'89 KACC 1989. 10. 27~28

Influence of air pressure, temperature, humidity and CO_2 concentration on optical phase changes in thin films

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__Abstract__: A new method for measuring optical phase changes of reflection beam from optical mirror is proposed. The optical phase change is liable to change with varying atmosphere conditions. This optical phase changes are measured against air pressure, temperature, humidity and CO_2 concentration variations. It is clarified that the optical phase changes are most effected by humidity change.

Introduction

As laser technology progresses, displacement measuring systems for optical interferometry become essential for high-precision work. To improve the accuracy of the optical interferometry, the precise refractive index of the air must be measured and the output of the interferometer must be compensated for using this index. Generally, the refractive index of the air is obtained by measuring the optical path change in a fixed gap, where two mirrors are placed at each end. Dielectric thin film is deposited on these mirrors to achieve a high reflection coefficient. By varying the atmosphere conditions, the index of refraction, the optical path length of the air, and the properties of the thin films are changed. The phase between the incident and reflected beams also changes with the optical characteristics. This is not desirable if we wish to determine the precise refractive index of air. Previously, these optical phase changes were only estimated from a calculation of the refractive index in air.

This paper takes up the optical phase changes and proposes a concrete measurement method. The measuring system is configured with a laser light source, a differential interferometer, a photo detector, computer system and a multilayer sample. The phase changes are measured against the following parameters of the atmosphere: air pressure, temperature, humidity and CO_2 concentration. These parameters are the important factors determining the refraction index of air. From the measurement results, the magnitude of the phase changes due to the influence of the atmospheric parameters are estimated. The results of the computer simulation of the thickness errors of the multilayer sample also show the relationship between the thickness error and the magnitude of the optical change.

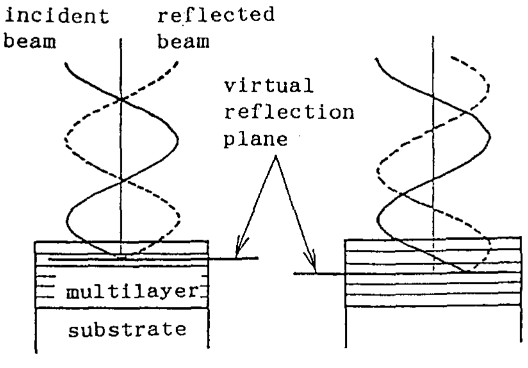
Optical Phase Change

The magnitude of the phase changes is determined by the optical characteristics of the multilayer thin film. Fig.1 shows the phase changes between the incident and reflected beams. In the multilayer, the phase of the reflected beam is referenced to the synthesis of multiple reflections at the boundaries of the each layer. It seems that there is a virtual reflection plane inside the multilayer, not on the surface. This virtual reflection plane moves with respect to the optical characteristics of the multilayer and the atmospheric conditions which surround the mirror. The movement of the virtual reflection plane is also shown in Fig.1 (from (a) to(b)). This movement can be observed as a change in the interference pattern. This pattern is formed by the signal beam and a reference beam. One beam is reflected from the measuring multilayer, and the other beam is reflected from a fixed reference mirror.

The measurement system is shown in Fig. 2. This system is configured with a He-Ne laser light source, a differential interferometer, a photo detector and a sample which has two reflecting mirrors. One mirror is the basic mirror for the signal beam and the other mirror is a reference mirror for the reference beam. The measuring dielectric multilayer is the signal mirror and it is coated at the front of the substrate. The Al thin film is used as a reference mirror and it is coated on the rear of the substrate to isolate it from the influences of the varying atmospheric conditions. In the differential interferometer, the beam from the light source is split into two beams, one a signal beam and the other a reference beam, which are reflected from the measuring multilayer and the reference Al film, respectively. The two reflected beams overlap in the interferometer to form an interference pattern. This pattern, which is the output of the interferometer, is converted to an electric signal at the photo detector. By varying the atmosphere conditions, the optical path length between the multilayer and the Al thin film changes. Equation (1) shows the optical phase change in the differential interferometer system. In this equation, the change in the optical path length of the substrate is also taken into consideration.,

$$\Delta\theta = 4\cdot(\Delta n_t \cdot t - \delta)/\lambda \qquad (1)$$

where, $\Delta\theta$ is the optical phase change, Δn_t is the change in the refractive index of the substrate, and t is the thickness of the substrate. δ is the displacement of the virtual reflection plane and λ is the wavelength of the incident light. From equation (1), it can be seen that the displacement of the virtual reflection plane is found from the optical phase change $\Delta\theta$.



(a) (b)

Fig. 1 Optical Phase Change

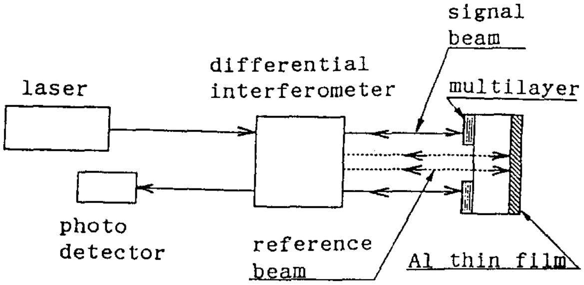


Fig. 2 Optics Arrangement

Sample Multilayer Thin Films

The measuring sample is a dielectric multilayer. It is designed to have a reflection coefficient not less than 97% for an incident beam of 633[nm] wavelength. It is made up of 24 layers by depositing the TiO_2, SiO_2, CeO_2 and MgF_2 alternately, where the thickness of every individual layer is a quarter of a wavelength. Here, an Au thin film is also prepared as another measuring sample for comparison with the optical phase change of the multilayer, because it has a higher packing density than dielectric thin films. This means that the influence of atmosphere conditions can be considered less for the Au thin film than for a dielectric thin film.

The optical phase changes of the two

samples are measured for the atmospheric conditions, including air pressure, humidity, CO_2 concentration and temperature. The following two types of reference mirrors were prepared to match the measuring atmosphere conditions and prevent the other atmospheric parameters from effecting the reference mirror.

- Air Pressure, Humidity and CO_2:

Fig. 3 shows the sample for measuring the influence of air pressure, humidity, and CO_2 concentration. A dielectric multilayer coating is deposited on the front of the substrate and an Al thin film on the back. The coated side of the substrate is used as the reference mirror. SiO_2 is used as substrate material because of its lower coefficient of thermal expansion and light absorption ratio compared to other classes of material.

- Temperature:

The sample shown in Fig.4 is used to measure the effects of temperature variations. Here, the surface of the substrate is used as the reference mirror to eliminate errors due to the thermal expansions of the reference mirror and substrate. TiO_2 was chosen as the substrate material, because of its high reflection coefficient. The other side of the substrate is frosted to eliminate interference from beams reflected from on the sides.

- Stability of Measuring System:

The stability of the measuring system is also checked. This can be measured by using a flat mirror, because the reference and the signal beams are reflected from the same plane. The Au thin film is used as the flat mirror to gain high reflection coefficient. The mirror is installed in a vacuum chamber. Stability is measured for temperature in a vacuum. The measured value is compensated for all measured values of optical phase changes.

Measurement System

The schematic diagram of the measuring system is shown in Fig. 5. It is configured with a two-wavelength laser light source, a photo detector, differential interferometer, measuring multilayer sample, vacuum chamber, computer system, vacuum pump, and humidity generator.

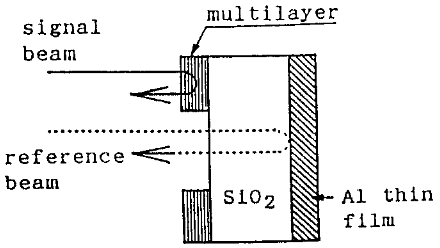


Fig. 3 Multilayer for Air Pressure, Humidity and CO_2 Concentration Influence Isolation

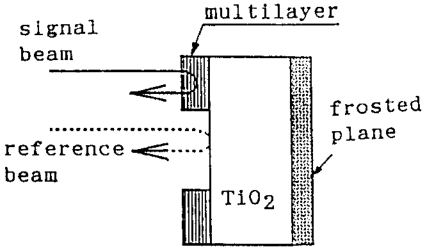


Fig. 4 Multilayer for Temperature Influence Isolation

The sample multilayer is installed in the vacuum chamber. The chamber is prepared to prevent disturbances from the other atmospheric conditions.

The air pressure is changed from $2x10^{-3}$[mmHg] to 800 [mmHg] with dry air. Humidity changes are realized by adopting a bubble type humidity generator. The structure of the humidity generator is shown in Fig.6. Variations in temperature are measured with the thermal sensor to an accuracy of $\pm 0.05^{\circ}C$. The measured temperature was near room temperature and different CO_2 concentrations in the chamber are realized using 4 types of standard air whose CO_2 concentrations are 0, 300, 1000, 1500ppm.

Simulation

Optical phase changes are also simulated for thickness errors of the multi-

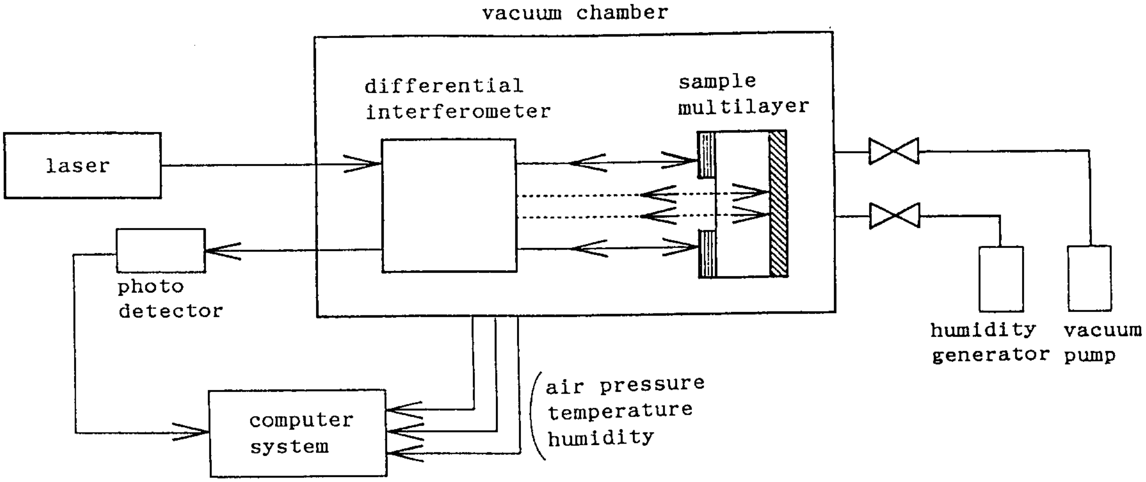


Fig. 5 Schematic Diagram of Measurement System

layer. Usually the optical multilayer consists of deposited dielectrics of quarter wavelength thickness. However, when a multilayer is configured, it is difficult to correctly control the thickness of each layer. It is also difficult to measure the thickness of the finished product. Conventionally, a layer was measured by comparing the optical characteristics with a previous standard. Therefore, it is necessary to determine the magnitude of the phase change produced by a thickness error. A numerical model of the sample multilayer was constructed for this purpose.

- Characteristic Matrix of Multilayer:

The multilayer is expressed in terms of characteristic matrices. If the tangential component of the electric and magnetic vectors of the incident beam are continuous on the boundaries of the layers, the electromagnetic field equation at both ends of the multilayer can be expressed as below.

$$\begin{vmatrix} E_0 \\ H_0 \end{vmatrix} = M \cdot \begin{vmatrix} E_{l+1} \\ H_{l+1} \end{vmatrix} \qquad (2)$$

where, E_0 is the magnitude of the electric field of the incident beam before it passes through the multilayer and E_{l+1} is the value after it passes through the multilayer. H_0 and H_{l+1} are the magnitudes of the magnetic field of the incident beam before and after of the multilayer, respectively. M is the characteristic matrix of the multilayer. It is also the product of the matrices of each layer.

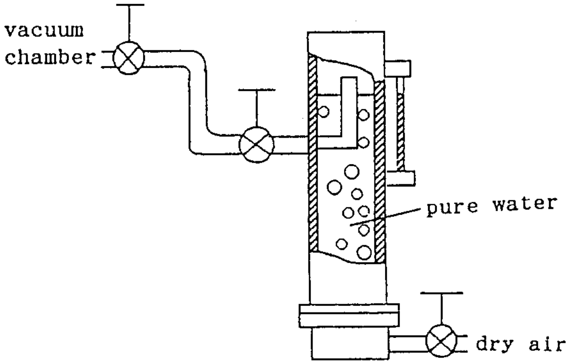


Fig. 6 Humidity Generator

$$M = \prod_{j=1}^{l} M_j = \begin{vmatrix} \cos\delta_j & i\eta_j^{-1}\sin\delta_j \\ i\eta_j\sin\delta_j & \cos\delta_j \end{vmatrix}$$

$$= \begin{vmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{vmatrix} \qquad (3)$$

where, M_j is the characteristic matrix of the j layer. η_j has components $-n_j\cos\phi_j$ (perpendicular to the incident plane) and

$n_j/\cos\phi_j$ (parallel to the incident plane). δ_j is $2\pi/(n_j d_j \cos\phi_j)$. n_j is the refractive index and d_j is the thickness of the j layer. ϕ is the incident angle of the beam. The law of refraction between the both ends of the multilayer is

$$n_0 \sin\phi_0 = n_j \sin\phi_j \qquad (4)$$

By substituting the optical constants of the layers in equations (2)~(4), the optical phase change with the thickness error is obtained.

Results

The measured optical phase changes are referred to below as the distance the virtual reflection plane moves.

Fig.7 shows the stability of the system. It is measured in a vacuum 2×10^{-3} [mmHg]. The periodic vibrations in the figure are the coherent noise error of the differential interferometer and they have a magnitude of about ± 5[nm]. The average value of the slope is -0.2[nm/°C].

Fig. 8, 9 and 10 show the measured results for the variations of air pressure, temperature, CO_2 concentration, respectively. The displacements of the virtual reflection plane are small enough to be ignored in relation to the coherent noise error.

Fig. 11 shows the measured result for humidity variation. The humidity changes from 0%RH to 50%RH. The maximum, 50%RH, was chosen to avoid condensation with changes in temperature. The displacement of the virtual reflection plane with humidity is -0.45[nm/%RH].

The simulation result for the thickness error of the layers is shown in Fig.12. It was simulated from 120% to 80% against the design thickness. It is shown that the thickness error of the layers is also an important factor in determining the optical path change. In Fig. 12, the thickness error refers to the error in the total optical path length of each layer. This total optical path length is determined by the packing density of the multilayers and the atmospheric conditions. This means that, in the future, it will be necessary to investigate the relation between the optical path length and the packing density of the multilayer.

Table 1 shows the measured values of the two samples, the dielectric multilayer

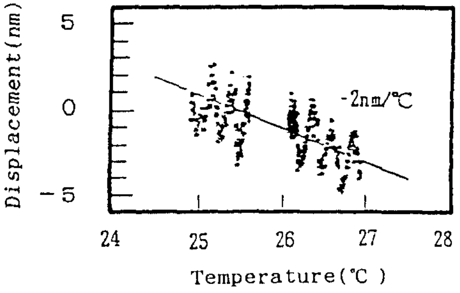


Fig. 7 Stability of system

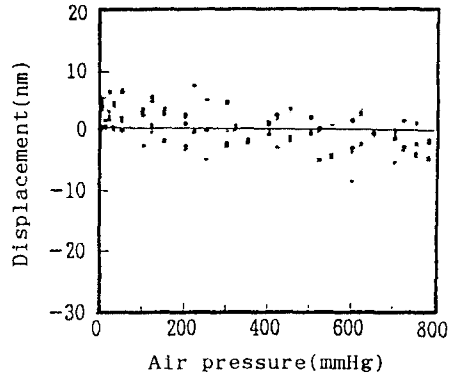


Fig. 8 Measurement of Influence of Air Pressure

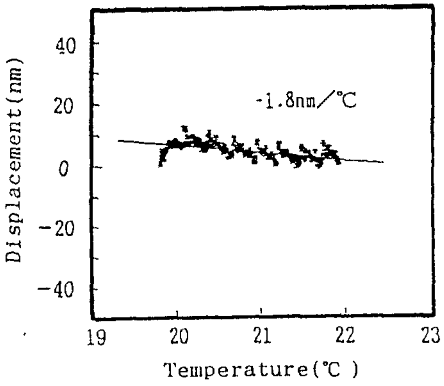


Fig. 9 Measurement of Influence of Temperature

and the Au thin film, for atmospheric conditions. The measured values for the Au thin film show that the Au thin film can be used as a reference for comparison with the dielectric thin films. Especially, the Au thin film is valid for testing for the influence of humidity.

Conclusion

The optical phase changes in the optical multilayer thin films are measured for the atmospheric conditions. The ability to change the 4 parameters which are the important factors for estimating the refractive index of the air was realized in the vacuum chamber.

From the measured results, it is seen that the humidity change has the most effect on the optical phase change. By comparing the results of the reference Au thin film, it can be theorized that the influence of humidity is related to the packing density of the dielectric thin films.

Acknowledgments

This work was performed under the Research and Development Program on "Advanced Material Processing and Machining System", conducted under a program set by New Energy and Industrial Technology Development Organization.

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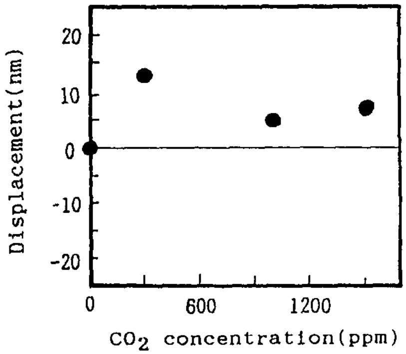

Fig. 10 Measurement of Influence of CO_2 Concentration

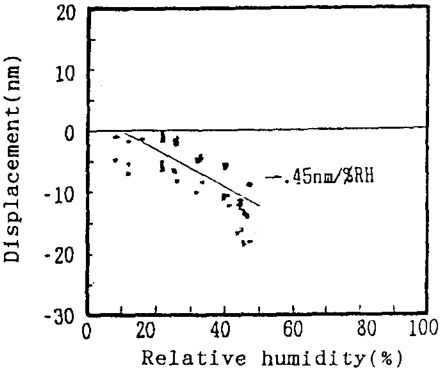

Fig. 11 Measurement of Influence of Humidity

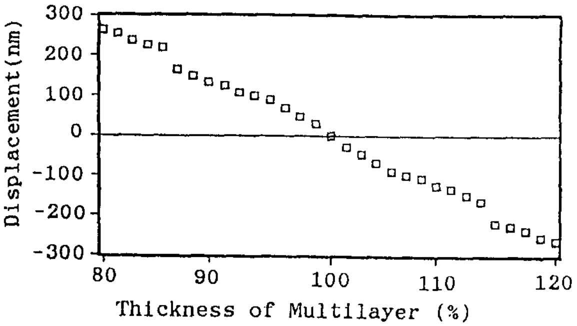

Fig. 12 Displacement of Virtual Reflection Plane for Thickness Error

Table 1. Displacement of Virtual Reflection Plane for Atmosphere Conditions

	Dielectric Multilayer	Au Thin Film
Temperature	-1.8nm/℃	0.9nm/℃
Air Pressure	-1.1nm/760mmHg	——
Humidity	-45nm/100%RH	0.7nm/100%RH
CO2 Concentration	0.2nm/300ppm	——