Air Waveguide from "Donut" Laser Beams

A waveguide sculpted in air with lasers transmits light over a distance of nearly 50 meters, which is 60 times farther than previous air-waveguide schemes.

By Ya Cheng

Conventional optical waveguides such as optical fibers and planar waveguides consist of a core surrounded by a cladding with a lower index of refraction. Light is efficiently confined in the core by total internal reflection at the core-cladding boundary. Optical fibers can transport light over 100s of kilometers, but there are applications—such as high-power transmission and atmospheric monitoring—where the use of fibers becomes impractical. Sending light directly through air is not an option, as diffraction effects cause the beam to spread out. A potential solution is to "sculpt" waveguides in the air with laser pulses that produce a low-density cladding around a central core of unperturbed air. Using a new method with donut-shaped beams, Andrew Goffin from the University of Maryland, College Park, and colleagues have created a 45-m-long waveguide in air [**1**], reaching 60 times farther than the record they previously established for an air waveguide. The achievement may enable delivery of high-power laser pulses to remote targets, opening up a range of applications such as remote sensing, lightning control (see Research News: A Laser-Based "Lightning Rod"), and microwave guiding.

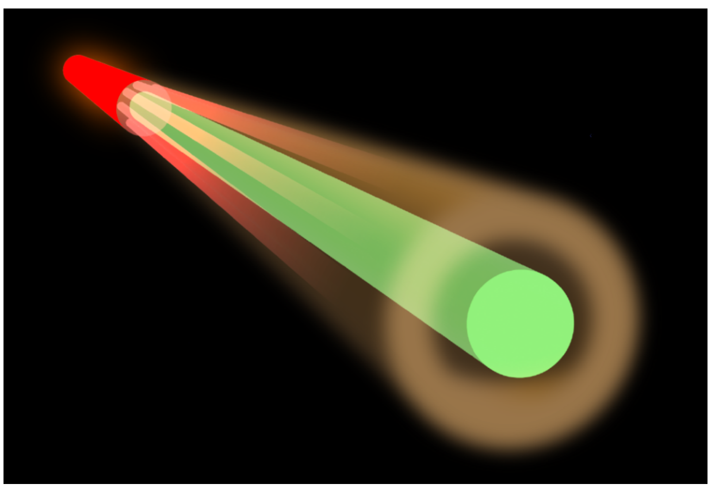

Figure 1: Researchers have used laser pulses with a donut-shaped profile to create an air waveguide. The pulses initially form thin filaments (red) that heat up the air and eventually form a low-density cladding (orange). Through this waveguide, the researchers are able to transmit a second laser pulse (green). **Credit: APS/A. Stonebraker**

The principle of an air waveguide is to fire a femtosecond laser pulse that opens a short-lived channel in the air through which a subsequent "probe" pulse can pass [**2**]. The first pulse generates the necessary refractive index contrast between the core and cladding by heating the air constituents (such as N_2, O_2, and noble gases). The heated air expands in such a way that the density of the cladding becomes lower than that of the surrounding air. The resulting air waveguide can last a few milliseconds—enough time to send the probe signal through it.

But one might wonder, why is the first laser pulse able to propagate ahead of the probe without spreading out? The answer lies in a nonlinear process, called filamentation, that results from the balance of two competing effects in air: a self-focusing effect induced by so-called Kerr nonlinearity and a defocusing effect induced by the formation of a plasma created by the pulse itself [**3**]. Filamentation can maintain a laser field narrowly confined over a distance much greater than that allowed by diffraction under linear propagation conditions. However, a laser filament can have a width no larger than $\sim$200 μm and a peak intensity no greater than $\sim 10^{14}$ W/cm^2, ultimately limiting the average power in the filament core. For this reason, the filaments generated by femtosecond laser pulses are not an effective means—by themselves—for delivering high power. But when used to generate an air waveguide, the filaments can create a path for high-power light beams.

Goffin and colleagues first demonstrated the principle of air waveguiding in 2014. In that earlier experiment, the team passed a red laser beam through a four-segment mask to create four laser filaments in a square pattern. These filaments formed a "light fence" that confined light within its core. The researchers used this air waveguide to transmit a 110-mJ pulse of green light over a $\sim$70-cm length in air (see **Viewpoint: A Waveguide Made of Hot Air**).

The team has now achieved an impressive extension of this earlier work. The relatively short length of the group's first air waveguide was due to the limited number of filaments in the light fence, which restricted the width of the waveguide and the strength of the density contrast between core and cladding. To increase the number of filaments, one could naively imagine using a mask with more segments to seed a larger number of filaments. However, in practice, it is difficult to ensure that the segments produce beam lobes with equal energy and locally smooth phase fronts. As an alternative, the authors use a donut-shaped beam or, technically speaking, a smooth Laguerre-Gaussian LG_{01} mode. They generate this mode using a spiral phase plate that concentrates the laser light into a ring with a diameter of a few millimeters (Fig. **1**). The concentrated light initiates random filamentation in a uniform distribution around the donut ring. Using a larger beam automatically produces more filaments—provided that the local laser fluence remains constant—which means the resulting cladding covers the whole waveguide circumference.

In a hallway next to their laboratory, the authors demonstrated air waveguiding over a distance of 45 m. Their waveguide generator was a 300-fs laser pulse with a wavelength of 800 nm and total energy of 120 mJ. This pulse was imprinted with the LG_{01} donut mode, causing it to form roughly 30 filaments around a ring with diameter of 5.6 mm. Through the resulting

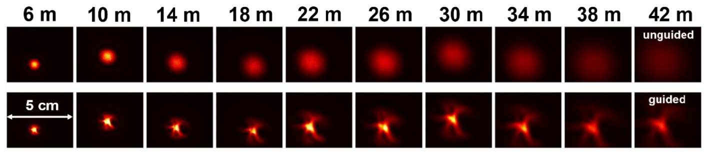

Figure 2: This series of images show the average intensity of the probe laser at different propagation distances. The top row gives the case without any waveguide, while the bottom row is with the air waveguide.
Credit: A. Goffin *et al.* [**1**]

waveguide, the researchers transmitted a 7-ns probe pulse with a wavelength of 532 nm and a total energy of 1 mJ. A detector recorded the amount of transmitted light at various distances, showing that the light delivered was around 20% greater with the waveguide than without (Fig. **2**). The researchers also showed that the air waveguide had a long lifetime of tens of milliseconds.

This waveguiding scheme, however, has a few drawbacks, including a relatively high propagation loss, a poor mode profile of the guided beam, and a high energy consumption in the formation of the air waveguide. To improve the scheme's performance, researchers will need to develop more sophisticated light-sculpture techniques. If the initial donut beam can be made more uniform, then the multiple filaments should form in a more deterministic way, and this should lead to air waveguides that are more stable and reproducible.

In the future, the authors envisage air waveguides that can deliver high-power light over distances of a kilometer or more. They estimate that achieving kilometer-scale transmission will require a high-energy (up to 2 J) LG_{01} pulse supporting ring coverage of 40–80 filaments. Such air waveguiding opens the door to many practical applications requiring efficient laser-energy delivery to remote locations in the atmosphere. One example is detecting gas pollutants by exciting them with UV light carried through the atmosphere by an air waveguide [**4**, **5**]. The emitted light from the excited pollutants could then be analyzed spectroscopically. A similar scheme could remotely detect radioactive materials [**6**]. Another possible application—which was recently demonstrated—is lightning protection through the generation of a plasma channel that could guide lightning to the ground.

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