Combating Thunder and Lightning with Lasers

Ultra-short pulses of light from a high-power laser allow long plasma channels to be generated in the air. This technology is not only useful for atmospheric research, it could also lead to significantly improved protection against thunderstorms

When a state-of-the-art, high-power, ultra-short pulsed laser was put into operation in Jena in 1996, new and previously undreamt possibilities became a reality for researchers. This high-power laser does not emit light continuously, but rather, it generates very short bursts of light referred to as pulses every tenth of a second. Each pulse lasts for a mere 100 femtoseconds, which is only 0.000 000 000 000 1 seconds and corresponds to the length of time it takes for light to travel the breadth of a human hair. However, in this very short period of time, these laser pulses posses a peak power of four terawatts, which is more than the total power output of all of the power stations in Europe combined. By irradiating matter with these laser pulses, it is possible – even in air – to break up a medium into its electrical constituents if the light is sufficiently concentrated. This in turn results in a bright flash of light referred to as a plasma focus.

When the laser in Jena was launched, researchers hoped that it would be possible to generate a plasma focus several kilometres long in the atmosphere and, in doing so, make an age-old dream come true: to create an artificial star, a guidable source of white light in mid-air. This would not only enable astronomical telescopes to be calibrated more precisely, but also allow fundamentally new remote sensing methods for atmospheric research. This is a particularly important challenge in view of the alarming climatic developments such as global warming, ozone depletion at high altitudes and increased ozone pollution at low altitudes.

Left: A spectacle of nature – jagged lightning cuts through the sky. Above: An artificial bolt of lightning in the evening sky: High-power pulses of laser light generate a long, white ray of light (a plasma focus) shining in the sky. This picture was taken from the courtyard of the Department of Physics at the University of Jena.

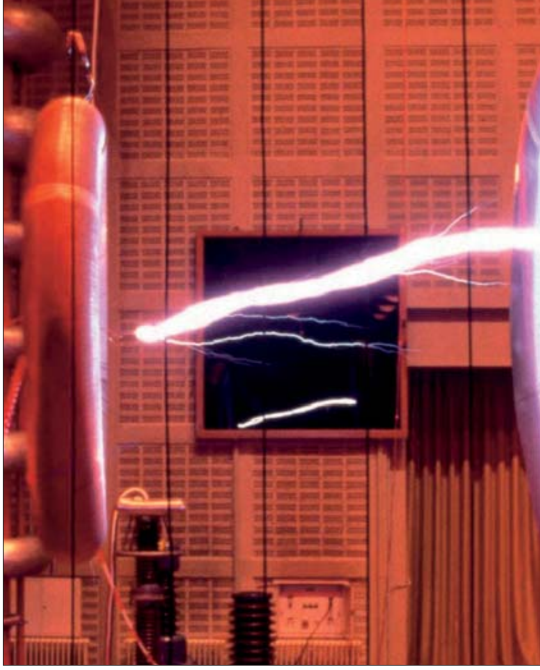
The Jena laser was directed vertically into the sky using a slightly convex lens to bundle the beam of laser light. Its pulse structure was designed in such a way that the blue component of the emitted light, which travels more slowly in air, was emitted ahead of the faster red component. This allowed for the different spectral constituents in the beams to converge after travelling for a certain distance in the air. Since the infrared light emitted by the laser should barely be visible to the naked eye, the spectral and temporal behaviour of the backscattered light was observed using a telescope, a spectroscope and suitable optical sensors similar to an optical radar, which gives this technique the respective name of LIDAR (Light Detecting and Ranging).

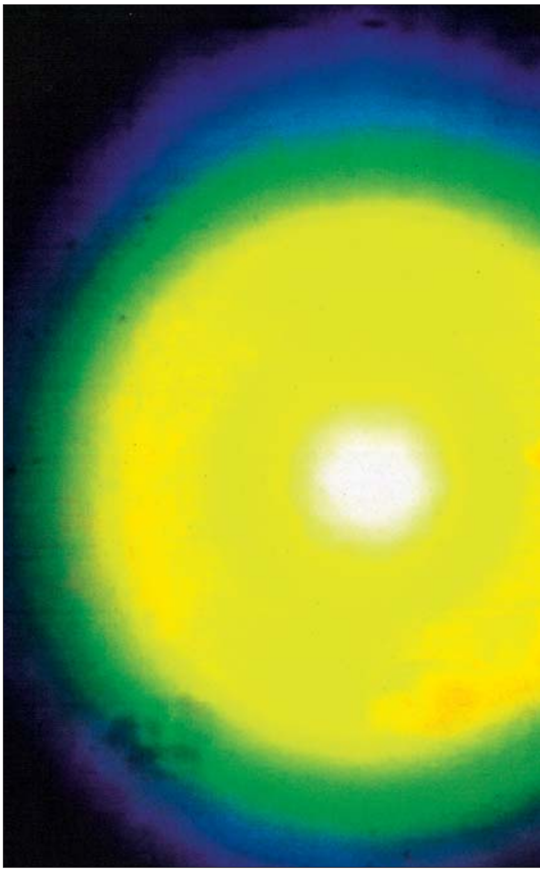
The results were astonishing from the very start. Instead of a dim plasma focus in the distance, a long channel of white light stretching out into the sky was clearly visible.

Spectral analysis of this ray of light revealed that it spanned the spectrum from the ultraviolet to the infrared. By measuring the time of flight for returning to the source, it could be determined that the white light had been emitted from altitudes of up to 12 kilometres. Similar light channels generated in the laboratory were found to be electrically conductive, meaning that they constitute plasma channels. This effect was of such great interest to scientists and promised such a wide range of applications that the Deutsche Forschungsgemeinschaft (German Research Foundation, DFG) and the Centre Nationale de la Recherche Scientifique (CNRS) decided to establish a Franco-German research project called Teramobile. The first stage of the project involved the development of a mobile femtosecond LIDAR system that could be used collaboratively to study the various aspects of the plasma channels observed in different locations. The experimental realisation of the Teramobile system is identical to the first system used in Jena, except that an extremely compact construction was chosen in order to allow all of the apparatus, including the laser and the receiver, to be housed in a mobile air-conditioned freight container. The apparatus has now been used to conduct measurements in Palaiseau, Berlin, Lyon, Jena, Toulouse and New Mexico.

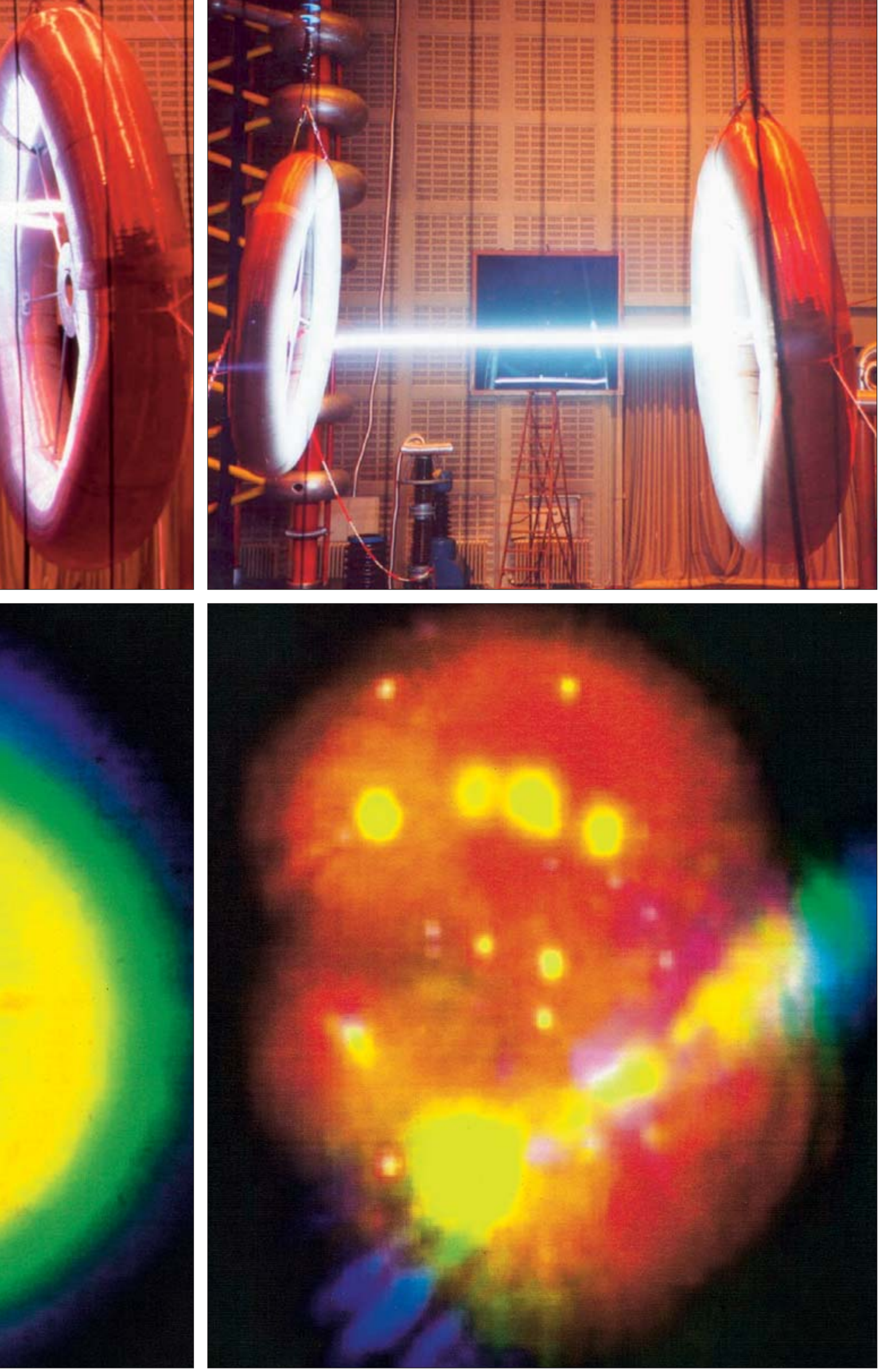
The physical phenomena that lead to the formation of a plasma channel – an effect that had previously been observed in the laboratory – are easily explained: the speed of light in air is ever so slightly reduced when it is exposed to light of such high field strengths, which in turn increases the refractive index in the air. The bell-shaped intensity distribution of the laser pulse makes this effect act as a lens that causes bundling of the laser beam, an effect generally referred to as self-focusing. This culminated, high-intensity light is capable of striping electrons from the air the beam passes through, causing ionisation of the air molecules. These electrically charged particles bring about a reduction in the air's refractive index. This in turn causes a divergence in relation to the bell-shaped intensity distribution of the laser pulse, leading to diffusion or defocusing of the laser beam. The combination of effects that result in focusing and defocusing allows the laser beam to propagate along thin, intense filaments, with the femtosecond temporal structure of the pulse being retained. At higher intensities, the single filament breaks up to form a bundle of filaments, a process referred to as multi-filamentation. This type of self-guiding filament has been observed to propagate over several kilometres in the atmosphere. The effect is just one example of a novel optical phenomenon termed optical turbulence. The broad spectral content of the white light generated in the propagation through the filament is due to the self-phase modulation of the high-intensity laser pulse in the atmosphere, where the term phase-modulation refers to the creation of new wavelengths or colours of light within the spectrum of the laser pulse as a result of the varying refractive index. Of particular interest is the spectral content of the white light measured after passing through an atmospheric absorption path. In this context, a large number of spectral lines have been observed that could be assigned to individual constituents of air. Careful scrutiny of the spectral content thus makes it possible to determine the composition and general properties of the atmosphere. So far, it has been possible to obtain information on ozone concentration, temperature and relative humidity at heights of up to four kilometres using this method. The unexpectedly high signal strength of the spectra that have been obtained indicates that the white light emitted by the plasma channels is predominantly backscattered, meaning that it travels back to the transmitter. This makes a very precise observation of the atmosphere and measurement of atmospheric pollutants possible.

The Teramobile project uses a compact LIDAR system that can be used in different locations





The obtained spectra not only contain the "signatures" or "finger prints" of gases, but also reveal im-



Top left: Spontaneous high-voltage discharge between two electrodes three meters apart. Top right: Directing a laser beam at the discharge transforms it into a controlled discharge that follows a straight path. Bottom left: In the air, the laser beam is transformed into a plasma channel that emits a variety of colours. Bottom right: Increasing the power of the beam causes multiple plasma channels to form.

portant information about aerosols, very fine suspensions of solid or liquid particles in the atmosphere. For instance, an analysis of the light signal allows for the aerosols' characteristics such as abundance, size and state of aggregation to be determined. This gives a justified cause for the hope that in the future, remote detection will be used not only to detect airborne water, dust and soot particles, but even pollen, spores or bacteria.

The intensity of the light within the filament is even sufficient to generate bright plasma sparks from solids, with a clear spectral signature that reveals the composition of the material being irradiated. Using this method, it was possible to identify the copper in the roof of a church at a distance of 100 meters. This offers a great potential for applications in the remote analysis of inaccessible locations such as fires, chemical reactors or contaminated rooms, where a quick and safe examination from a distance is easily possible.

The fact that these plasma channels are electrically conductive also raises the possibility of performing electrical discharges in a controlled manner over large distances. So far, this has only been demonstrated by an electrical discharge three meters long in air. The voltage was set so that no discharge took place without the laser. However, when a plasma channel was emitted, the discharge was released and followed a straight path through the air along the filament bundle. This experiment clearly demonstrates the potential such filaments have for use as lightning conductors. To date, lightning in thunderstorms has only been discharged successfully on a straight, controlled pathway using metal wires that were fired into storm clouds from the ground with rockets. Yet, it is only a logical step to replace these wires with plasma channels in order to be capable of safely discharging storm clouds in a controlled fashion, before lightning strikes. This is an especially important application in aviation – particularly for take-off and landing – as aircraft remain vulnerable to lightning strikes despite the numerous safety precautions that are already taken.

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