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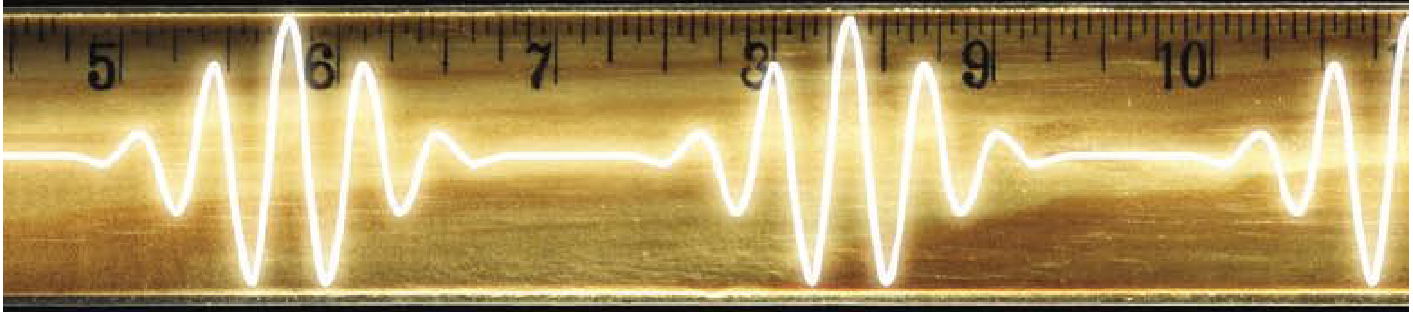
RULERS



A revolutionary kind of laser light called an optical frequency comb makes possible a more precise type of atomic clock and many other applications

KEY CONCEPTS

- A new kind of laser light—called an optical frequency comb—can be used to measure frequencies of light and intervals of time more precisely and easily than ever before.
- The comb is made of a train of evenly spaced, ultrashort laser pulses with a spectrum that looks like tens of thousands of “teeth.”
- Applications include a more precise atomic clock, ultrasensitive chemical detectors, laser control of chemical reactions, higher-capacity telecommunications using optical fibers and improved lidar (light detection and ranging).

—*The Editors*

In the blink of an eye, a wave of visible light completes a quadrillion (10^{15}) oscillations, or cycles. That very large number presents both opportunities and a challenge. The opportunities promise numerous applications both inside and outside of laboratories. They go to the heart of our ability to measure frequencies and times with extremely high precision, a skill that scientists rely on for some of the best tests of laws of nature—and one that GPS systems, for instance, depend on. The challenge has centered on the impossibility of manipulating light with the techniques that work so well for electromagnetic waves of much lower frequencies, such as microwaves.

Now, thanks to a decade of revolutionary advances in laser physics, researchers have at hand technologies that can unlock the latent potential that visible light’s high frequencies previously kept us from realizing. In particular, scientists have developed the tools to exploit a type of laser light known as an optical frequency comb. Like a versatile ruler of light with tens or hundreds of thousands of closely spaced “tick marks,” an optical frequency comb provides exquisitely precise measurements of light. Such a comb can form a bridge spanning the huge frequency gap from microwaves to visible light: very precise microwave measurements can, with an optical comb, produce equally exact data about light.

Myriad applications are in the pipeline. Optical combs will enable a new generation of more precise atomic clocks, ultrasensitive chemical detectors and the means to control chemical reactions using lasers. The combs could greatly boost the sensitivity and range of lidar (*l*ight *d*etection *a*nd *r*anging)—and also provide a vast increase in the number of signals traveling through optical fiber [*see box on page 76*].

Combs will greatly simplify the task of measuring optical frequencies with extremely high precision. In the 20th century such a measurement would have required a team of Ph.D.s running rooms full of single-frequency lasers. Today a graduate student can achieve similar results with a simple apparatus using optical frequency combs. The new optical atomic clocks also spring from this simplification. Much as a pendulum in a grandfather clock requires gears to record its swings and slowly turn the clock’s hands, an optical atomic clock uses an optical frequency comb to count the oscillations of light and convert them into a useful

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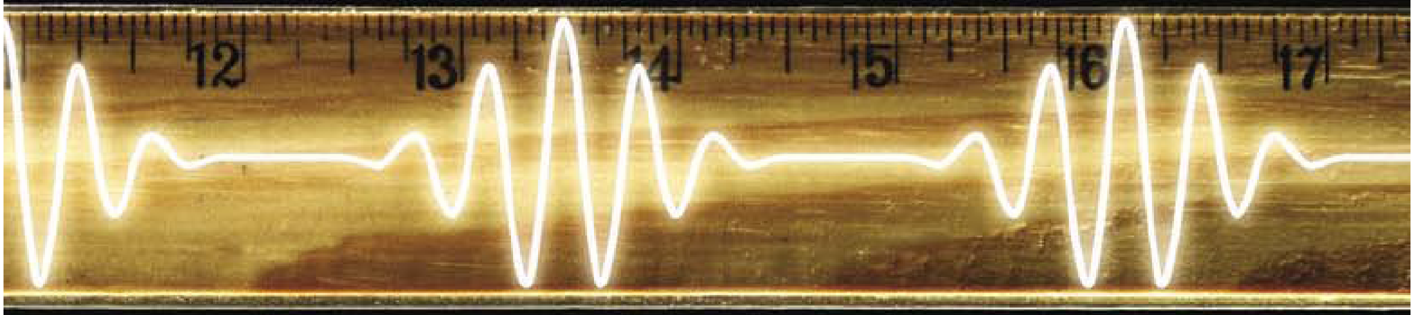
OF LIGHT



LASER PULSES can form a kind of ruler of light, which scientists use to measure the frequencies of other lasers with great precision.

By Steven Cundiff, Jun Ye and John Hall

electronic signal. In just the past year, researchers have used optical combs to surpass the cesium-based atomic clocks that have been the best system available for decades.

In some respects, the scene-changing advent of optical combs is similar to the leap forward that resulted from the invention of the oscilloscope about 100 years ago. That device heralded the modern age of electronics by allowing signals to be displayed directly, which facilitated development of everything from television to the iPhone. Light, however, oscillates 10,000 times faster than the speed of the fastest available oscilloscopes. With optical combs, the same capability to display the waveform is becoming available for light.

Optical frequency comb applications require exquisite control of light across a broad spectrum of frequencies. This level of control has been available for radio waves for a long time but is only now becoming possible for light. An analogy to music helps in understanding the required level of control. Before the development of combs, lasers could produce a single color, like a single optical tone. They were akin to a violin with only one string and no fingerboard, capable of playing only one note (ignore for the moment that musical notes are much richer than pure tones). To play even a simple piece would require many different instruments, each painstakingly tuned. Each violin would require its own musician, just as every single-frequency laser requires its own operator.

In contrast, one operator can use an optical comb to cover the entire optical spectrum, not merely like a pianist at a piano but like a keyboardist playing an electronic synthesizer that can be programmed to mimic any musical instrument or even an entire orchestra. Comb technology, in effect, enables symphonies of hundreds of thousands of pure optical tones.

Anatomy of a Comb

Optical frequency combs are generated by devices called mode-locked lasers, which create ultrashort pulses of light. To understand the important features of such pulses, begin by imagining the light wave of the other chief kind of laser, a continuous-wave (CW) laser. Ideally, such a wave would be an endless stream of perfectly regular oscillations (representing the light wave's electric field), every wave crest and trough having the same amplitude and arriving at an unchanging rate. A pulse from a mode-

[APPLICATIONS]

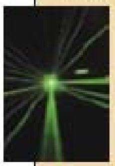
COMB TECHNOLOGIES

◂ OPTICAL ATOMIC CLOCKS

The most accurate and precise clocks ever made, optical atomic clocks have already surpassed the microwave-based systems that have been the standard since 1967. They will play a central role in space navigation, communications between satellites, exquisitely sensitive tests of fundamental physics and other measurements.

CHEMICAL SENSORS

Researchers have demonstrated ultrasensitive chemical detectors based on optical combs and are now developing prototypes for commercial instruments. Comb-based sensors will let security screeners rapidly identify hazards such as explosives or dangerous pathogens. Doctors will diagnose illnesses by detecting chemicals in a patient's breath.



◂ SUPERLASERS

With frequency combs, the outputs of many lasers can be stitched together to form a single stream of pulses whose light is as organized ("coherent") as light from a single laser. Eventually it should be possible to control the electromagnetic spectrum coherently all the way from radio waves to x-rays.

TELECOMMUNICATIONS ▸

Optical combs will increase the number of signals that can be sent down a single optical fiber by orders of magnitude, requiring only one comb instead of a large number of individual lasers. Interference between the channels will be reduced. Secure communications, in particular, will benefit from the use of combs.

◂ DESIGNER CHEMISTRY

Scientists are already investigating how to use lasers' coherent light to control chemical reactions. Optical combs will make this technique more predictable and reliable and will be instrumental in developing a new class of so-called ultracold chemical reactions. One day the combs will manipulate biological reactions, which are far more complicated than other chemical reactions.

LIDAR

Laser radar, or lidar (light detection and ranging), uses laser light to determine the position, velocity and characteristics of distant objects. By generating waveforms with custom-designed shapes, optical frequency combs are expected to boost lidar's sensitivity and range by orders of magnitude.

locked laser, in contrast, is a short series of wave crests and troughs whose amplitude rises from zero to a maximum and then falls back to zero [*see box on opposite page*]. The shortest pulses, with durations of less than 10 femtoseconds, contain just a few full oscillations of the light wave. The general outline of the pulse—its overall rise and fall—is called its envelope. One can think of the pulse as being like the earlier continuous wave (the "carrier wave"), with that wave's amplitude multiplied by the changing height of the envelope.

The carrier wave consists of light of one pure frequency. A plot of its spectrum would have a single spike at that frequency, representing the presence of that frequency alone. You might expect that the pulse you are imagining would also consist of light only at that frequency—after all, it is just the single-frequency carrier wave with its amplitudes changed—but that is not how waves and spectra work. Instead the pulse is made up of light of many frequencies all traveling together. The frequencies form a small, continuous band centered on the carrier frequency. The shorter the pulse, the broader the spread of frequencies.

Two additional features of the pulses emitted by mode-locked lasers are keys to the development of optical frequency combs. First, shifting the envelope a little relative to the carrier wave results in slightly different pulses. The peak of the pulse envelope may occur at the same time as a crest of the carrier, but it may also be shifted to any other stage of the oscillation. The amount of displacement is called the phase of the pulse.

Second, mode-locked lasers emit trains of pulses at a very regular rate, called the repetition rate. The frequency spectrum of such a train of pulses does not form a continuum spread on each side of the carrier frequency but rather breaks into many discrete frequencies. Plotted, the spectrum looks like the teeth of a hair comb, spaced at precisely the laser's repetition rate.

A typical repetition rate is around one gigahertz (a billion cycles per second), somewhat slower than modern computer processors. An optical comb that spanned the visible spectrum would have 400,000 teeth if they were spaced at one gigahertz. Scientists can measure repetition rates in the gigahertz (microwave) range very accurately using high-speed photodiodes, which detect each pulse in turn—and an optical comb would appear to leverage that accuracy up to visible wavelengths. Why not, then, use the teeth of the frequency comb as reference points to measure against?

There is, however, a catch. It relates to the phase. Everything is fine if the phase of every pulse in the train is exactly the same, because in that case the comb teeth will be precisely at integer multiples of the repetition rate. Thus, you would know the teeth positions once you had measured the laser's repetition rate.

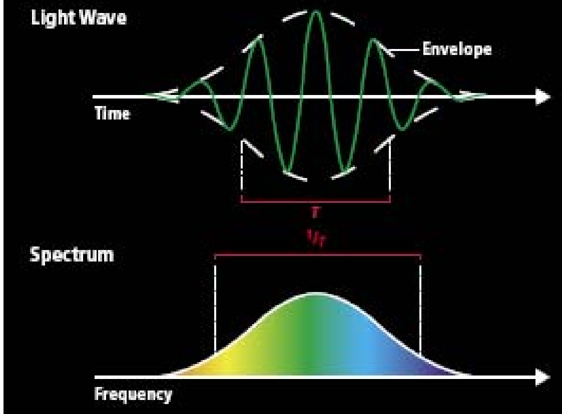
But it usually happens that the phase changes from one pulse to the next by some unpredictable but fixed amount [*see box on page 79*]. In that case, the comb teeth are shifted in frequency away from the exact integer multiples of the repetition rate by an amount called the offset fre-

SORA/CORBIS (*clock*); EMILY HARRISON (*illustration on clock*); ROBERT KOHLHUBER *iStockPhoto* (*laser*); CONEY JAY *Getty Images* (*optical fiber*); STEVE DIBBLE *iStockPhoto* (*flask*)

[WHAT IT IS]

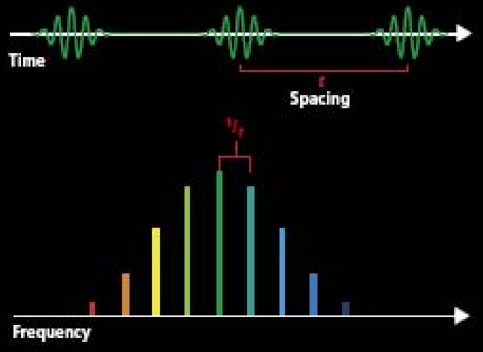
A COMB OF LIGHT

An optical frequency comb consists of a series of laser pulses that are virtually identical and spaced at very regular intervals, making them useful for precise measurements. The light is called a comb because, unlike a single pulse, the series has a spectrum made up of evenly spaced spikes.



SINGLE PULSE

Although the electric field (*top, green*) of a laser pulse oscillates at regular intervals, such a pulse does not consist of light of one pure frequency. The rise and fall of the wave's envelope (*dashed lines*) can occur only if the light is actually composed of a band of frequencies (*bottom*). The shorter the pulse (*top*, T), the greater the spectral width (*bottom*, $1/T$). The frequencies in a one-femtosecond pulse span about half of the visible spectrum, not counting the low-intensity tails.



MULTIPLE PULSES

You can be forgiven for expecting a train of pulses (*top*) to have the same spectrum as a single pulse. In actuality, the train's spectrum is split into spikes like the teeth of a comb (*bottom*), meaning that the light consists of a series of discrete frequencies and not a continuous band of them. If a pulse occurs every t nanoseconds, the frequency comb teeth are spaced by $1/t$ gigahertz. Researchers can thus determine the comb spacing very accurately by measuring the rate at which the laser emits pulses.

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quency. To know the frequencies of the comb teeth, one must measure that frequency as well as the repetition rate. Measuring the offset frequency was a barrier to progress with optical combs. This barrier fell resoundingly in 2000. It took the combined efforts of scientists from two separate branches of laser research and the discovery of a new material.

Converging Disciplines

For most of the past 40 years, ultrafast-laser researchers—those who focus on making and using the shortest pulses—largely ignored the pulse phase and the theoretical comblike spectrum of an ideal series of pulses. Their experiments typically only depended on the intensity of individual pulses, in which case the phase has no effect. Although the members of the ultrafast community often measured the spectrum of their mode-locked lasers, they rarely did so with sufficient resolution to observe the underlying comb spectrum; instead the lines would blend together and look like a continuous band of frequencies.

High-resolution measurements were the domain of specialists in precision spectroscopy and optical frequency metrology, wherein highly stable CW lasers reigned as the preferred tools. As mentioned earlier, a CW laser sends out a steady stream of light at a precise frequency, and its spectrum looks like one sharp spike. Not many researchers in the metrology community were cognizant of the workings of mode-locked lasers, and those who did know about them were skeptical that such lasers could produce a well-defined comb spectrum in practice. They expected that modest fluctuations in the timing or the phase of the pulses would wash it out.

But a few researchers, most notably Theodor W. Hänsch of the Max Planck Institute for Quantum Optics in Garching, Germany, had faith that mode-locked lasers could one day be a useful tool for high-precision spectroscopy and metrology. In the 1970s, while a faculty member at Stanford University, Hänsch used mode-locked dye lasers (which have a colorful liquid dye as the medium where the laser light is generated) to do a series of measurements that established the basic concept of the comb spectrum and its offset frequency. These seeds then lay dormant for almost 20 years until laser technologies had advanced enough for further progress with combs to be practical.

In the late 1980s Peter Moulton, then at Schwartz Electro-Optics in Concord, Mass., developed titanium-doped sapphire as a laser gain medium with a large bandwidth. Wilson

[THE AUTHORS]

Steven Cundiff, **Jun Ye** and **John Hall** bring different backgrounds to their collaboration on developing and applying femtosecond optical frequency combs. Hall has been a leader in precision measurement using ultrastable continuous-wave (CW) lasers for more than four decades. In 2005 he shared the Nobel Prize in Physics for his work, including development of comb techniques. Ye began his career about 15 years ago with a focus on ultrastable CW lasers, but since the advent of comb techniques he has been making significant contributions to the broad field of ultrafast science. Cundiff worked in ultrafast science, mainly spectroscopy but also on mode-locked lasers, before teaming up with Hall and Ye 10 years ago. All three are fellows at JILA, a joint institute between the National Institute of Standards and Technology and the University of Colorado at Boulder.

COMBINED SOUND of two tuning forks, one of them slightly out of tune, produces the phenomenon known as beating: the sound's volume oscillates up and down at a rate that is the beat frequency—the difference in frequency of the two forks. Beating of light waves is used in many laser measurements, including those involving optical combs.

THE STANDARD SECOND

Optical frequency combs will one day be used for the official standard of time.

- Today the standard is based on the frequency of microwave radiation absorbed by cesium atoms to excite them between two specific "hyperfine" energy states.
- One second is defined to be the time it takes for such light to oscillate precisely 9,192,631,770 times.
- An optical standard would use light emitted or absorbed by some chosen atom or ion at roughly 60,000 times the cesium frequency.

Sibbett of the University of St. Andrews in Scotland pioneered its use in mode-locked lasers in the early 1990s. Within only a few years, titanium-sapphire lasers were routinely generating pulses shorter than 10 femtoseconds, corresponding to only three cycles of light [see "Ultrashort-Pulse Lasers: Big Payoffs in a Flash," by John-Mark Hopkins and Wilson Sibbett; Scientific American, September 2000].

With these titanium-sapphire lasers available, Hänsch dusted off his 20-year-old idea of optical frequency combs. He performed a series of experiments in the late 1990s that demonstrated the latent potential of mode-locked lasers. In one measurement, he showed that comb lines at opposite ends of the output spectrum are well defined with respect to one another. The comb teeth were revealed to be like the marks engraved on a steel ruler and not like lines drawn along a rubber band. In another experiment, he measured the frequency of an optical transition in cesium atoms (a change in their state that absorbs or emits light at a precise frequency) using a mode-locked laser to span the difference in frequency between two CW lasers. His results inspired a group of us to undertake serious research in this arena.

At JILA, a joint institute between the National Institute of Standards and Technology (NIST) and the University of Colorado at Boulder, we were in a unique position to take the technological advances in two branches of laser physics and run with them. JILA has a strong tradition in optical frequency metrology and precision spectroscopy, largely built on the ultrastable CW laser technology developed over 40 years by one of us (Hall). In 1997 another one of us (Cundiff) joined JILA, bringing expertise in mode-locked lasers and short-pulse techniques. It took many hallway and lunch table conversations before we surmounted our conceptual divide and decided to join forces, along with a pair of postdoctoral fellows: Scott Diddams, now at NIST, and David Jones, now at the University of British Columbia. The third of us (Ye) joined the fun at JILA in the summer of 1999, just as the revolution began in earnest; he soon led the way to finding applications for the new frequency combs.

Magic Fiber

As impressive as Hänsch's results were, we knew that his motivation was to dispose of most of his complex apparatus. The techniques to accomplish this simplification, however, required that a mode-locked laser produce an enormous bandwidth, preferably an octave. (An octave is a factor of two in frequency, whether it be in music, electronics or optics.) Although titanium-sapphire lasers produced impressive bandwidth at the time, they could not yet yield an octave of light.

The final puzzle piece fell into place at the 1999 Conference on Lasers and Electro-Optics where Jinendra Ranka of Bell Laboratories presented a paper on a new kind of optical fiber known as microstructure fiber. In this medium, micrometer-size airholes in the fiber guide light along its core. The fiber's properties allow pulses at the frequencies produced by a titanium-sapphire laser to travel along it without being stretched (as occurs in ordinary fiber and most other optical media). The lack of stretching keeps the pulse intensity high, which in turn leads to much greater spectral broadening than occurs in ordinary optical fiber [see "The Ultimate White Light," by Robert R. Alfano; Scientific American, December 2006]. The results are visually stunning. The output of a titanium-doped sapphire laser is in the near-infrared,

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just beyond the limits of human vision. It appears as a faint red color to the eye. Spectral broadening in microstructure fiber converts that faint red to visible wavelengths, causing the fiber to glow with successive colors of the rainbow.

In the fall of 1999 we managed to acquire some of this magic fiber. The timing could not have been more perfect. We had just completed a series of experiments demonstrating the use of a titanium-sapphire laser to span a gap nearly three times wider than Hänsch's initial demonstration. We already had an operating setup into which we could almost drop the new microstructure fiber. Within two weeks of receiving the express package from Bell Laboratories, we had done a proof-of-principle experiment showing that the spectral broadening in the microstructure fiber preserved the frequency comb structure in the original laser pulse.

The importance of an octave-spanning spectrum is that it allows the offset frequency to be measured directly as a radio frequency, thus surmounting the aforementioned barrier to using combs to measure other frequencies. There are several specific methods of determining the offset frequency given an octave-spanning spectrum, many of which can be traced to techniques employed in radio engineering for measuring frequencies before high-speed counters were readily available. (Counters do the job by simply counting how many oscillations occur in a radio wave per unit of time but cannot keep up with the much higher frequencies that light has.) We will now describe the simplest and most versatile of the methods for measuring the offset frequency—self-referencing.

The key idea is that an octave-spanning spectrum enables scientists to compare the frequencies of two comb lines at opposite ends of the spectrum with each other. If the offset frequency is zero, then each line at the low-frequency end of the spectrum has a corresponding line with exactly twice its frequency at the high-frequency end. Any deviation from this exact ratio turns out to be precisely the offset frequency [*see box below*]. The scheme is called self-referencing because one is comparing the comb's light against itself.

ULTIMATE BREATHALYZER

Optical frequency combs may be used to rapidly detect molecules in a person's breath that could signal a variety of conditions:

METHYLAMINE: Liver and renal diseases

AMMONIA: Renal failure

ETHANE: Some forms of cancer

CARBON ISOTOPE RATIOS: Presence of *Helicobacter pylori*

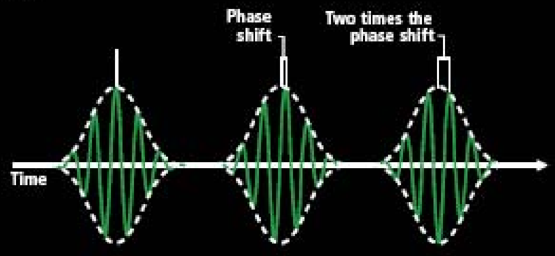
[MAKING IT USEFUL]

"CALIBRATING" THE COMB

The comb's teeth are offset slightly because of a subtle effect that changes their frequencies. Before scientists can use the combs to measure the light of another laser, they first have to correct for this offset.

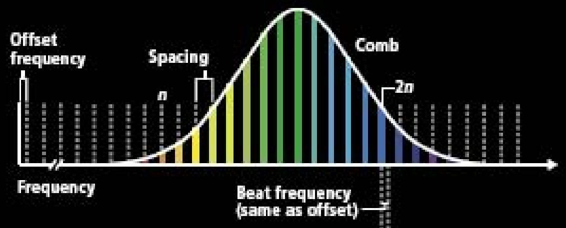
THE PROBLEM

With each successive pulse, the alignment of the highest amplitude of the pulse wave relative to the maximum of the envelope changes, an effect called phase shift.



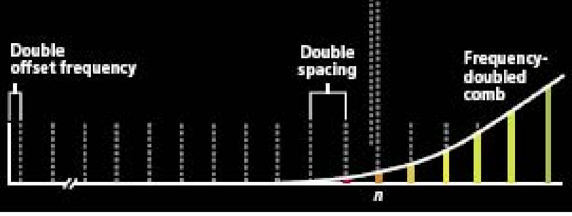
HOW THE COMB CHANGES

Phase shift moves the optical frequency comb's teeth by an amount called the offset frequency. The comb teeth will be at the offset frequency plus integer multiples of the comb spacing. A technique called self-referencing can determine the offset frequencies; it relies on the optical comb's spanning a full octave—that is, running all the way from one frequency (*red, line* n) to twice that frequency (*violet, line 2*n).



SOLUTION: COMPARE COMBS

Researchers send part of the comb light through a crystal that produces comb lines at double the original frequencies (and some other lines not shown here). Because the doubled low-frequency lines differ from the original high-frequency lines by the offset frequency, combining them produces beating at just that frequency, which is measured. The researchers now know the precise frequencies of their comb lines.



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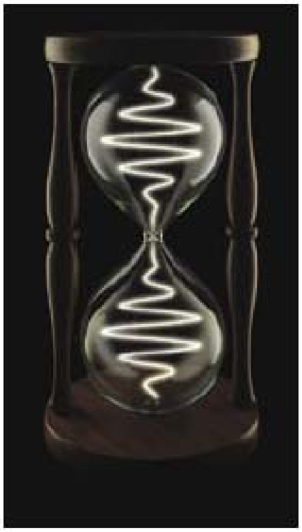
TIME NUTS

While scientists develop clocks based on optical combs, traditional atomic clocks have become a tool for amateur science. At www.leapsecond.com/great2005, Tom Van Baak describes his family's road trip up Mount Rainier in Washington State with three atomic clocks to observe gravitational time dilation (for their trip, 22 nanoseconds) predicted by general relativity.



Self-referencing is carried out in practice by passing some of the laser light through a so-called second-harmonic generation crystal, which doubles the light's frequency. Thus, one can split off the light that forms the lower-frequency end of the comb using a mirror that only reflects longer-wavelength light but passes shorter wavelengths, then send it through the doubling crystal, and finally direct both it and the light of the higher-frequency end of the comb onto the same photodetector. The combined light oscillates in intensity—it "beats"—in just the same fashion as the combined sound of a tuned and a mistuned note beats. In both cases, the frequency of the beats equals the amount of mistuning. For the light pulses, the beats have the same frequency as the comb's offset frequency because every doubled low-end line will be mistuned by that amount from a high-end line. In electronics and optics, this procedure of combining signals to get the beat frequency is called heterodyne detection.

Redefining Time

The simplicity of optical frequency metrology based on optical frequency combs can only be appreciated in comparison to techniques used prior to their development. Briefly, these techniques consisted of frequency multiplication chains, where each link in the chain consisted of an oscillator that had a multiple of the frequency of the previous link. The first link in the chain was a cesium clock, a kind of atomic clock used as the international time standard that defines the second. The cesium clock is based on nine-gigahertz microwaves absorbed by cesium atoms. To reach all the way from nine gigahertz to the frequency of visible light (a factor of at least 40,000) required about a dozen stages. Each stage used a different technology, including lasers for visible light. Running these chains was resource- and personnel-intensive; just a few in the world were built, and measurements were made only intermittently. In addition, in practice the many links in the chain impaired the accuracy of the ultimate optical frequency measurement.

Once stabilized optical frequency combs were invented, it was much easier to precisely measure the frequency of a CW laser. As with a frequency chain, comb-based frequency measurements still must be referenced to a cesium clock. As we will now see, a cesium clock's ability to measure frequencies up to about nine gigahertz is all that you need to use an optical comb to determine the frequency of a laser line. Several pieces of information involving the comb are needed. First, as we discussed earlier, the comb's offset frequency and the spacing of its lines must be measured. From those two numbers the frequencies of all the comb's lines can be calculated. Next, the unknown laser light is combined with the comb's light to get the beat frequency (that is, the difference in frequency) between it and the nearest comb line.

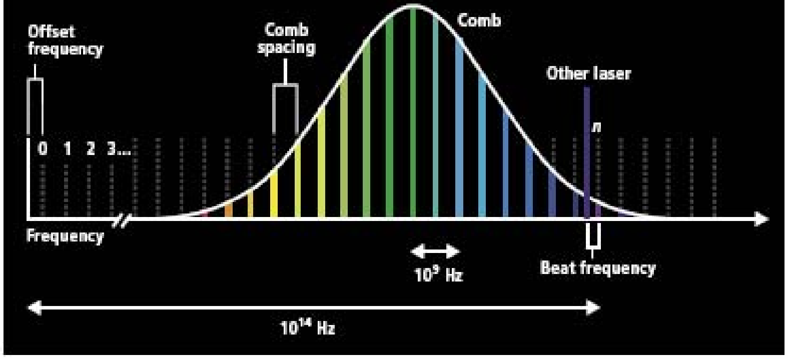
These three frequencies are all within the microwave range that can be measured extremely accurately using a cesium clock. Recall that the comb's line spacing is the same as the repetition rate of the pulses producing the comb. Most mode-locked lasers operate at a repetition rate of 10 gigahertz or less, making that quantity easy to measure against the cesium clock. Both the offset frequency and the beat frequency are also within range to be measured by the cesium clock because they must be smaller than the comb spacing.

Two further pieces of data must be determined: to *which* comb line was the unknown laser light closest and on *which side* of the line? Commercial wave meters can measure an optical line's frequency to within less than one gigahertz, which is good enough to answer those two questions. In the absence of such a wave meter, you can systematically vary the repetition rate and the offset frequency to monitor how the beat frequency changes in response.

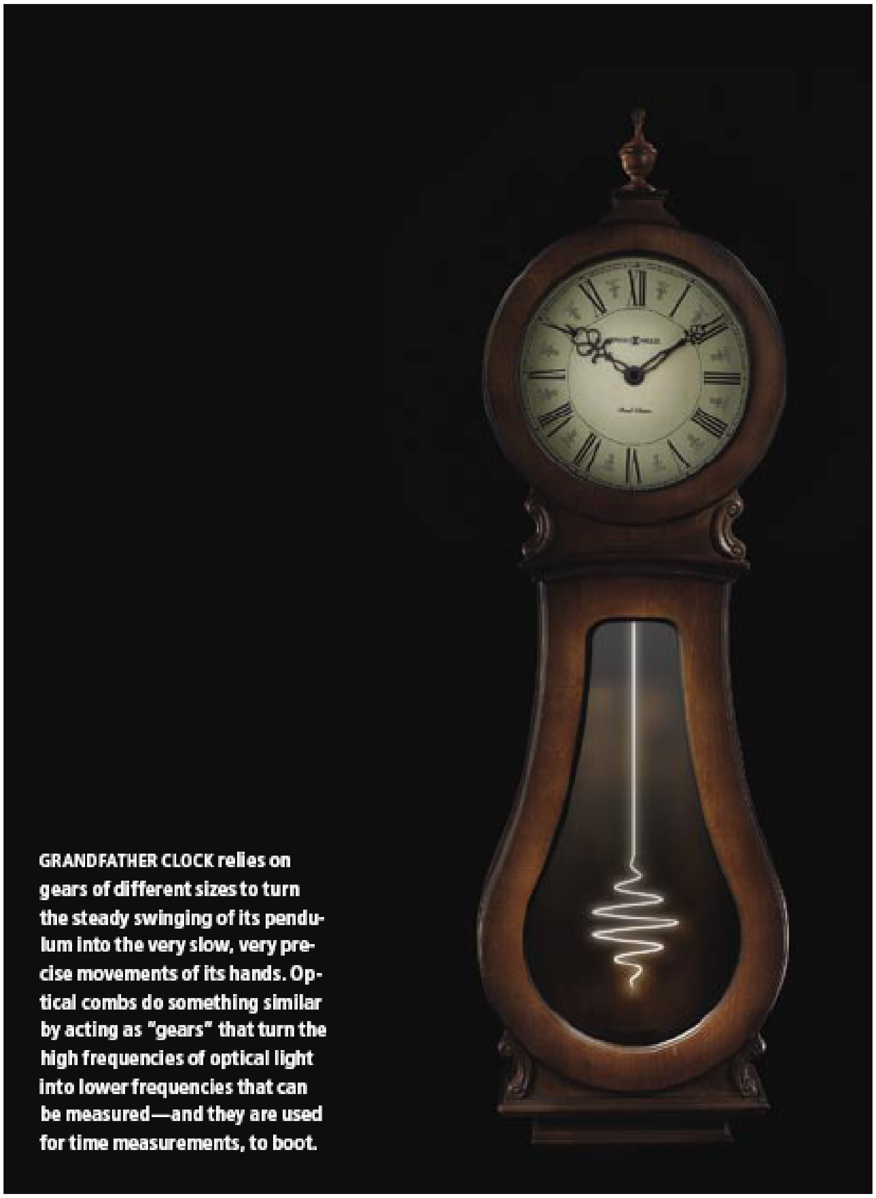
[USING IT]

MEASURING LIGHT

To determine the frequency of another laser (*violet*), physicists combine its light with optical comb light and measure the beat frequency generated with the closest comb line (*n*). They can learn which comb tooth the laser is nearest from approximate knowledge of the laser's frequency obtained by standard, less precise techniques. Thus, by measuring three frequencies in the gigahertz range—offset frequency, comb spacing and beat frequency—researchers can determine the frequency of light very precisely in the 100-terahertz, or 10^{14}-hertz, range.



DAVID EMMITE (hourglass); LISA APFELBACHER (graph)



GRANDFATHER CLOCK relies on gears of different sizes to turn the steady swinging of its pendulum into the very slow, very precise movements of its hands. Optical combs do something similar by acting as "gears" that turn the high frequencies of optical light into lower frequencies that can be measured—and they are used for time measurements, to boot.

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With enough of those data points, you can work out where the line must be.

The simplicity of optical combs has not only increased how often scientists around the world make these extremely precise frequency measurements but also greatly decreased the uncertainty in those measurements. Such benefits may one day lead to an optical time standard replacing the present microwave cesium-based one. With this in mind, groups at NIST led by James C. Bergquist and at JILA led by Ye have been measuring frequencies relative to clocks that use light and a comb to produce the output signal. Already the uncertainties in measurements using the best of these clocks are smaller than those in measurements using the very best cesium standards. It is an exciting time, with many laboratories around the world poised to build optical frequency standards that can surpass what has been the primary frequency standard for many decades. Measurements by Leo Hollberg's group at NIST, as well as by other groups elsewhere, suggest that the intrinsic limit of the optical comb is still a couple of orders of magnitude better than the uncertainty in current optical frequency measurements.

Higher and Higher

Adopting an optical time standard remains years in the future, however. Metrologists must first carefully evaluate numerous atomic and ionic optical transitions before selecting the one that seems to be the best for a standard.

In addition to the many practical applications of combs, fundamental comb research continues apace on many fronts. For example, Ye's group can use a single comb to detect very sensitively many different transitions of atoms and molecules all at once. Thus, the whole range of energy states of an atom can be analyzed in one measurement. Alternatively, this technique can be applied to detect many trace species in a sample.

Comb technology has already had a large impact on studies of how atoms and molecules respond to the strong electric fields obtainable in intense, ultrashort light pulses. Much of this work has been led by a collaborator of Hänsch's, Ferenc Krausz, who is now at the Max Planck Institute for Quantum Optics. Among other achievements, his group has used the response of electrons to measure the electric field of a laser's ultrashort pulses and display the waveform, much like displaying a radio-frequency wave on an oscilloscope. Krausz used optical combs to stabilize the pulses' phase to have an unchanging waveform from pulse to pulse.

Another very active area of research is the quest to push comb techniques to higher frequencies of the electromagnetic spectrum. (Producing lower-frequency combs, including combs that run from microwaves all the way to visible light, is straightforward.) In 2005 Ye's group at JILA and Hänsch's group in Garching generated a precise frequency comb in the extreme ultraviolet (not far below x-rays in frequency). Scientists are using this extended comb to study the fine structure of atoms and molecules with extreme ultraviolet laser light.

In the space of a few short years, optical frequency combs have gone from being a research problem studied by a small number of scientists to being a tool to be used across a broad gamut of applications and fundamental research. We have only begun to explore the full potential of these rulers of light. ■

➡ MORE TO EXPLORE

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