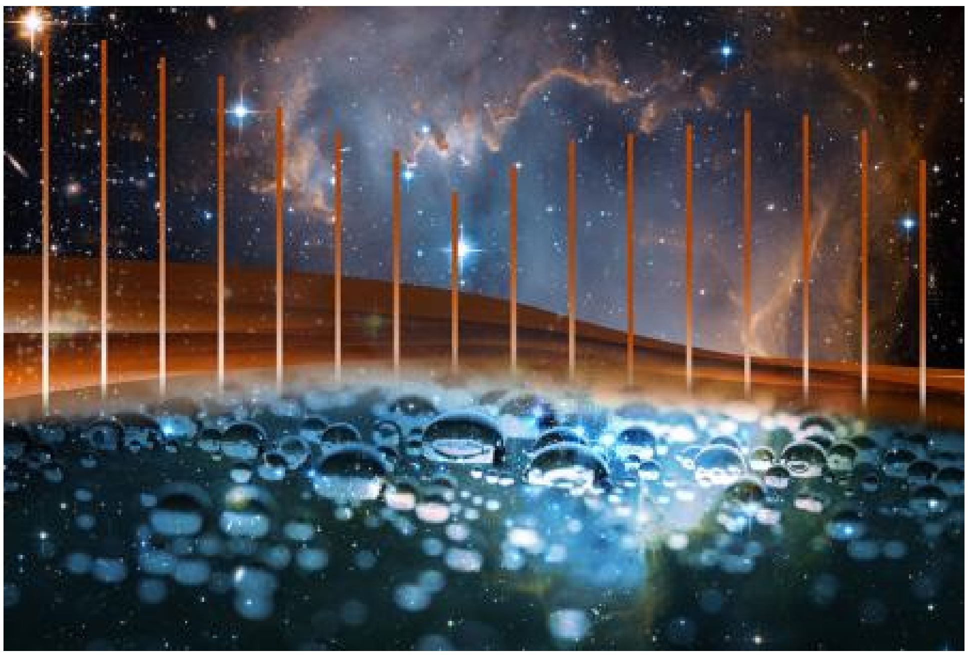
Chemists create 'comb' that detects terahertz waves with extreme precision

April 22 2015, by Kimm Fesenmaier



Caltech chemists have developed a precise ruler of terahertz light that will aid in the study of organic molecules in space, and the soft interactions between molecules in water. Due to its resemblance to a hair comb, the ruler is called a terahertz frequency comb. Credit: Lance Hayashida/Caltech and NASA/ESA/ and the Hubble Heritage Team (STScI/AURA) - ESA/Hubble Collaboration

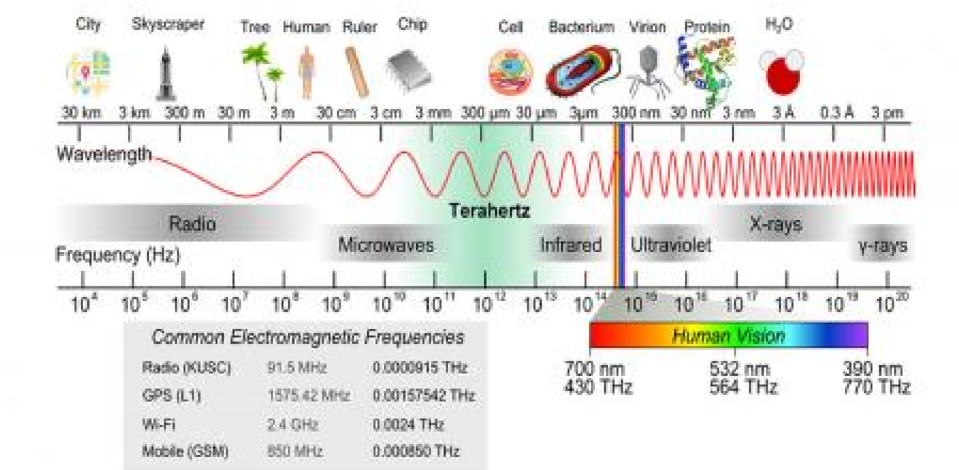
Light can come in many frequencies, only a small fraction of which can be seen by humans. Between the invisible low-frequency radio waves used by cell phones and the high frequencies associated with infrared light lies a fairly wide swath of the electromagnetic spectrum occupied by what are called terahertz, or sometimes submillimeter, waves. Exploitation of these waves could lead to many new applications in fields ranging from medical imaging to astronomy, but terahertz waves have proven tricky to produce and study in the laboratory. Now, Caltech chemists have created a device that generates and detects terahertz waves over a wide spectral range with extreme precision, allowing it to be used as an unparalleled tool for measuring terahertz waves.

The new device is an example of what is known as a frequency comb, which uses ultrafast pulsed lasers, or oscillators, to produce thousands of unique frequencies of radiation distributed evenly across a spectrum like the teeth of a comb. Scientists can then use them like rulers, lining up the teeth like tick marks to very precisely measure light frequencies. The first frequency combs, developed in the 1990s, earned their creators (John Hall of JILA and Theordor Hánsch of the Max Planck Institute of Quantum Optics and Ludwig Maximilians University Munich) the 2005 Nobel Prize in physics. These combs, which originated in the visible part of the spectrum, have revolutionized how scientists measure light, leading, for example, to the development of today's most accurate timekeepers, known as optical atomic clocks.

The team at Caltech combined commercially available lasers and optics with custom-built electronics to extend this technology to the terahertz, creating a terahertz frequency comb with an unprecedented combination of spectral coverage and precision. Its thousands of "teeth" are evenly spaced across the majority of the terahertz region of the spectrum (0.15-2.4 THz), giving scientists a way to simultaneously measure absorption in a sample at all of those frequencies.

The work is described in a paper that appears in the online version of the journal *Physical Review Letters* and will be published in the April 24 issue. The lead author is graduate student and National Science Foundation fellow Ian Finneran, who works in the lab of Geoffrey A.

Blake, professor of cosmochemistry and planetary sciences and professor of chemistry at Caltech.



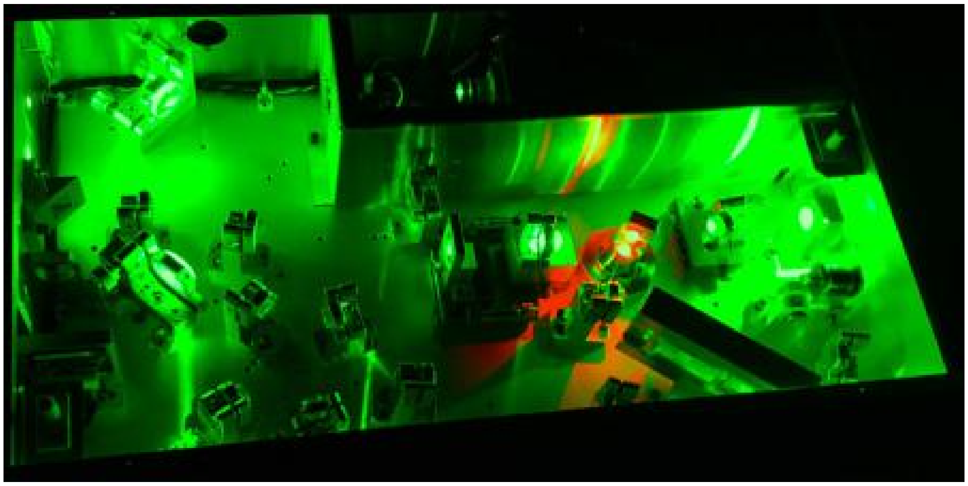
Light can come in many different frequencies, from the radio waves used in cell phones, to the light that is seen by human eyes. Terahertz light lies between radio waves and infrared light, with wavelengths near the width of a human hair. Credit: Daniel Holland/Caltech

Blake explains the utility of the new device, contrasting it with a common radio tuner. "With radio waves, most tuners let you zero in on and listen to just one station, or frequency, at a time," he says. "Here, in our terahertz approach, we can separate and process more than 10,000 frequencies all at once. In the near future, we hope to bump that number up to more than 100,000."

That is important because the terahertz region of the spectrum is chock-full of information. Everything in the universe that is warmer than about 10 degrees Kelvin (-263 degrees Celsius) gives off terahertz radiation. Even at these very low temperatures molecules can rotate in space, yielding unique fingerprints in the terahertz. Astronomers using telescopes such as Caltech's Submillimeter Observatory, the Atacama Large Millimeter Array, and the Herschel Space Observatory are searching stellar nurseries and planet-forming disks at terahertz frequencies, looking for such chemical fingerprints to try to determine the kinds of molecules that are present and thus available to planetary systems. But in just a single chunk of the sky, it would not be unusual to find signatures of 25 or more different molecules.

To be able to definitively identify specific molecules within such a tangle of terahertz signals, scientists first need to determine exact measurements of the chemical fingerprints associated with various molecules. This requires a precise source of terahertz waves, in addition to a sensitive detector, and the terahertz frequency comb is ideal for making such measurements in the lab.

"When we look up into space with terahertz light, we basically see this forest of lines related to the tumbling motions of various molecules," says Finneran. "Unraveling and understanding these lines is difficult, as you must trek across that forest one point and one molecule at a time in the lab. It can take weeks, and you would have to use many different instruments. What we've developed, this terahertz comb, is a way to analyze the entire forest all at once."



Extremely short pulses of red light (quadrillionths of a second) are generated by a titanium-sapphire laser, and then converted into terahertz light. The red glowing component in the photograph shown above is the titanium-sapphire crystal, surrounded by mirrors used in the laser. Credit: Brandon Carroll/Caltech

After the device generates its tens of thousands of evenly spaced frequencies, the waves travel through a sample—in the paper, the researchers provide the example of water vapor. The instrument then measures what light passes through the sample and what gets absorbed by molecules at each tooth along the comb. If a detected tooth gets shorter, the sample absorbed that particular terahertz wave; if it comes through at the baseline height, the sample did not absorb at that frequency.

"Since we know exactly where each of the tick marks on our ruler is to about nine digits, we can use this as a diagnostic tool to get these frequencies really, really precisely," says Finneran. "When you look up in space, you want to make sure that you have such very exact measurements from the lab."

In addition to the astrochemical application of identifying molecules in space, the terahertz comb will also be useful for studying fundamental interactions between molecules. "The terahertz is unique in that it is really the only direct way to look not only at vibrations within individual large molecules that are important to life, but also at vibrations between different molecules that govern the behavior of liquids such as water," says Blake.

More information: "Decade-Spanning High-Precision Terahertz Frequency Comb." *Phys. Rev. Lett.* 114, 163902 – Published 21 April 2015. dx.doi.org/10.1103/PhysRevLett.114.163902

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