Ultra Precise Distance Measurement Technology and Ultra Precise Light Source Technology Created with an "Optical Ruler"

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Instruments and technologies for measuring length

When we want to measure the length of some object, we normally turn to a tape measure or a plastic ruler. A standard tape measure or plastic ruler measures lengths down to the millimeter. With a tape measure, you can measure lengths several meters long.

For more precise measurements of length, we have the vernier scale. While vernier scales can only measure a maximum length of about 20 centimeters, they provide detailed measurements as fine as one-twentieth of a millimeter. The micrometer provides even finer precision measurements. Micrometers can measure lengths to an accuracy of one one-hundredth of a millimeter. Unfortunately, they can only measure objects up to about three centimeters long.

Today's vernier scales and micrometers have been improved significantly in terms of their measurement resolution and usability thanks to the introduction of digital technology. The measurement resolution of standard digital vernier scales and digital micrometers today is one one-hundredth of a millimeter and one one-thousandth of a millimeter respectively.

Vernier scales and micrometers are suitable for measuring the lengths of relatively small objects that can be placed on a tabletop. The instrument used to measure lengths of several meters to several hundred meters is the laser rangefinder, which is used on building or wooden home construction sites. Portable laser rangefinders are available commercially that can measure distances up to 200 meters at one-millimeter accuracy.

Length standards created by repeated ultrashort light pulses

All the instruments that measure length mentioned so far are off-the-shelf products. At the laboratory level, however, "rulers" are being prototyped with precisions far in excess of any conventional off-the-shelf product.

These rulers are based on a technology known as an optical frequency comb or frequency comb. Professor Minoshima is researching optical frequency combs (see Figure 1).

Optical frequency combs are called so because of their characteristic "teeth" that are arranged uniformly across the frequency spectrum.

An ultrashort pulse laser (mode-locked laser), which generates repeated, extremely short pulses of laser light, is used to generate an optical frequency comb. The width of the light pulses generated by an ultrashort pulse laser are extremely short, on the order of femtoseconds. One femtosecond is only 1×10^{-15} second (one quadrillionth of a second). Since light travels at 300 million meters per second, a light ray travels only 3×10^{-7} meters (0.3 micrometers) in one femtosecond. Because the light pulses are so short in both time and space, they can be used as a probe to measure very small times or distances. And the ultrashort pulse laser's light is composed of light at many frequencies spaced at intervals determined by the pulse repetition frequency — in other words, an optical frequency comb.

Professor Minoshima started her appointment at the university in 2013. Previously, she had been involved in optical frequency comb research at the National Institute of Advanced Industrial Science and Technology (AIST). Optical frequency combs can be used as a means of creating very precise standards of length: namely, the definition of the meter.

Many people, when they hear of the definition of the meter, probably think of the prototype meter bar composed of an alloy. The prototype meter bar, however, has not been used as a standard since 1960, about 55 years ago. Since 1960, the meter has been defined by physical phenomena rather than an object like the prototype meter bar. The first physical phenomenon used was a multiple of a specific lamp's wavelength. Since 1983, however, the meter has been defined based on the speed of light

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itself. One meter is defined as “the length of the path travelled by light in vacuum during a time interval of 1 / 299,792,458th of a second.”

The most important point of the post-1983 definition of the meter is that time is included in the definition. The accuracy demanded by the time of 1 / 299,792,458th of a second is precisely the accuracy in the definition of the meter, and, thus, length. Since time is the inverse of frequency, the precision by which a frequency is found translates into the precision of the length.

The model light source that maintains a consistent frequency (wavelength) with high accuracy is the laser light source. This is why, initially, the iodine-stabilised helium-neon laser’s wavelength was used as the practical means of realizing the length standard. The precision of lengths at this time was about 11 digits. The optical frequency comb developed by AIST, however, improved this length precision by about 300 times. Since July 16, 2009, the optical frequency comb instrument developed by AIST has been used as Japan’s official length standard.

In practice, however, lengths cannot be measured accurately just by deciding on a highly precise definition of the meter. Nevertheless, precision measurements of lengths have been realized using optical frequency combs as very accurate rulers. For example, experiments have verified that optical frequency combs can be used to measure a distance of 240 meters to approximately 1.6 micrometers, an extremely high resolution. This was the result of research done by Professor Minoshima and her research team. To visualize this kind of accuracy, consider that the instrument can measure the difference of a single piece of paper in a stack of paper 10 kilometers high.

Realizing an intelligent optical synthesizer

A representative and promising research area Professor Minoshima plans to engage in at the university is the intelligent optical synthesizer. The intelligent optical synthesizer is a technology to extend the concept of a music synthesizer, used to make music and musical compositions, to the optical field. The intelligent optical synthesizer will allow the performer to freely manipulate light in time and space as well as control the frequency (wavelength), phase, intensity, polarization, and other parameters. Professor Minoshima plans to develop this kind of light source by applying optical frequency comb technology.

The intelligent optical synthesizer was selected as an Exploratory Research for Advanced Technology (ERATO) project by the Japan Science and Technology Agency (JST). The JST ERATO Minoshima Intelligent Optical Synthesizer Project, which will run from October 2013 to March 2019, aims to advance development of intelligent optical synthesizers and explore application fields. Specific fields being considered include astronomical observations, environmental sensing, and imaging.

[Interview and article by Akira Fukuda (PR Center)]

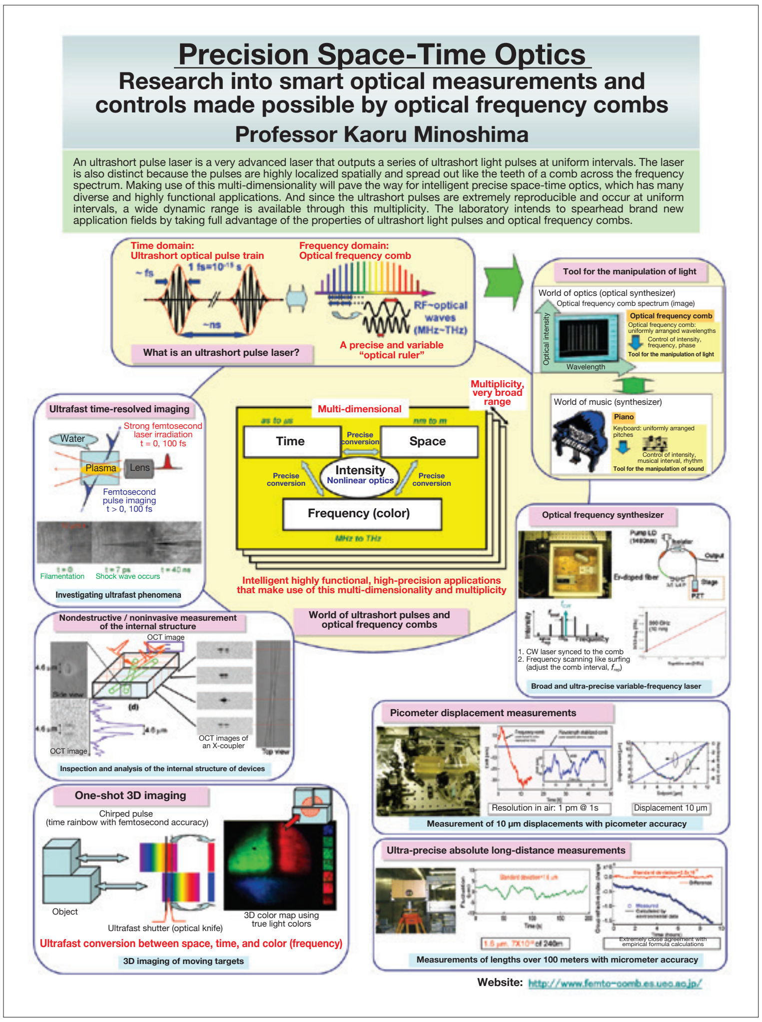

Figure 1: Details of the Minoshima laboratory’s research. The laboratory is developing optical frequency combs using ultrashort pulse lasers for various applications.

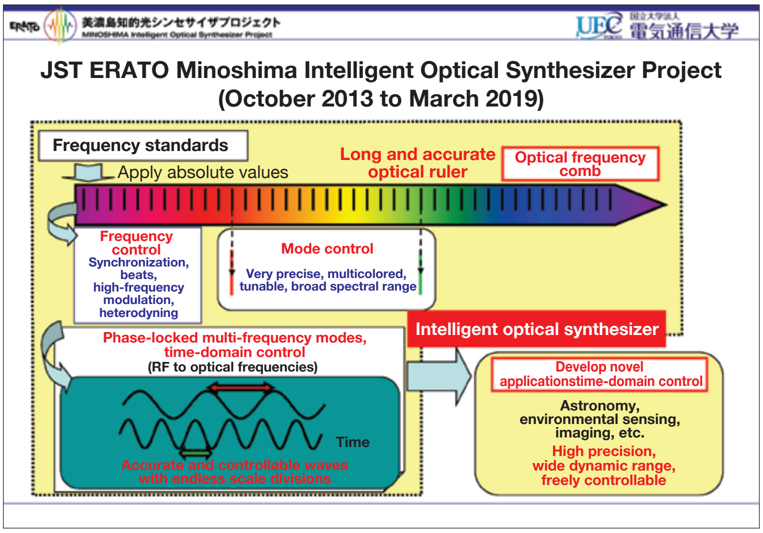

Figure 2: Summary of the JST ERATO Minoshima Intelligent Optical Synthesizer Project. The aim is to realize and explore applications for an intelligent optical synthesizer that can freely manipulate light.