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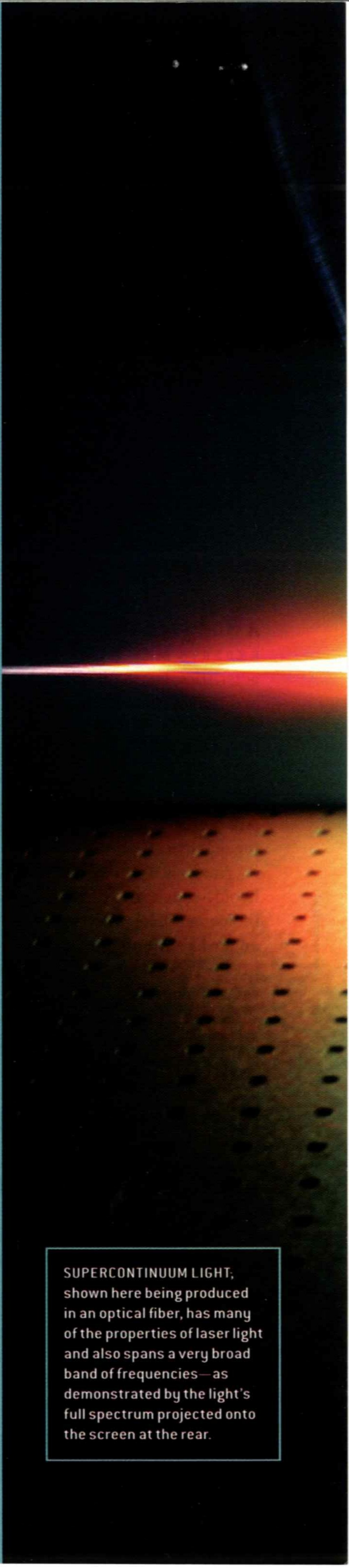
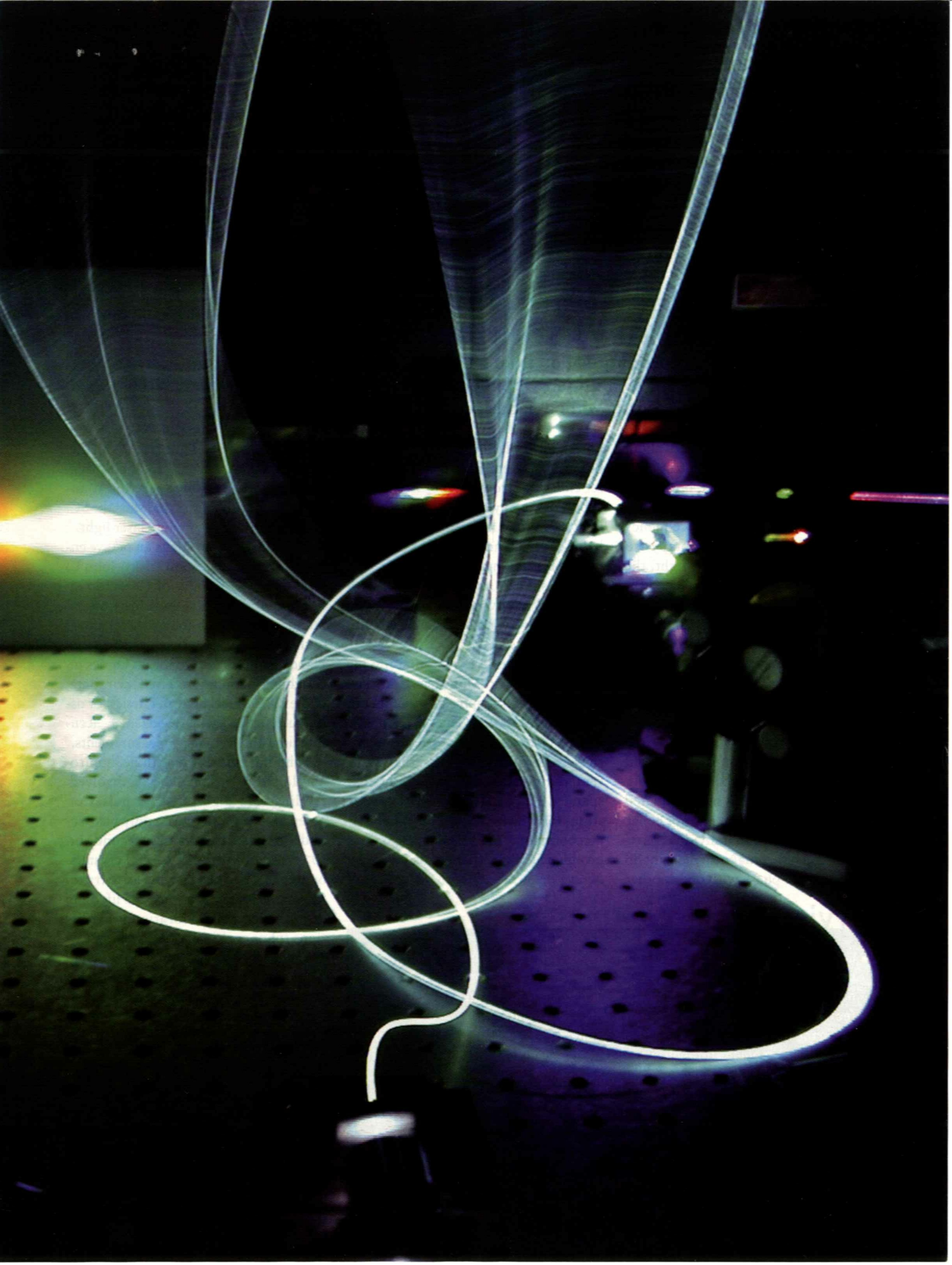
THE ULTIMATE WHITE LIGHT

By Robert R. Alfano

"Supercontinuum" laser light has enabled the most precise frequency and time measurements ever and might drive optical data transmission rates to record speeds



SUPERCONTINUUM LIGHT, shown here being produced in an optical fiber, has many of the properties of laser light and also spans a very broad band of frequencies—as demonstrated by the light's full spectrum projected onto the screen at the rear.



LIGHT IS ONE OF THE MOST IMPORTANT AND VERSATILE PHENOMENA IN NATURE.

Like a courier, it can transfer information from one point to another. Like an alchemist, it can alter matter. More specifically, it can initiate and moderate key processes in chemistry, biology and condensed matter. And of course, without it one could not see.

The versatility of light comes about because of the many forms it can take: brief flashes, focused spots, broad continuous beams, dim or intense light, polarized light, low- or high-frequency light, and light containing many frequencies at once. For visible light, the frequency determines the color and is related to the light's wavelength (shorter wavelengths correspond to higher frequencies). That most familiar of artificial light sources, an incandescent bulb, emits light across the full visible spectrum, resulting in white light.

If you want to do anything other than bathe a room in a warm glow, however, light from an incandescent bulb has several drawbacks: it is relatively low intensity, it is not collimated in a single direction and it is not coherent, meaning that the individual particles (photons) that make up the light do not oscillate in phase with one another. Lasers solve all three of those problems, but instead of emitting white light, a laser emits a narrow band of frequencies at best. For many applications, coherent light at a single frequency or a narrow band of frequencies is more than adequate. But having a light source that combines the properties of a laser with the broad bandwidth of an incandescent bulb opens up a whole new realm of possibilities.

In 1969, while I was pursuing my Ph.D. at New York University, I worked with Stanley L. Shapiro as a member of the technical staff at General Telephone and Electronics Laboratories (now Verizon) in Bayside, N.Y. Together we invented a new kind of laser light that spanned a large part of the visible spectrum, for which I coined the name "supercontinuum" (SC). Today researchers produce SC light that spans an entire octave or more. As with an octave of sound, an octave of light extends all the way from one frequency to double that frequency. The visible spectrum is approximately an octave, and thus the SC realizes the dream of white laser light.

Overview/*Supercontinuum*

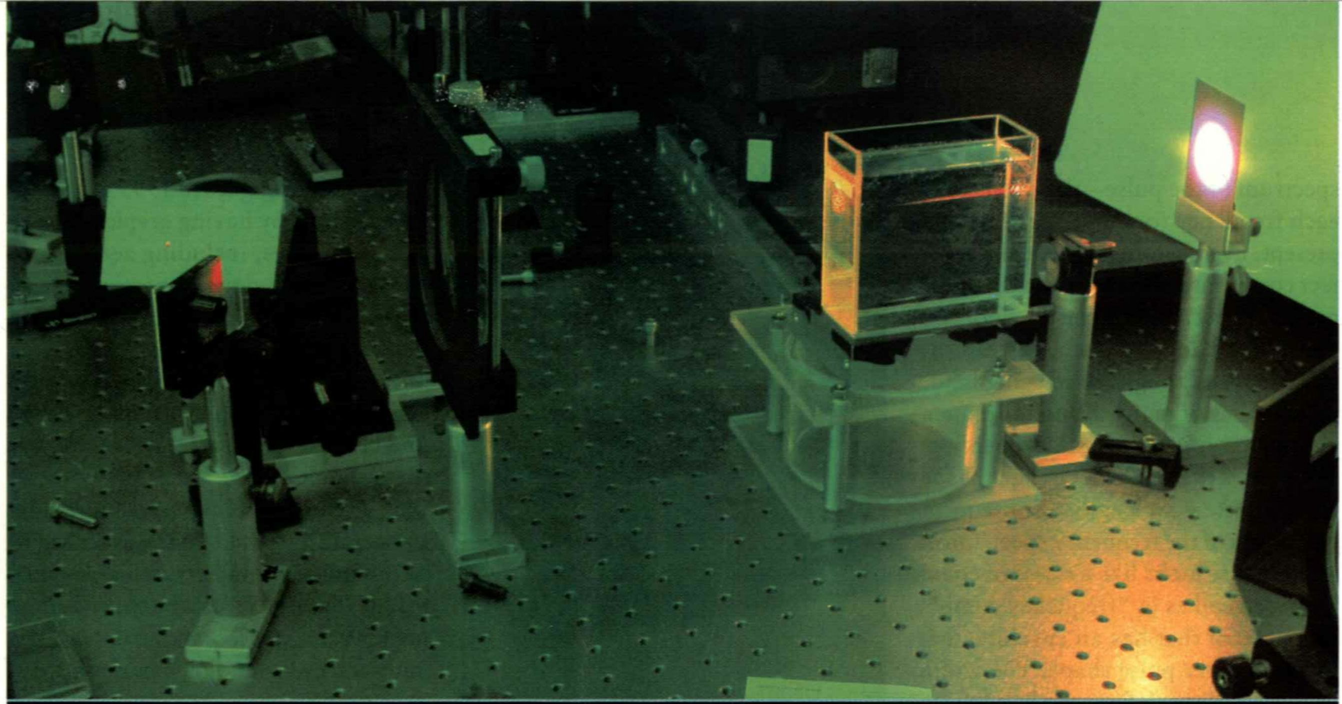
- Laser light is so useful because it has high intensity and a property known as coherence. Unlike white light, however, laser light usually contains only a narrow band of frequencies. "Supercontinuum" light combines the useful features of laser light with the broad bandwidth of white light.
- Today the favored method for producing supercontinuum light is to send high-intensity laser pulses through specially designed optical fibers. As the light travels down the fiber, it interacts with the fiber material by a number of so-called nonlinear optical processes that broaden its bandwidth.
- Applications for supercontinuum light include extremely accurate frequency and time measurements, high throughput telecommunications, detection of chemicals in the air, and medical imaging.

A laser light that spans an octave enables certain very useful tricks. John L. Hall of the University of Colorado at Boulder and the National Institute of Standards and Technology there, along with Theodor W. Hänsch of the Max Planck Institute for Quantum Optics in Garching, Germany, received their share of the 2005 Nobel Prize in Physics for using such light to achieve extremely accurate time and frequency measurements.

The basic technique that Shapiro and I used to produce the SC involved sending very high intensity pulses of green laser light that were only picoseconds long (trillionths of a second, or 10^{-12} second) through special crystals or glasses. I had been setting up to try to determine for the first time the lifetime of high-frequency vibrational excitations (phonons) in crystals such as calcite when I observed white light being generated. The light pulses had interacted with the medium in a way that broadened their bandwidth dramatically. Later, we also used liquids, and others used liquids and gases as the interaction medium to extend the SC spectrum further into the infrared.

The first application of the SC was to study the dynamics of vibrational excitations in liquids [see "Ultrafast Phenomena in Liquids and Solids," by R. R.

COURTESY OF JONATHAN KNIGHT *University of Bath (preceding pages)*



EXPERIMENTAL SETUP to produce supercontinuum light sends high-intensity laser light (*red*) through a suitable optical medium (here a container of liquid) that greatly broadens the light's bandwidth (*white light*).

COURTESY OF ROBERT R. ALFANO

Alfano and S. L. Shapiro; SCIENTIFIC AMERICAN, June 1973]. Soon thereafter investigators also used the SC as a novel tool to probe fundamental picosecond and femtosecond (10^{-15} second) processes. These included the primary chemical events that occur when photons of light are absorbed in photosynthesis and vision, the individual steps that make up chemical reactions, and the ways that molecules excited by light can relax without emitting light themselves.

In 1999 a new boom in SC research began when Jinendra K. Ranka, Robert S. Windeler and Andrew J. Stentz of Lucent Technologies generated an SC in a special kind of optical fiber. Among other advantages, the fiber confines the light to a small cross-sectional area, maintaining high intensities even as the light travels over long distances. (The nonlinear optical processes that the SC relies on become more pronounced at high intensities.) Researchers can also tailor the way that the optical properties of the fiber vary for different frequencies of light so that they optimize SC generation and exploit new physical effects in manipulating the light. As a result, today the SC has a plethora of applications, including extremely accurate time and frequency measurements, high-bandwidth optical communications, atmospheric science, an imaging technique called optical coherence tomography, the compression of ultrashort pulses to even shorter time spans, and perhaps spatial gravity measurements for oil and mineral detection.

Producing the Supercontinuum

MANY DIFFERENT physical effects can contribute to the bandwidth broadening that results in SC pulses. The main one is a process known as self-phase modulation, in which the light modifies the material it is passing through in such a way that the altered material, in return, acts on the light to increase its bandwidth. To understand how this process works, consider the detailed waveform of a laser pulse: a graph of the electric field of the pulse would show a series of oscillations that start off small, grow to some maximum size and then diminish to nothing again [*see box on page 69*]. The general outline, or envelope, of the oscillations defines how the light's intensity steadily rises and then falls over the course of the pulse. How the oscillations travel through the medium depends on a property of the medium called the refractive index. The speed that light travels in a medium is the speed of light in a vacuum, *c*, divided by the refractive index.

Now, if the pulse has a sufficiently high intensity, the wave's electric field significantly distorts the electron clouds of the atoms making up the medium, increasing the material's refractive index at that location by a small amount. This phenomenon, called the optical Kerr effect, alters the phase of the pulse's oscillations, meaning that it alters the positions of the oscillations' peaks and troughs. Specifically, the increased index delays the peaks and troughs.

The amount by which the refractive index increases depends on the light's intensity, so as the pulse passes by a given location in the medium the refractive index there varies continuously, and so do the induced phase changes. In the front half of the pulse, the intensity and thus the refractive index are rising in time, so the relative positions of the peaks and troughs are increasingly delayed, which reduces the frequency of the wave. In the rear half, the index is falling in time and, correspondingly, the wave's frequency is increased.

When the pulse emerges from the medium, its oscillations are wider at the front of the pulse and narrower at the rear. Graphed, it looks somewhat like a spring stretched between two points with the middle of the spring pulled a short distance toward one end.

The broadening of the bandwidth becomes clearer when we consider the spectrum of the pulse—the intensity of each frequency (or wavelength) that is present. Even before the optical Kerr effect comes into play, a pulse such as the one I have been describing does not consist of one pure frequency. Instead the pulse can be thought of as being made up of waves of many different frequencies added together. One property of any laser is that it produces light at specific discrete wavelengths. Consequently, a graph of the frequency spectrum of a laser pulse looks like a series of equally spaced spikes (a "frequency comb") in a pattern that has an envelope that forms another pulse shape. The width of this envelope defines the bandwidth or range of frequencies present. After an intense pulse travels through a medium where the Kerr effect is significant, the frequency envelope is wider.

In our 1969 discovery of the SC, Shapiro and I used picosecond pulses with an energy of a millijoule. A millijoule may sound like a low energy (it is the energy required to lift a paper clip several centimeters against the earth's gravity), but when it is packed into a picosecond and focused into a tight spot it represents a gigawatt of power and an extremely high intensity, capable of performing many tricks in that brief interval. Such a high intensity was necessary because the pulses could propagate through only a few centimeters of the glass where the Kerr effect was active. The high intensity could induce an effect strong enough to spread the pulses' bandwidth considerably even in the short time that they passed through the glass.

If the pulses traveled through more than a few centimeters of the glass, they started to come apart because of another property involving the refractive index called the dispersion of the medium.

DIFFRACTION, as occurs when a wave emerges from a small aperture, can influence supercontinuum generation. At the top, diffraction of a near-infrared laser beam through a 300-micron hole and onto a nearby glass slide produces a spot intense enough for supercontinuum generation (*white*). At the bottom, light diffracted by a straight edge generates supercontinuum light from two spots. The two beams interfere with each other, producing lines.

Dispersion in a normal medium means that the refractive index is slightly higher for higher-frequency light, which is therefore slowed down more than the lower-frequency light. Consequently, the different frequency components of the pulse travel at different speeds, and the pulse, whose existence depends on all the frequencies being tightly aligned ("in phase") at the center of the pulse, is quickly smeared out.

The optical fibers first used by Ranka and his colleagues in 1999 overcome this problem by having atypical dispersion properties, including zero dispersion and anomalous dispersion (meaning the refractive index decreases as the light frequency increases). With such fibers, SC pulses can propagate 1,000 times farther without coming apart. And because the pulses travel in the fiber for a much longer time, phenomena such as the Kerr effect have more time to operate and need not be as strong to have significant effects, which in turn means that the SC can be generated using lower-power lasers that emit microjoule and even nanojoule pulses instead of the millijoule pulses used earlier by researchers.

Another very important phenomenon plays a major role when the fiber has anomalous dispersion at the frequency band of the input pulse. In that situation, each pulse develops into a special kind of wave called a soliton. The characteristic property of a soliton is that it does not change its shape as it travels (usually a pulse tends to gradually spread out). This constancy arises because the anomalous dispersion acts on the soliton in a way that counterbalances the effects of other properties of the medium. When a material has anomalous dispersion, these solitons generate the SC rather than the self-phase modulation described earlier.

In either instance (normal or anomalous dispersion), the bandwidth of the SC is further broadened by a wide variety of other nonlinear optical effects, including four-wave mixing and Raman processes. In four-wave mixing, three frequencies of light interact in a nonlinear optical medium to generate light at a fourth frequency. Raman processes involve light interacting with the vibrational excitations of molecules making up the medium; as a result, the photons of light lose or gain energy, which changes their frequency.

All these interactions contribute simultaneously to greater or lesser degrees to the evolution of the pulses. Which processes dominate depends on all the factors that researchers can vary: the frequencies of light, the intensity

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COURTESY OF ROBERT R. ALFANO

and the time duration of the input pulses, and the optical properties of the fiber. A reliable way to predict the final result is to carry out numerical computer simulations of light pulses traveling through the fiber. Otherwise it is a matter of trying out the experiment and seeing what happens.

The fibers used for SC generation are a special kind known as microstructure fibers. A cross section of such a fiber reveals a pattern of holes that runs continuously through the entire length of the fiber [*see box on next page*]. In one commonly used design, the pattern of holes surrounds a solid silica core, like a honeycomb with only the central hole filled. The core has a high index of refraction, whereas the surrounding cladding, with its air holes interspersed with silica, has a lower index. That concentric arrangement of refractive indices serves to guide the light pulses along the fiber. Using these kinds of fibers with zero and anomalous dispersion, researchers have generated SC light extending more than two octaves from the infrared to the ultraviolet.

Metrology

AS MENTIONED EARLIER, the generation of SC light in optical fibers has unleashed a wide range of applications. The most important and mature of these applications is the development of extremely accurate frequency measurements and clocks. In this domain, the SC finds its usefulness in what are called optical frequency comb techniques, which enable improved accuracy with much simpler and smaller systems than the older methods. In particular, a trick called self-referencing, first demonstrated in 2000 independently by groups led by Hall and Hänsch, becomes possible when the frequency comb extends across a full octave. In this approach, scientists double the frequency of light at the low-frequency end of the spectrum and use it to interfere with light at the high-frequency end. [*Editors' note: A future article will discuss how self-referencing works in more detail.*]

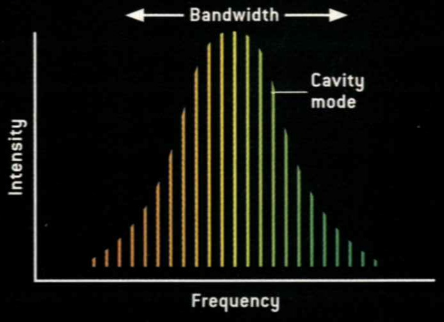
Building on Hall and Hänsch's work, scientists are now striving to develop

GENERATING SUPERCONTINUUM LIGHT

Pulsed lasers emit bursts of light with a limited range of frequencies. When a pulse of sufficiently high intensity passes through a medium such as an optical fiber, certain nonlinear processes occur, including one called self-phase modulation. These processes generate additional frequencies of light, creating the broad-spectrum supercontinuum output.

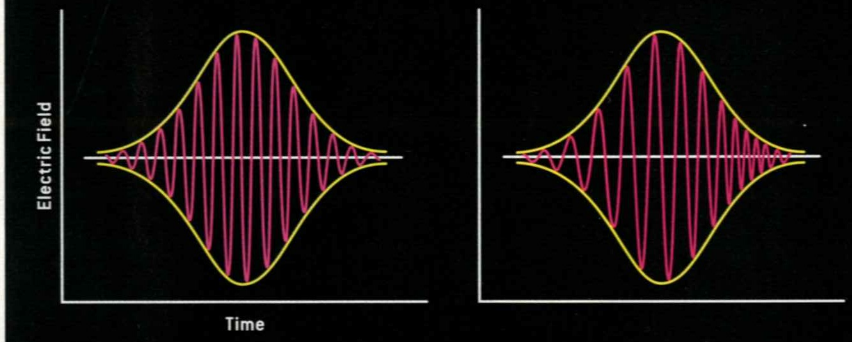
FREQUENCY COMB

Pulsed lasers emit a repeating series of pulses. Each pulse consists of many component beams and has a small range of frequencies. The spectrum of the series of pulses forms a frequency comb—an array of equally spaced discrete frequencies (cavity modes).



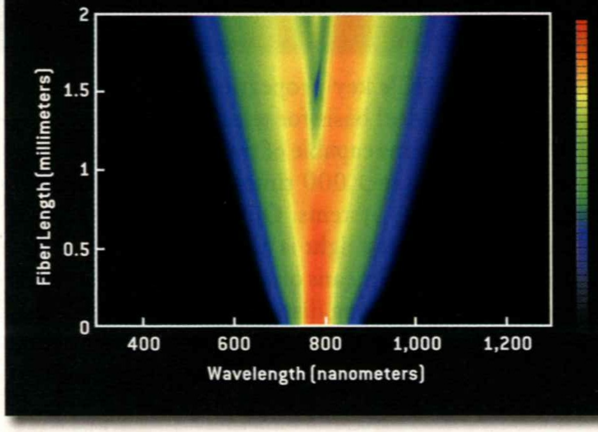
SELF-PHASE MODULATION

The electromagnetic oscillations of a laser pulse (*left, magenta*) have a constant wavelength but rise and fall in intensity (the envelope of the pulse, *yellow*). A pulse with high peak intensity can momentarily increase the medium's refractive index by an amount proportional to the intensity at each instant in time. As the medium's refractive index changes over time, it in turn modifies the wave's phase (the positions of the peaks and troughs, *right*), leading to new wavelengths and frequencies.



SPECTRAL BROADENING

A simulated 20-femtosecond (2×10^{-14} second) pulse traveling along an optical fiber reveals how nonlinear effects, including self-phase modulation, broaden the pulse's spectrum. Colors represent the intensity of light at each wavelength on a logarithmic scale (red is high intensity). In this example, after two millimeters of travel through the fiber, the light's spectrum spans just over an octave. (Like an octave in music, an octave of light spans from one frequency to double that frequency.)

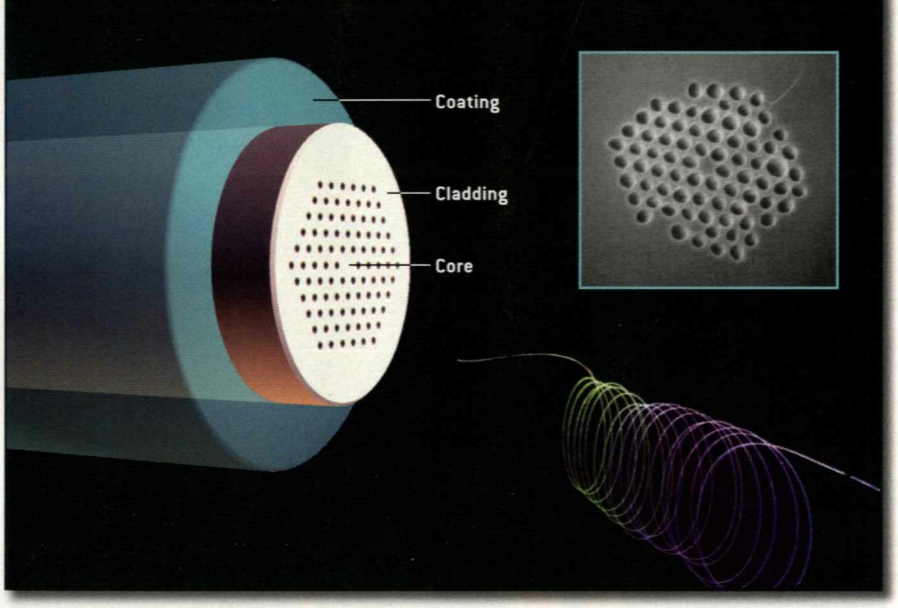


MELISSA THOMAS (*top and middle*); RÜDIGER PASCHOTTA *RP Photonics Consulting* (*bottom*)

systems capable of measuring frequencies to a fractional accuracy of 10^{-16} to 10^{-18}. (The best achieved so far is about 10^{-14}.) Such extreme accuracy would have practical implications for improvements in Global Positioning Systems, space navigation, and the alignment of very large arrays of radio telescopes. It will also be put to use in tests of special relativity and related fundamental principles such as the isotropy of space, the symmetry of matter and antimatter, and the constancy of the constants of nature [see "The Search for Relativity Violations," by Alan Kostelecký; SCIENTIFIC AMERICAN, September 2004; "Making Cold Antimatter," by Graham P. Collins; SCIENTIFIC AMERICAN, June 2005; and "Inconstant Constants," by John D. Barrow and John K. Webb; SCIENTIFIC AMERICAN, June 2005].

MICROSTRUCTURED FIBERS

Optical fibers that have patterns of air holes running through them have revolutionized the generation and use of supercontinuum light. In one design [*below* and *top right*], the holes lower the index of refraction in the cladding that surrounds the small core of solid silica, a feature that confines light to the core. The changing color of light traveling along such a fiber [*bottom right*] reveals the bandwidth broadening that the fiber induces, which is enhanced by other properties of the fiber's refractive index.



MELISSA THOMAS (*illustration*); REPRINTED WITH PERMISSION OF LUCENT TECHNOLOGIES, INC./BELL LABS, COURTESY OF ANDREW STENTZ, JINENDRA RANKA AND R. S. WINDELER (*micrograph and spiral*)

Frequency measurements and clocks are two facets of the same technology. Researchers are currently pushing to develop clocks with an accuracy of a femtosecond (10^{-15} second) over a second. Ultimately, the optical frequency comb might enable fractional accuracies of 10^{-18}, which would be ideal for timing in optical computers and perhaps for detecting oil and mineral deposits by their minute effects on the nearby gravitational field.

Telecommunications

AN APPLICATION with more immediate commercial implications than ultraprecise frequency measurements is telecommunications. Indeed, several of the SC's key properties could make it an ideal basis for telecommunications systems capable of transmitting data more than 1,000 times faster than present-day systems. Optical fiber carrying infrared light is already the most widely used means of sending data at high rates over long distances. Scientists and engineers are working incessantly to cram ever more data into a fiber, in an effort to keep up with the ever increasing worldwide demand for larger-capacity communications systems and networks. The goal is to achieve transmission rates of terabits (10^{12}) and petabits (10^{15}) a second. Typical fiber-optic systems currently transmit data between cities at about 10 gigabits a second, or 0.01 terabit a second.

The ultrabroad bandwidth of the SC makes it a cost-effective way to obtain numerous wavelength channels without having to resort to using hundreds of lasers. That bandwidth could be put to work by the technique of superdense wavelength division multiplexing, in which data streams are encoded onto many different wavelengths of light that are transmitted simultaneously. The SC, unlike the light from 100 individual lasers, can be coherent across a wide range of frequencies (meaning that all the channels are oscillating in a kind of synchrony instead of each narrow band dancing to its own drummer), which aids in the degree of control that can be brought to bear on the light.

Alternatively, a series of ultrashort pulses of SC light (shorter than 100 femtoseconds, or 10^{-13} second) can be sent, with sequences representing different data channels interleaved with one another, a process called time-division multiplexing. With such short pulses, it is important to be able to control the precise relation between the individual oscillations of the electric field (the carrier wave) and the pulse envelope. This property, called the relative phase of the carrier and the envelope, determines, for example, whether the peak of the pulse envelope occurs at an instant when the electric field of the wave is at a peak or a trough, or somewhere in between. The properties of the SC facilitate such control.

Several Japanese groups have already achieved data transmission rates of terabits a second using a small segment of SC spectrum. Many challenges remain to be overcome to improve the speed to achieve petabit-a-second operation. These hurdles include reducing the duration of a bit to about a picosecond and increasing the number of coherent wavelengths in the SC.

Atmospheric Science

THE TELECOMMUNICATIONS applications rely on producing the SC in the completely controlled environment of an optical fiber, but for some purposes the SC is generated in the open air. One such purpose is remote sensing of molecular species present in air. When intense ultrafast laser pulses travel through the air, they can produce long, narrow "filaments" in which the air is ionized—that is, within those filaments electrons are knocked off the air's molecules, forming a plasma of positive ions and negatively charged electrons. These filaments can guide the light pulses and keep them from spreading, a process that scientists attribute to a balance between defocusing caused by diffraction (the tendency for a wave to spread out from a small aperture) and self-focusing caused by the ionized plasma.

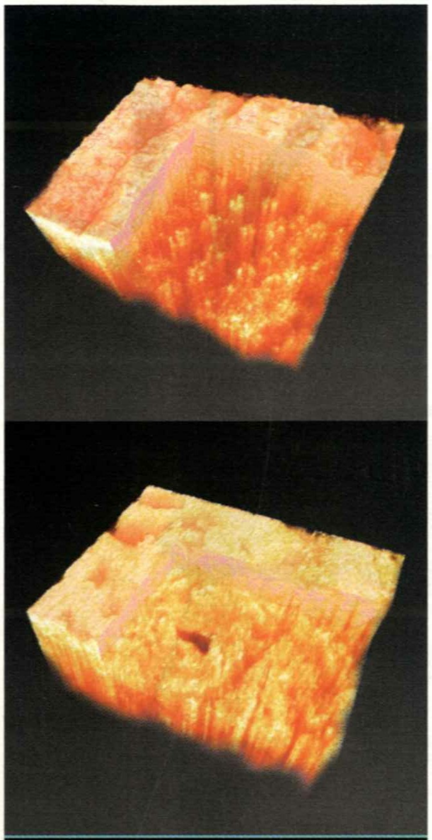
Within the filaments a significant amount of the pulses' power can convert to SC white light over distances greater than 20 meters. Pollutants and aerosols in the air will absorb the light at characteristic frequencies, and the broad spectrum of the SC light enables one to detect their absorption spectra simultaneously in the ultraviolet, visible and infrared bands.

Imaging

IN ADDITION TO probing the air around us, SC light is useful for producing high-resolution images of the tissues inside us. The technique, optical coherence tomography (OCT), was pioneered by James G. Fujimoto of the Massachusetts Institute of Technology and his co-workers and can be carried out in situ in living organisms or on samples that have been removed. It has been used for studies of the retina, skin diseases, gastrointestinal diseases and carcinoma cells—in humans and in animals.

To produce an OCT image, the light is split into two parts—one part illuminates a spot of the sample, whereas the other ("reference" light) enters a length of fiber. When the reference light recombines with light that the sample reflected or scattered, the two interfere strongly—provided that they each spent the same length of time on their respective journeys. A property of the source light called its coherence length determines how accurately the timing has to match. High-resolution OCT imaging relies on a short coherence length, which requires the match to be very accurate.

Thus, when the spot of light penetrates into the sample, only light coming back from one specific depth will interfere with the reference light. Scanning the light laterally across the sample while keeping the travel time of the reference light fixed therefore produces a two-dimensional image of the sample at a certain depth. The thickness of the layer that contributes to the image is called the axial resolution of the image.



OPTICAL COHERENCE TOMOGRAPHY (OCT) uses light to produce images analogous to ultrasound but with much finer resolution. These three-dimensional OCT images of normal tissue (*top*) and a benign tumor (*bottom*), both from surgical specimens taken from the colon, reveal the disorganized glandular structure that is a signature of the latter. The use of supercontinuum light enabled resolution about four times finer than standard OCT images.

REPRINTED FROM "ULTRAHIGH-RESOLUTION AND 3-DIMENSIONAL OPTICAL COHERENCE TOMOGRAPHY EX VIVO IMAGING OF THE LARGE AND SMALL INTESTINES," BY PEI-LIN HSIUNG ET AL., IN *GASTROINTESTINAL ENDOSCOPY,* VOL. 62; 2005, © 2005; USED WITH PERMISSION OF ELSEVIER

Early OCT imaging systems relied on a type of diode to provide the light and had an axial resolution of 10 to 15 microns. (For comparison, high-frequency ultrasound images have a resolution of about 100 microns.) Femtosecond pulse lasers optimized to have short coherence lengths pushed the axial resolution to below two microns—nearly a 10-fold improvement.

The axial resolution also depends on the bandwidth of the light source—broader bandwidth enables finer resolution. SC light has a short coherence length and a bandwidth broader than any femtosecond laser, making it ideal for high-resolution OCT imaging. In 2002 Boris Považay, now at the Medical University of Vienna, and his co-workers used SC light generated in microstructured fibers to produce images of human carcinoma cells with an axial resolution of 0.5 micron (a typical cell is about 10 microns in diameter).

The supercontinuum is one of the most dramatic and elegant effects in optical physics: light of one color from an intense laser pulse passes through a crystal, optical fiber or a gas and turns white. But as well as being impressive to the naked eye, SC generation enables diverse applications, ranging from chemical sensing to the most precise time and frequency measurements available. The SC continues to grow to new heights of scientific activity 35 years after its discovery. SA

MORE TO EXPLORE

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