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Research Article

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In-Situ Interferometric Metrology with Optical Comb

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Abstract

Optical frequency comb has various characteristics such as short pulse, broad spectra, many spectral lines, and high temporal coherency. In this paper, historical progress of the optical frequency comb is introduced in the metrology field and its temporal-coherence inteferometric applications are discussed for optical metrology. Specially, in-situ length metrology is presented on new measurement applications using the characteristics of the repetition frequency, brad spectra and high accuracy of the optical frequency comb.

1. Introduction

On the concept of "optical frequency comb", a long time, many studies have been carried out using a continuous wave (cw) or pulsed laser lasers, but were not enough to establish important research fields. However, it can be said that the progress of the study of ultra-short optical pulse of femto-seconds in the research field of spectroscopy has played as significant role. At the time, we had a great interest in femto-seconds laser application technology, and also joined the national research project for measuring the physical quantity from around 1993. At the time, it was faced with the impact of the new technology in our Laboratory tour of Professor J. L. Hall, who won the 2005 Nobel Prize (National Science Standard Institute, USA), and so we repeated a lot of discussions. In particular, we have very interested in several discussions by Professor T. W. Hänsh of the Max Planck Institute in the United States and Europe [1,2].

In addition, taking into account the evolution of the technology of femto-seconds mode-locked laser, we proposed an optical frequency measurement as the new research project of past Agency of Industrial Science and Technology at the end of 1996. The new project is to do phase-locking at the same time of ten femto-seconds mode-locked pulse lasers and then proposed to cover an octave in optical frequency. In this case, we considered the mode-locked laser of Inc. Imura provided compact product. Figure 1 is a conceptual diagram of the frequency measurement which is theoretically possible but it has been concerned that it is difficult in terms of cost [3]. However, there was a great innovation in the middle term of this project. It was the discovery of photonic crystal optical fiber (new optical fiber). As a result, when the femto-seconds mode-locked pulse laser is incident on the optical fiber, new optical frequency comb (so called as shown in Fig.2) were generated over one-octave frequency span, and then new technology of arbitrary optical frequency measurement was made rapid progress. Around 1999, we were provided the photonic crystal optical fibers through joint research with the Bath University of United Kingdom, and also has enabled to realize the optical frequency measurement [4].

In this paper, we pull out the features of the specific optical frequency comb, and introduce the status of the development of measurement technology. In the fields of industry and science, stable compactness, and real-time measurement technology, and so we introduce some research developments with an emphasis on low-cost technology for users in near future, though new functional expression of precision measurement is much important.

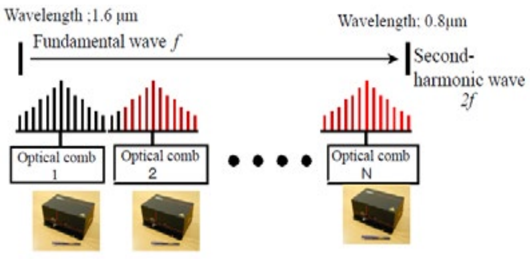


Figure 1: Our idea of optical frequency measurement in 1996.

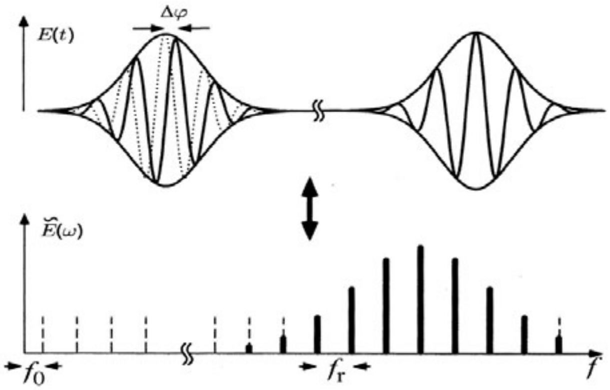


Figure 2: Outline of optical frequency comb; *E(t)*; Electric field, *Δφ*; Phase slip, *fo*; Offset frequency, *fr*; Repetition frequency.

2. Optical Frequency Comb and Its Characteristics

2.1 Ti-Sapphire Mode-Lock Laser

Femto-second mode-locked laser had been considerable progress using a medium of dye solution, but a lot of know-how is required for realizing stable oscillation, and so the deep acknowledgement was necessary. On the other hand, the argon-ion-laser is used as the pumping light source which uses much cooling water of a large amount because the large current discharge is required. However, the non-linear crystal for second harmonic generation of a laser-diode pumped YAG laser is made available as a pumping light source as a laser medium and so a thermal heating-problem is much reduced, and then cooling water circulation was also in a small amount. As a result, the stability and reproducibility of the oscillation of femto-seconds mode-locked laser was significantly improved. Thereafter, as the pulse width reaching 10 femto-seconds was also commercially available, the optical frequency comb with much-broad-spectral-width is available for temporal-coherence interferometry with high accuracy. Along with this, by using the photonic crystal fiber, the broad optical comb extending over one octave frequency was realized. Further, a nonlinear optical crystal for optical frequency doublers gives the carrier envelop offset-frequency (fo in Fig.2) of optical frequency comb with an accuracy better than 10-12 by the measurement method traceable to the Definition of Second [5-10].

2.2 Optical Fiber Mode-Locked Laser

Even if it becomes easy to use stable Ti-Sapphire laser, considerable technology was so necessary for the continuous operation of all-day in practical use, because long-term continuous measurement is very important. In parallel with this technology, as a base point in 1991, the oscillation of ultra short pulse laser with fiber-optic ring resonator by Prof. M. Nakazawa and his colleagues at Tohoku University is a foundation of great development. By using this technique, the all-optical fiber system is implemented in the development of the optical comb. As a result, generation system of the optical comb becomes quite compact of the optical comb. The continuous operation of the optical frequency measurement for 8 days has been demonstrated in National Institute of Advanced Industrial Science Technology [11,12]. It is an optical system which is arranged in a ring type and a highly nonlinear optical fiber and normal optical fiber generally with optical fiber coupling of the semiconductor laser as pumping light source. Self-mode-locked condition is achieved by controlling the fine polarization state, and its technology is capable of generating an optical comb with high quality used as a seed for the measurement. In order to control the inter-mode frequency of the comb, it is necessary to change the ring resonator length by a piezo-electronic transducer (PZT). As a result, the characteristic of the optical comb derived moreover strong interests in metrology field.

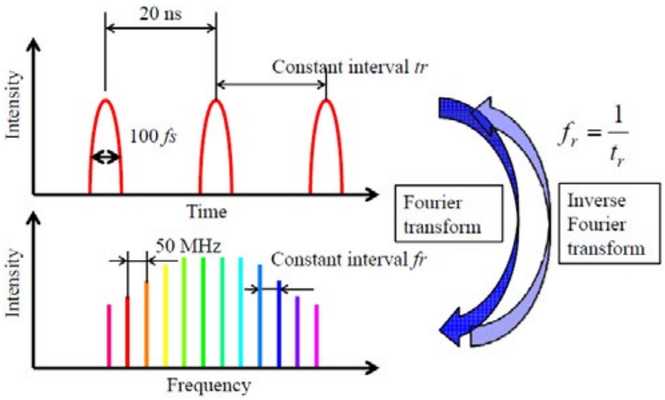


Figure 3: Concept of optical frequency comb.

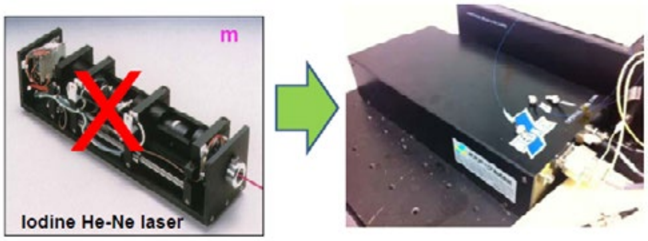


Figure 4: Designated Length standard in Japan(NMIJ/AIST document)

2.3 Recent Progress

Recently, the progress of femto-second pulsed-laser is fast and the advanced new lasers are useful in the research field of optical metrology because it is excellent in accuracy, compactness, and cost. Therefore, this situation is very laky in the metrology field. In practice, the new advanced industry requires the new metrology, because it is very wide applications which are important in the global industry. This technology is, I think, important to develop the in-situ optical metrology. Fortunately, the laser companies offer new lasers on stability, compactness, power, and cost. Based on the consideration of usefulness of the optical frequency comb, it was designated as the length standards on ISO 17025 in Japan as shown in Fig.4. Moreover, the carrier envelop offset frequency of the optical comb was measured with an accuracy of about 1MHz by the 2-type interferometers [13,14].

3. General Distance Metrology

3.1 The Principle of Interference and Air Turbulence

A general principle of the optical comb is very simple, but it is important to be change from conventional measurement instruments to new measurement instrument without various risks. Therefore, it is serious many problems in the various every technology of metrology. However, new temporal interferometry with the optical comb has many possibilities in grovel or future industry, though they are very serious in product industrial aspect, because the technology has many professional measurement possibilities. Specially, the effect of air turbulence is important in the field of large-size metrology which is not realized by CW laser technology. On the other hand, the present technology has many possibilities for realizing the in-situ metrology.

Figure 5 is Michelson interferometer with unbalance optical path-difference, using the principle of the temporal behavior of the optical comb. For example, depending on the pulse width of the optical comb to (several tens fs), generated interference fringes are localized to a small space in time. In this case, the pulses of optical comb are to meet at overlapping position, when then the optical path difference of the interferometer is an integer multiple of the propagation distance of the pulse interval. Moreover, the light of the pulse train of the long arm does interference with the light pulse train of short arm of the interferometer (temporal coherence interference).

The interference fringes equivalent to low-coherence interference are formed at discrete positions in space. Thus, there is a possibility to be precisely measure the peak as the same to the envelope of the low coherence interference fringes, and it is possible to achieve a resolution of nanometer order spatial positioning if necessary. In this case, it is considered that the coherency of the optical comb in the pulse train is very long and then is also possible application to positioning in long distance [15-20].

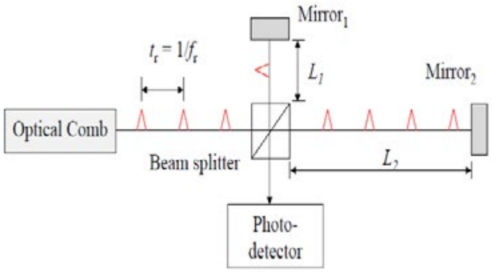


Figure 5: Temporal-coherence interferometry of optical frequency comb.

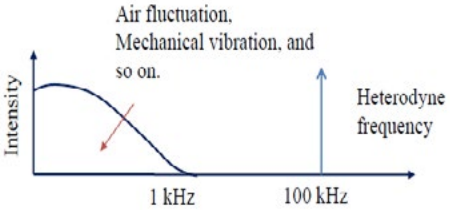


Figure 6: Frequency range of interferometric fringe noises.

In order to achieve temporal coherence interference for long distance, the reduction of noise due to mechanical vibration and atmospheric turbulence as shown in Fig.6 is important. Since these noises are the frequency range of below several kHz, the interference measurement is performed in the frequency range of several tens of kHz and so the heterodyne technique is useful. Therefore, an acousto-optic modulator (AOM) is used for shifting the frequency of the optical comb, and heterodyne interference fringes are generated.

3.2 Position Measurement of Long Distances

Figure 7 is a schematic of the temporal coherence interferometer developed. For the repetition frequency fr=100MHz of the optical comb used, the AOM shifts by 100.1 MHz of the optical comb, and then the heterodyne signal of fh=100 kHz is generated with high SN ratio. As a result, the SN ratio of interference fringe is improved by using phase-sensitive detection method with a lock-in amplifier of frequency-selective amplifier. Further, for utilizing the interferometer in the field, the optical fiber system is introduced because it is easy to isolate from the turbulence air and is arranged to be compact. In the reference optical path, the AOM and piezo-electronic transducer (PZT) for scanning the interference fringes is provided [21,22].

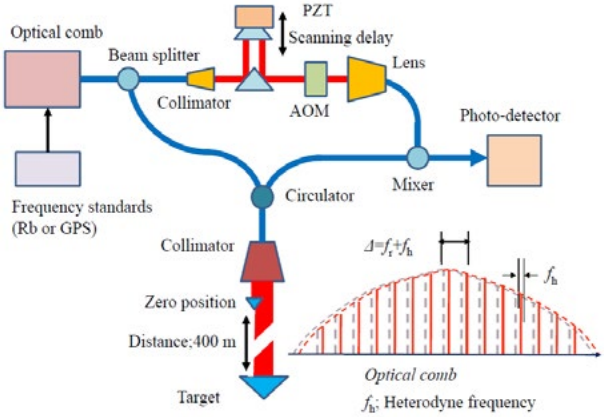


Figure 7: Heterodyne temporal-coherence interferometer.

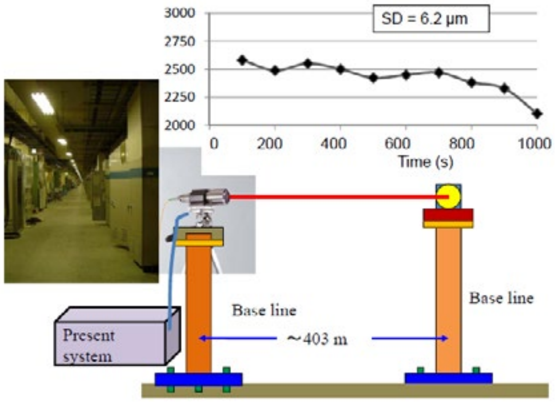


Figure 8: Experimental place (KEK) and results.

Furthermore, the zero-position is arranged to be near the measurement collimator, and the drift of the optical fiber interferometer is compensated by generating the reference with measurement signal, simultaneously. The difference between the measurement signal and the reference signal is measured with a high accuracy because the noises are changed in time range. as a result, the interferometer is isolated from various measurement noises such as air temperature and mechanical vibration and it is minimized the influence of those.

As a result, even in the field, the high SN ratio of the detection the interference fringe signal is generated a high accuracy spatial positioning is performed precisely. The optical comb used herein is a C-fiber laser (Menlo Corporation). The output power was about 12 mW. Also, the spectral width is approximately 60 nm, the central wavelength is about 1560 nm. Repetition frequency (fr=100 MHz), rubidium-locked oscillator (stability order of 10-11) because it is controlled by, and each distance of 1.5 m the interference fringes are generated with the optical frequency comb, and it is possible to determine the spatial position with high accuracy.

High Energy Accelerator Organization (KEK) is interested in the measurement technology to manufacture the accelerator for next generation of high-intensity radiation. In the hallway of about 500 m of the accelerator-beam line-control system, the controller is installed in 10 m each, the study site is controlled by the temperature around 25 ºC as the crow flies, as shown in Fig.8.

We made the experiment of space positioning at a distance of up to 403 m. In tens of minutes, it was smaller than 3 µm which is sufficient reproducibility of the spatial position. The relative accuracy is 1×10^{-8}, which is the accuracy that cannot be achieved only by the optical frequency comb. From Fig.10 (a), it can be seen that sufficiently smaller than about 6 µm repeatability of spatial position. It is 1.5×10^{-8} as the relative accuracy. In view of the impact of air fluctuation, the accuracy of measurement system according to the present method is considered to be the relative accuracy 0.75×10^{-9} or less small.

4. Fast Optical Comb Metrology

4.1 Fast Optical Comb

The new industry technology is considerably required in high accuracy and good technique in feature, because the conventional technology did not resolve the interests of many users. However, it is important to reduce the effects on mechanical vibration and air turbulence. Moreover, a large majority of the optical combs available oscillates at the repetition frequencies of 40 ~ 250 MHz and so it is important to measure objects with fine-positioning, because it is difficult to use the interference principle of about several meters.

For this reason, the use of Fabry-Perot etalon (etalon) is considered, but the existing etalon available is a bulk type, which is not easy in in-situ metrology. Therefore, we developed new fiber etalons, because it is very easy in use and specially is not very affected by the effects of the air turbulence and mechanical vibration. At first, the etalons with free-spectral ranges of 1 GHz and 5 GHz are developed and then they are applied to the CMM calibration. In this case, the important role is only to filter the lines of the optical comb, and then the accuracy of the improved optical comb is not changed to be a high accuracy of 10-11. In this case, the repetition frequency of the optical comb used is changed from fr=100 MHz to the high-repetition frequencies of 1 or 5 GHz frequency [23-25]. Moreover, the application technology of the optical combs requires the ultra-fast repetition frequency such as 15 GHz for better metrology. we have nearly developed an etalon without additional alignment as shown in Fig.9. As a result, the etalon can be mounted as with FC/PC connectors and typically the alignment is not required. It is useful on the effects by measurement conditions.

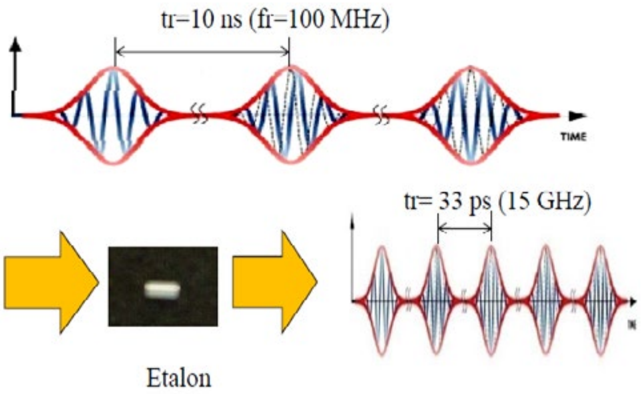


Figure 9: Fast optical frequency comb by optical fiber-etalon for industrial metrology

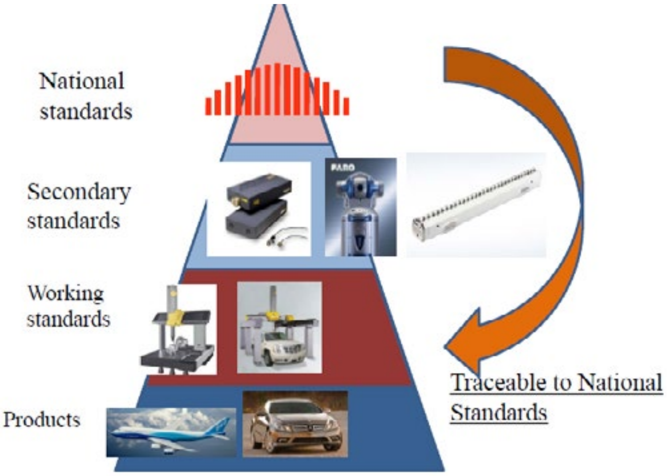


Figure 10: Industrial application of the optical comb.

4.2 Industrial Length Metrology

Figure 10 shows the traceability system using an optical comb. I we use the optical comb interferometry, we don’t need Secondary standards and sometimes Working standards, because the present measuring system offers the absolute length and can measure directly object under measurement.

In industrial measurements, an application to three-dimensional coordinate measuring machine (CMM) is discussed in the case of using the optical comb, because it is difficult to mount the reflector on the CMM. Fortunately, the optical comb is very short pulse-width, and then it is a possibility of measuring the accurate positions in space. Really, we can say that the optical comb has a possibility of deriving the many applications of spatial position measurements [26].

Therefore, it is considered to be capable of handling most of the industrial instruments and metrology instruments. The practical applications of the present system were achieved with an accuracy of 0.06 µm. The CMM may be calibrated by the comb interferometer in the place of step gauge blocks required for manufacturing. Therefore, the calibration of the CMM was then compared the comb interferometer to calibration by step gauge, and it was found that the measurement accuracy by the optical comb reaches to 0.1 µm. Figure 11 is an example of the interferometer by the optical comb. The majority of the interferometer is composed of optical fibers because the effects of atmospheric turbulence and mechanical vibrations. The experimental results of the comparison show the mean difference of better than 0.2 µm using the fast optical comb with the repetition frequency of 5 GHz, which means to measure at each 3-cm length in space. In this case, the probe of the CMM used is utilized, and so this technique is limited in the application.

Moreover, the rough-surface ball (roughness Ra=0.1 µm as shown in Fig.12) is used in place of a retro prism in order to use the probe of the CMM, directly [27]. The reproducibility of the experimental measurements was less than 0.3 µm, which of accuracy is enough in general industrial metrology. Also, a ball lens with the refractive index n=2 (Ohara glass S-LAH79) is applied as the probe of the CMM in order to measure the large-size object.

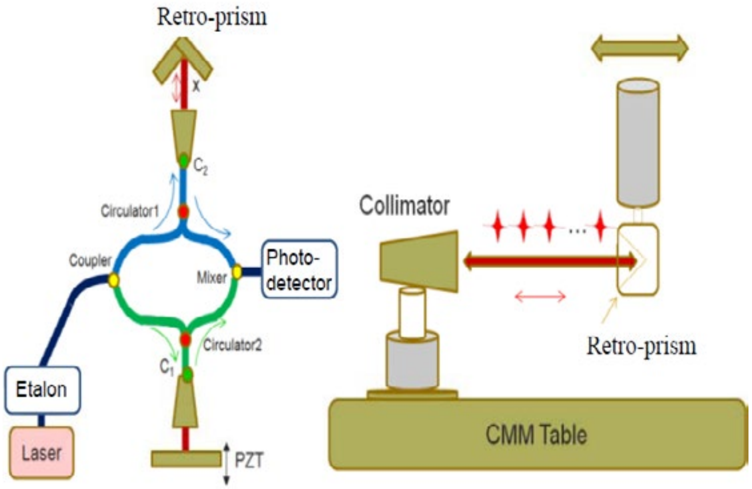
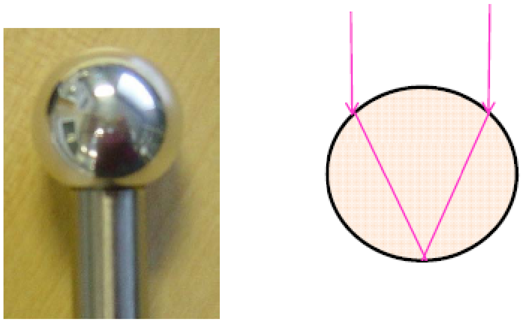


Figure 11: Optical-fiber interferometer for CMM.



Rough-surface ball

Ball lens of refractive index n=2.0

Figure 12: Various probe targets for CMM.

4.3 New Huge-Object Flatness Metrology

Recently, advanced industries are interested in high quality products and safety construction, which are huge-size in the range of several meters to several tens meters. We are studying about the measurement system using the optical comb interferometer which uses the ball lens as a target as shown in Fig.14. In this case, the collimated beam is very easy though the scanning system of the laser beam is required [28].

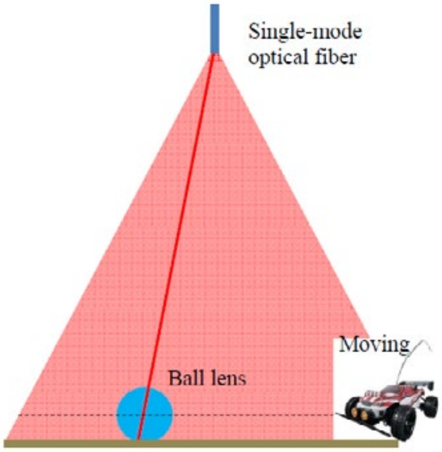


Figure 13: Flatness measurement of Large object.

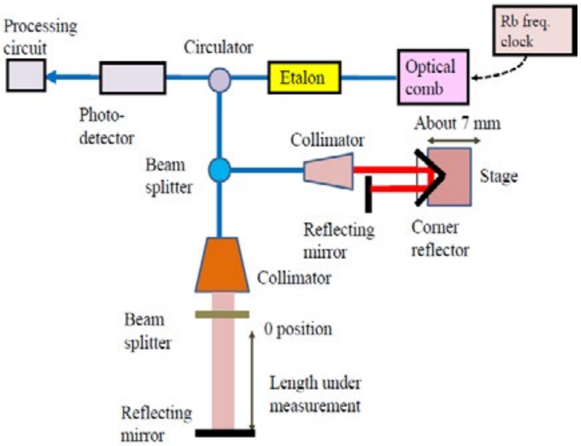


Figure 14: Length measurement system with temporal coherence interferometer.

4.4 Length Metrology

In this present, the length measurement using the repetition frequencies of 15.0 GHz and 14.9 GHz is discussed and then the scanning rage of the stage is about 14 mm long. Figure 5 shows the outline of distance measurement with an un-balanced arm interferometer and a scanning stage. For reducing the effect due to the drift of the measurement system, the zero-point of each interference fringe order is generated by using a window plate and the electric signal is always displayed at each order. The object mirror is at the position of the target mirror under measurement in space. The interference fringes of 0 mm position are always generated at the same position by scanning over 12 mm. On the other hand, the interference fringes of the target are generated at every position corresponding to the length under measurement within 12-mm scanning, because the 15-GHz repetition frequency is equal to the 10 mm-interval. Figure 6 shows the behavior of interference fringe generation in the length range of 100 mm to 120 mm. In measurement, the interval between the zero-position signal and the measurement position signal is determined by the moved displacement of the stage with a high accuracy of better than 0.1 µm. Secondly, the order of the interference fringe is determined by the same measurement by the 14.9 GHz repetition frequency of the comb [29].

Figure 16 shows the outline of automatic processing of interference fringes for determining the length/distances in the range of short distances [30]. In this case, the signal, which shows the peak of fringe pattern, is generated. At first, the photo detection signal is squared, and then is filtered by a low-path filter, and next is differentiated. Finally, pulse signal is generated at the zero-crossing position for doing the trigger of a short length-measurement sensor.

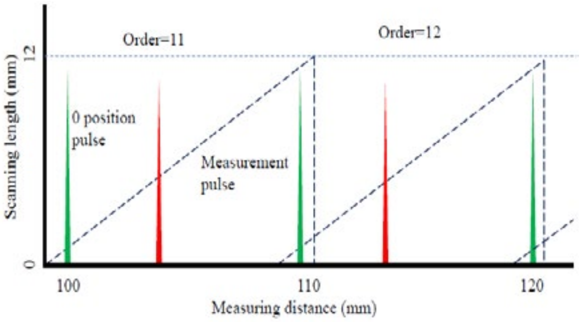


Figure 15: Measurement principle by temporal coherence interferometry with a scanning stage of 14 mm length.

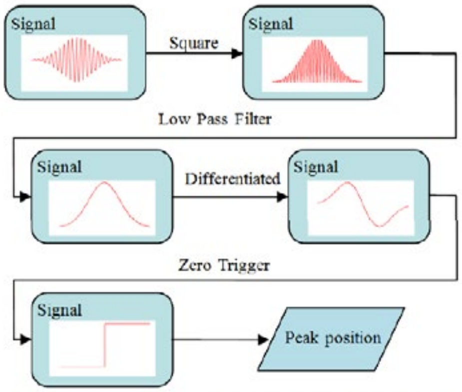


Figure 16: Automatic processing of interference fringe pattern.

5. Rough Surface Object Measurement

Non-contact measurement is very important in practical measurement for establishing the qualities of production industry and safety society. For example, the engine and body-form of air plane is big size and so it is difficult to measure them with high accuracy and high efficiency.

Figure 17 is a high-sensitive interferometer to realize a non -contact measurement in distance around the 9 m distance. The laser beam from the optical comb is divided in a ratio 5%:95%. High sensitivity is achieved by phase-sensitive measurement method with a lock-in amplifier and heterodyne interferometry with the AOM. The scanning of the interference fringes was achieved by a voice coil stage (moving length: about 14 mm), and was scanned at a frequency of about 9 kHz. In the measurement optical path, using a single-mode optical fiber was efficiently collect light reflected from the object and good SN ratio signals were obtained. I focused sometimes on the rough surface object by the divergent light from the optical fiber with a lens (80-mm focal length). The single mode optical fiber is useful to introduce the effective use of the interference function. Further, the reference signal of the lock-in amplifier is obtained from the output from the frequency synthesizer.

The rough surface object of Ra=1.6 µm was measured at a distance of 9 m as shown in Fig18, and the standard deviation of the measurements was 1 µm or less. Further, at a distance of about 3 m, the rough surface object is tilted by 20 degrees, and the experimental results show the standard deviations of 2.73 µm, respectively. In this case, there is a need to define the concept of spatial position [31].

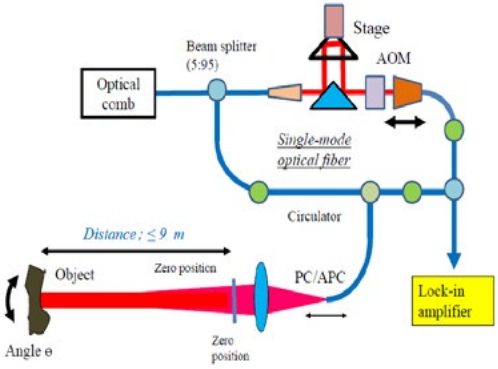
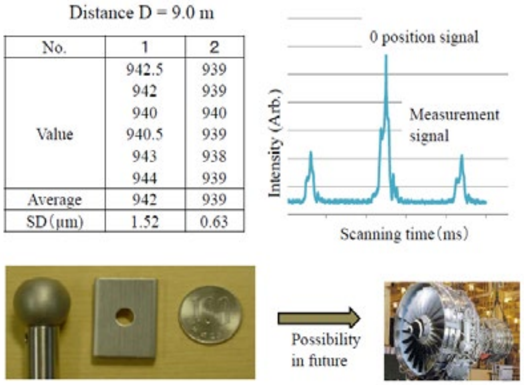


Figure 17: Optical system for non-contact measurement.

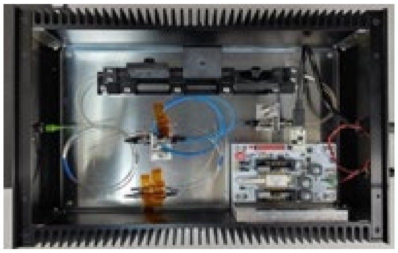


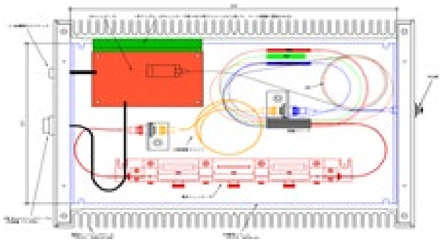
Distance D = 9.0 m

No.	1	2
Value	942.5	939
	942	939
	940	940
	940.5	939
	943	938
	944	939
Average	942	939
SD (μm)	1.52	0.63

Figure 18: Experimental example for Rz=1.6 rough target at 9-m distance.

Recently, optical frequency combs have been commercialized with a stable frequency and so they are realized with very low cost and compactness by reducing the number of parts in 2021. Therefore, we may easily use them for various practical applications. (Responsible for the Optical Metrology Office).





Items	Spec.
Center Wavelength	About 1.55 μm
Output Power	About 5 dBm
Repetition Frequency	30~40 MHz
Spectral Width	30~80 nm
Input Source	5V

6. Conclusions

As described above, development of optical frequency comb is remarkable, and it will be accepted in society and industry, though low cost is required. In the near future, it will be key technology of the Unit System in the Meter Convention because the Unit System will be changed in 2018 or 2019. In the field of length metrology, particularly, the optical comb is attractive because it has a possibility of realizing new many measurement systems in addition to conventional length measurement systems. Our preliminary experiments show a strong possibility. In future, length standards will be offered through communication optical fiber systems.

Acknowledgements

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