博士論文（要約）

Absolute Length-Measuring Interferometers Using Heterodyne Signal of Optical Frequency Comb Laser

（光周波数コムレーザのヘテロダイン信号を用いた絶対測長干渉計）

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1. Object and optical frequency comb

The precision measurement for long distance will contribute to the industry and the scientific researches. The optical interference method is usually used for the length measurement, because of its traceability to the frequency of the light and its high resolution. However, the existing methods hardly realize all the measurement needs, so a new interferometer system using new optical frequency comb is proposed.

The optical frequency comb (optical comb) emits ultra-short pulses in time domain, and has many frequency modes with a certain rate in the frequency domain. The good stability and high accuracy of its frequency modes allow it to realize new measurement methods which are impossible for the conventional light sources. There are two parameters of the optical comb, the repetition frequency and the carrier envelop offset frequency, by which the frequency of any mode of the comb can be determined. The repetition frequency can be easily stabilized to a frequency standard, and it leads to many new methods of the interferometers.

In this thesis, an interference system based on an optical comb is proposed for absolute distance measurement. There are two objects. One is to realize the position measurement for the long distance longer than 50 m, and the other is to realize the absolute length measurement for several meters. The heterodyne interferometer technique, for the pulse interferometric technique and the multiple wavelength interferometric technique, is used for the measurement system.

2. Position measurement using a pulse interferometer

For the first object, a new heterodyne interferometer is proposed which utilizes an acoustic optical modulator and an optical comb as the light source. The temporal coherence interference of the optical comb is used directly as the light source of the interferometer. The pulse interference of the optical comb is affected by air turbulence, but the heterodyne technique is useful for reducing this effect because the heterodyne frequency is usually outside the air turbulence frequency region, which extends to a few kilohertz. Absolute position measurement using the temporal coherence interference for discrete distances is realized by scanning the heterodyne interference fringe with a phase-sensitive detector (lock-in amplifier). The experimental setup is used to measure distances up to 403 m.

The reproducibility of 5 μm is realized and the stability evaluated for the distance of 51 m is 0.5 μm. The positions which can be measured depend on the repetition frequency of the optical comb. The space interval is 1.5 m when the repetition frequency is 100 MHz, and 2.56 m when the repetition frequency is 58.417 MHz. Febry-Pérot etalons can also change the space interval of the positioning measurement by working on the spectrum of the optical comb, and the space interval can be shortened to around 1 mm.

3. Super-heterodyne interferometer using multiple laser diodes and on optical comb

For the second object, a new super-heterodyne interferometer is developed and multiple-wavelength interferometric method is used to realize a step by step measurement. For precision measurement, it is necessary to stabilize each wavelength to a standard, which makes the measurement method traceable and the measurement stability and accuracy can be proved. One optical comb is used as a frequency standard to stabilized two continuous wave laser diodes (CW LD). And a super-heterodyne interferometer is developed using multiple CW LDs and the optical comb as the probe light sources. The beat signals of the CW LDs and the optical comb are used directly as the heterodyne signal. The measurement accuracy is better when the synthetic wavelength is shorter, while the measurement range is shorter. Therefore it is possible to realize a step-by-step measurement since the synthetic wavelength is changed by using different CW LDs as the probe light. And finally, the accuracy and resolution of the whole absolute distance measurement system depend on the heterodyne interferometer using a single CW LD, whose frequency is also stabilized.

The wavelengths of the three laser diodes used in the developed system are 1.540 μm, 1.542 μm and 1.570 μm. The frequency differences of 3.7 THz and 8 GHz are used, so the synthetic wavelengths are 80.5 μm and 42 mm. The realized resolution is 0.1 μm for the former and 10 μm for the latter. So the multiple-wavelength interferometers can refine the measurement result of the pulse interferometer.

The heterodyne interferometer using single stabilized continuous wave laser diodes is the last step of the developed system. Its final resolution and accuracy depends on this step. The wavelength of the stabilized laser diodes in use is 1542 nm. Since the realized resolution of the multiple-wavelength interferometer is 0.1 μm, the order of the interference fringe can be determined. The realized resolution of the heterodyne interferometer is 3 nm, which is also the resolution of the whole measurement system.

4. Comparison of the pulse interferometer and the super-heterodyne interferometer

The comparison experiments between the pulse-heterodyne interferometer (pulse interferometer) and the supper-heterodyne interferometer using laser diodes have been done. At first the measurement stabilities of the pulse interferometer and a heterodyne interferometer using a stabilized laser diode are compared by experiments. Then the super-heterodyne interferometer using two laser diodes is compared with a pulse interferometer, and the laser diodes are phase-locked to each mode line of the optical comb. The stabilities of the two interferometers are compared and the pulse interferometer can be used to evaluate the measurement accuracy of the super-heterodyne interferometer. The results show that the measurement stability and accuracy of the two kinds of interferometers match with each other, so the two interferometers can be combined to measure the same target using the step-by step method.

5. Discussion

It is known from the experimental results of each part of the absolute distance measurement system that the environment condition and the fiber lengths will influence the measurement stability and the accuracy. The parameters of the environment need to be controlled or be recorded for the compensation.

For the last step of the system, the frequency stability and accuracy of the laser diodes directly determine the stability and accuracy of the length measurement. In the experiment, the laser diode is phase locked to an optical comb, but the carrier envelope offset frequency of the optical comb is not stabilized. So there is a drift of several megahertz. If the stability of the carrier envelope offset frequency is improved or measured, the stability of the length measurement will also be better.

6. Originality of the research

For the pulse interferometer based on an optical comb, the heterodyne technique is developed on the frequency modes of the optical comb. The measured distance is up to 403 m and the measurement stability is 6 μm without compensation of the air refractive index. And the method to determine interference order is proposed, so the absolute measurement is realized.

For developing the super-heterodyne interferometer, the optical comb is used as both the probe light and the frequency standard. The beat signals of the optical comb and the laser diodes are used as the heterodyne signal of the interferometer. A standard interferometer is set in the system. Electric and optical switches are firstly used to change the data source of the interferometer, and the influences caused by environment and the fiber are reduced.

For the comparison experiments, the measurement stabilities of the difference laser sources are compared at the distance of 22.5 m. The pulse interferometer is used to evaluate the measurement accuracy of the super-heterodyne interferometer.