberg's group discovery. Other applications that will need more development include cavity-free lasing in the atmosphere and atmospheric laser communication, both of which will require finding ways to keep the filaments parallel, stable, and uniform over distances exceeding the meter-range explored so far. A more speculative possibility is that the group's work could lead to the successful implementation of filament-based lightning protection, an idea proposed more than 15 years ago [6]. The idea was to use the plasma string behind a femtosecond pulse as an effective lightning rod, which would be faster to implement than wiring a rocket and less damaging to the atmosphere than cloud seeding. But the plasma was always so short-lived that discharges couldn't be controlled over more than a few meters. One way to increase the lifetime of the plasma string is to send a second, long laser or microwave pulse to accompany the filament. Milchberg's group findings now give a new kick to this proposal.

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