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Development of multi-channel optical sensor based on dispersive interferometry

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Abstract
In this investigation, we propose an efficient multi-channel optical sensor based on dispersive interferometric principle. This sensor consists of a single optical source, a spectrometer and fiber optic components such as an optical circulator (OC), a coarse wavelength division multiplexer (CWDM) and fiber optic probes. A spectrometer is used to detect the spectral interferograms of the measuring probes according to their own spectral bandwidths and the interference signals can be separated by the spectral bandwidth filtering by CWDM. The principle of the proposed sensor system was verified with feasibility experiments with the home-built 4 channel sensor system. The measuring range of each channel was 1 mm and the resolution was a few tens of nanometers determined by the deviation of linear motions and the stability of the sensor was better than 30 nm. With the aid of a broadband source and a spectrometer, the measurement channel can be extended further by using a suitable CWDM. In the presentation, we show the home-built optical sensor system and the experimental results to confirm system performances.

Keywords: Multi-channel sensor, dispersive interferometry

1. Introduction

According to the demands of precision industry, distance or gap measurements have been important because of the assembly and alignment of several components. Moreover, precise moving stage needs to be calibrated by measuring some motion errors. Capacitive sensors have been widely used to measure very small gaps between the probe and the target precisely [1]. However, they have some practical limitations caused by their fundamental operation, which the electricity should be stored in the gap. The material of the target is limited as conductive and the working distance is in the range of a few hundreds of micrometers. In order to overcome these limitations, several optical sensors [2,3] have been developed but their resolution cannot reach the expected region. On the other hand, optical interferometry is very attractive tool to measure distances precisely [4]. Especially, dispersive interferometry is suitable for the optical gap sensor to replace the capacitive sensors because it can measure distances without any mechanical and electrical scanning parts and it is free for well-known ambiguity problem [5]. Moreover, the measurement channel can be extended by using a spectral band-pass filter because a broadband light source is used in dispersive interferometry.

2. Multi-channel optical sensor

Figure 1 shows the optical configuration of proposed multi-channel optical sensor. A super-luminescent diode (SLD) is used as a light source and the light is incident to a CWDM after passing through OC. The CWDM can split the light as the number of measurement channels and the output of each channel has its own filtered spectrum because the CWDM acts as a kind of spectral filtering beam splitters for the incident light. The output of the CWDM is delivered to each measurement probe, which consists of a collimating lens and a beam splitter (BS) to realize a Fizeau-type optical configuration as shown in the inlet of Fig.1. Then, the reflected lights from the BS and a target are recombined by the CWDM and go to a spectrometer to detect spectral interferograms after passing through the OC. Because of the spectrum filtering by the CWDM, the spectral interferogram corresponding to each probe can be isolated and obtained without crosstalk in the spectral domain.

The measuring principle of the sensor is based on the dispersive interferometric technique to extract the distance of each channel. In this case, no additional optical sources and spectrometers are needed for the extension of probes and the system cost can be lowered.

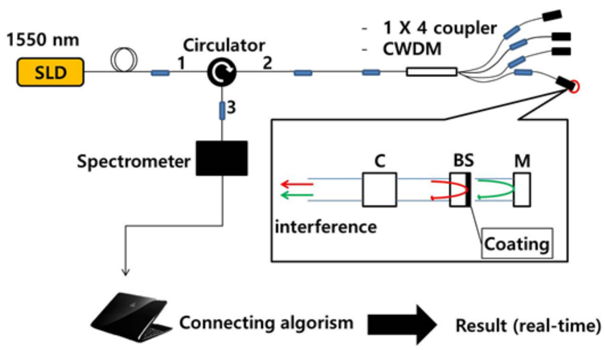

Figure 1. Optical configuration of the multi-channel optical sensor.

3. Dispersive interferometry

In dispersive interferometry, the interference fringe produced by the spectrum of the broadband source varies with the optical frequency (ν) in the form of [5]

$$i(\nu) = a(\nu) + b(\nu)\cos\phi(\nu) \quad (1)$$

The mean intensity a(ν) and the modulation amplitude b(ν) are directly related to the spectral power density s(ν) of the source as follows.

$$a(\nu) = \frac{1}{2}s(\nu)[r_r^{\,2}(\nu) + r_m^{\,2}(\nu)] \quad (2)$$

and

$$b(\nu) = s(\nu) r_r(\nu) r_m(\nu)] \quad (3)$$

where $r_r(\nu)$ and $r_m(\nu)$ denote the reflection coefficients of the reference and measurement mirrors, respectively. In general, the reflection coefficients tend to vary slowly with ν and for simplification, they may be assumed unity within the spectral range of $s(\nu)$. Consequently the spectral power density of Eq.(1) can be rewritten as

$$i(\nu) = s(\nu)[1 + \cos\phi(\nu)] \quad (4)$$

Then, attention needs to be paid to the phase $\phi(\nu)$, which is related to the distance L between the reference and measurement arms in the reflective type interferometry such as

$$\phi(\nu) = \frac{2\pi(2L)}{\lambda} = \frac{2\pi(2L)}{c} n\nu \quad (5)$$

where λ is the wavelength, c is the speed of light in vacuum, and n is the refractive index of air. Further, the phase $\phi(\nu)$ can be expressed as $\phi(\nu)=2\pi\tau\nu$ in which τ_0 denotes the time delay between two paths being defined as $\tau_0=2nL/c$. Now it is noted that τ (=1/ν) and ν become the Fourier transform pair. Fourier-transforming Eq.(4) in consideration of Eq.(5) leads to the result of

$$I(\tau) = S(\tau) \otimes [\delta(\tau) + \frac{1}{2}\delta(\tau + \tau_0) + \frac{1}{2}\delta(\tau - \tau_0)] \quad (6)$$

If it is assumed that the spectral power density $s(\nu)$ is a real function, its Fourier transform $S(\tau)$ becomes symmetric and three peaks appear at locations $-\tau_0$, 0, andτ_0. The peaks are convoluted by the function $S(\tau)$ and the location of τ_0 is related to the distance L abovementioned. Thus, L can be directly traced in the τ-domain.

4. Experiments

For the verification, the multi-channel optical sensor was constructed and feasibility tests were implemented. Figure 2 shows the experimental setup which consists of the home-built measurement system with probes, a moving stage and a PC to calculate the distances. In the measurement system, a SLD (SLD1550S-A2, Thorlabs) which has 1550 nm center wavelength with 90 nm bandwidth, a spectrometer (NIRQuest, Ocean Optics) and all kinds of fiber optical components were well packaged in an enclosed case and the measuring probes were connected to the system by using fiber optic adapters (FC/PC connectors). A CWDM has 4 channels of which the outputs have 1530 nm, 1550 nm, 1570 nm and 1590 nm center wavelength with 20 nm bandwidth. In the experiment, the target was a plane mirror attached to the motorized moving stage (XCV630, Suruga Seiki) and the distances between the probe and the target were measured. In order to confirm the performances, the measuring range and the working distance were checked by using the moving stage. In the proposed system, each measurement channel has the spectral bandwidth of 20 nm and the spectrometer has 0.32 nm resolution. As the result, the theoretical minimum and maximum measurable ranges are approximately 130 μm and 1.2 mm, respectively, for all probes [6]. From these values, we set the 200 μm working distance and 1 mm measuring range. The stage was moved in the range of 2.5 mm with 5 μm step size and the distances were measured by 4 probes. Figure 3 shows the measurement results of 4 probes which confirm each probe can measure the distance from 200 μm to 1.2 mm successfully. Beyond 1.2 mm movement, the measuring system could not measure distances because of the maximum measurable range. In addition, the linearity were checked with the open-loop stage positions and they were within 0.6%. For 15 minutes as the relatively long term, the stability was less than 30 nm caused by the power fluctuation of the optical source.

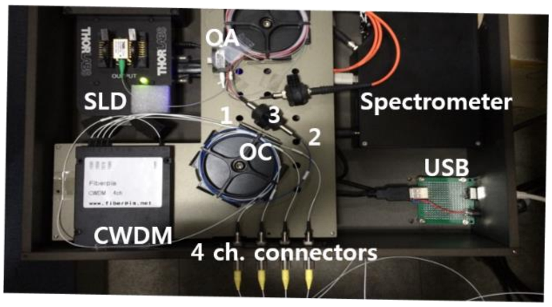

Figure 2. Optical configuration of the multi-channel optical sensor; SLD, super luminescent diode; CWDM, coarse wavelength division multiplexer; OA, optical attenuator; OC, optical circulator.

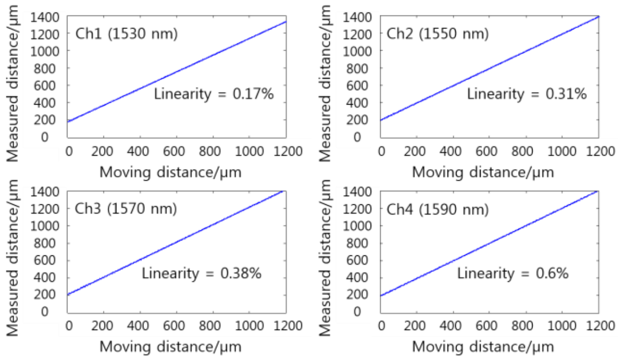

Figure 3. Distance measurement results of 4 probes.

5. Conclusion

In this investigation, we propose a multi-channel optical sensor to be used for precision industry to measure small gaps without any mechanical or electrical moving parts. The operating principle of the sensor is based on the dispersive interferometry, where the spectral interferogram using a broadband light source is detected by a spectrometer. Each channel possesses its own spectrum as a result of spectral filtering of a CWDM and measures the distance independently. The main advantage of this sensor is that it can measure several distances at once with a single light source and a single spectrometer because the spectrometer can detect the whole spectral interferogram. As the experimental results, the optical sensor can measure the distances up to 1 mm with the repeatability of less than 30 nm.

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