An Improved Illumination System for Spatial Coherence Control

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Abstract

A longitude coherence control system needs a source that is temporally coherent and yet spatially incoherent. For this reason, a zone plate-like pattern is imaged onto a rotating ground glass. Generally the ground glass exhibits a strong directivity. It is far from an ideal uniform diffuser that is implicitly assumed in the theory. To solve this problem, we propose a new illumination system. In our system, the beam illuminating the zone plate-like pattern is focused on the test surface. We measured the longitudinal coherence functions in our optical system. The result shows that the longitude coherent function is better controlled in our interferometer.

1. Introduction

A light source with high temporal coherence is commonly used in a conventional interferometer to improve the contrast of the interferogram. However, the high temporal coherence of the source also gives rise to noisy spurious fringes in the interferogram. An ideal light source for interferometry would be the one that has good temporal coherence for the light used for testing and low coherence for the unwanted light.

Low coherence interferometry and optical coherence tomography have been studied extensively[1, 2]. These techniques use a broadband source to reduce the contrast of unwanted fringes while maintaining the contrast of the desired signal fringes at the location of an object to be detected. However, the broadband light has an indeterminate wavelength to be used as the accurate scale of the length. Moreover, the system suffers from dispersion problem.

Interferometry XII: Techniques and Analysis, edited by Katherine Creath, Joanna Schmit,
Proceedings of SPIE Vol. 5531 (SPIE, Bellingham, WA, 2004)
0277-786X/04/$15 · doi: 10.1117/12.560350

Rosen and Takeda[3] proposed a technique to control spatial coherence by using an extended spatially coherent quasi-monochromatic source. Then, Wang et al.[4] gave a new interpretation to the principle and verified it by experiment. Duan et al.[5] and Gokhler et al.[6] further developed this method and applied to profilometry.

The extended light source used in Rosen and Takeda's technique has the characteristic that it is temporally coherent and yet spatially incoherent. To realize this special characteristic a rotating diffuser is used together with a spatial light modulator (SLM) on which a Fresnel-zone-plate-like pattern is displayed. A parallel beam is used to illuminate the SLM, and the zone-plate-like pattern displayed on the SLM is imaged onto the rotated ground glass. In their theory, the ground glass is implicitly assumed to have an ideal Lambertian characteristic to diffuse the light uniformly in all directions. However, a real ground glass exhibits a strong directivity of scattering in the direction of the incidence beam. For this reason, the coherence function cannot be controlled exactly as expected from the theory.

In this paper, we propose a new illumination system to remove the influence of the directivity of the ground glass. By using this illumination system, the coherence function can be controlled according to the theory even if the ground glass has strong directivity. First, we explain the principle of our illumination system, and then show some experimental results to demonstrate the advantage of our illumination system.

2. Principle

Figure1 shows an interferometer used for coherence control. In Fig.1, S is a point on the rotating ground glass on which a zone-plate-like source pattern displayed on SLM is imaged. Light from this point source S is collimated by a lens L3 of focal length *f*. The collimated light illuminates the test and the reference mirrors (M1 and M2), and the beams reflected from these mirrors interfere on CCD. A lens (L4) is used to image the test surface onto CCD.

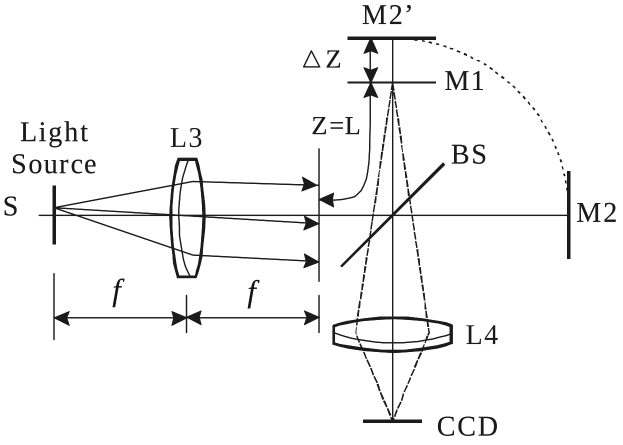

Figure1 Interferometer for coherence control.

Generally, the intensity of light scattered by the ground glass is not uniform, and the light is directed more in the direction of the illuminating beam. Figure2 shows a typical example of the scattering characteristic of a ground glass, where the lengths of the arrows represent the brightness of scattered light, and θ is the angle between the incident ray and the scattered ray. If we take into account the scatter directivity function $P(\theta)$, the filed distribution on mirror M1 can be written as:

$$\begin{aligned} u(x,y,z) &= \frac{u_s(x_s,y_s)}{j\lambda f}P(\theta) \\ &\times \exp\left[j\frac{2\pi(z+2f)}{\lambda} - j\frac{2\pi}{\lambda f}(x_s x + y_s y) - j\frac{2\pi z}{\lambda f^2}\left(x_s^2+y_s^2\right)\right] , \qquad (1) \end{aligned}$$

where, λ is the wavelength, $j=\sqrt{-1}$, (x,y,z) the coordinates of the observation point with their origin at the rear focus of L3, and $u(x_s,y_s)$ is the complex amplitude of the scattered light at a point (x_s,y_s) on the ground glass.

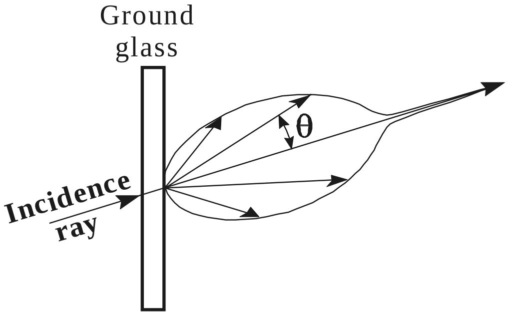

Figure2: Typical scattering characteristic of a ground glass.

The scattering directivity function $P(\theta)$ in Eq.(1) can be rewritten by the geometrical parameters of the illuminating system defined in Fig.3. In Fig.3, f is the focus length of

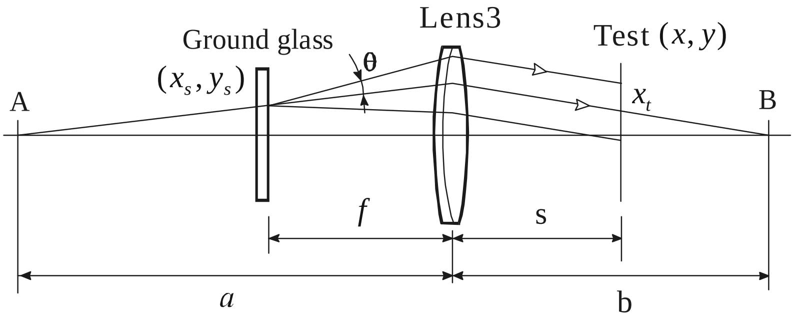

Figure3 Illumination system.

collimator lens L3, s is the distance between lens L3 and the test surface. The ground glass is illuminated by a point source at A, located at a distance a from the collimator lens L3. The ray passing through the ground glass without being scattered forms the image of the point source A at another point B on the optical axis through lens L3; b is the distance from lens L3 to point B.

Let us note one ray in the illumination beam that reaches the ground glass at x_s. The ray passes through the ground glass directly (without being scattered), and is bended by lens L3 to meet the test surface at x_t and to cross with the optical axis at point B. Therefore, we have

$$x_t = x_s \frac{-a}{f-a} \frac{b-s}{b} \quad . \tag{2}$$

Since the ground glass is placed at the front focal plane of lens L3, the light scatted at (x_s, y_s) is collimated by lens L3. Therefore, θ can be written as

$$\theta = \frac{x - x_t}{f} \quad , \tag{3}$$

where x is the height of the ray scattered at angle θ. Because θ is related to (x_s, y_s) through Eq.(2) and Eq.(3), the intensity distribution of the fringes cannot be calculated directly from the formula given by Wang et al. [4]. In order to make the actual system to meet the theory, we propose an additional condition for the illumination system.

We form the image of the point source A on the test surface such that

$$b = s \quad , \tag{4}$$

which makes x_t =0. Then, because of the axial symmetry of the optical system, Eq.(3) becomes

$$\theta = \frac{r}{f} = \sqrt{\frac{x^2 + y^2}{f}} \quad . \tag{5}$$

The field distribution described by equation (1) becomes

$$u(x, y, z) = \frac{u_s(x_s, y_s)}{j\lambda f} p\left(\frac{\sqrt{x^2 + y^2}}{f}\right) \times \exp\left[j\frac{2\pi(z + 2f)}{\lambda} - j\frac{2\pi}{\lambda f}(x_s x + y_s y) - j\frac{\pi z}{\lambda f^2}\left(x_s^2 + y_s^2\right) \right] \quad . \tag{6}$$

In this field distribution, scattering directivity function $P(\theta)$ has now become independent from the coordinates (x_s, y_s). Because the light source is spatially incoherent, the intensity of interferogram on CCD is given by the superposition of the fringe intensity created by the individual point sources.

$$
\begin{aligned}
I(x,y,L) = \left[p\left(\sqrt{\frac{x^2+y^2}{f}} \right) \right]^2 \iint \Bigg| & \frac{u_s(x_s,y_s)}{j\lambda f} \\
& \times \exp\left[j\frac{2\pi(L+2f)}{\lambda} - j\frac{2\pi}{\lambda f}(x_s x + y_s y) - j\frac{\pi L}{\lambda f^2}\left(x_s^2+y_s^2\right) \right] \\
& + \frac{u_s\left(x_s,y_s\right)}{j\lambda f} \times \exp j\left[\frac{2\pi(L+2\Delta z+2f)}{\lambda} - j\frac{2\pi}{\lambda f}(x_s x + y_s y) \right. \\
& \left. - j\frac{\pi(L+2\Delta z)}{\lambda f^2}\left(x_s^2+y_s^2\right) \right] \Bigg|^2 dx_s dy_s \qquad (7)
\end{aligned}
$$

Now the directivity of the ground glass appears only as a non-uniform intensity distribution observed on the measured object surface. Accordingly, the validity of the coherence controlling theory can be maintained even when the ground glass has a scattering function with a strong directivity.

As a specific example, let us consider a special case in which the ground glass is illuminated with a collimated beam from a point source A located at infinity. Rays passed by the ground glass without being scattered are focused on the rear focus of the collimation lens L3. According the proposed illumination condition, the object surface should be placed in the rear focal plane of lens L3 to satisfy the requirement $b = f$. Under this condition, one can use Eq. (7) for the field distribution on the test surface.

3. Experiment

We conducted an experiment to demonstrate the improved performance of the proposed illumination system. A schematic illustration of the interferometer is shown in Fig.4. A laser beam is expanded to illuminate SLM and is focused at point A by relay lenses L1 and L2 to form a secondary point source. This beam is modulated to have the zone plate-like intensity distribution displayed on SLM. The zone plate-like pattern displayed on SLM is imaged onto a rotation ground glass by lens L1 and L2. The lenses L1 and L2 have the same focal length ~81mm. Distance between the two lenses is ~162mm. A rotating ground glass is placed in the front focal plane of lens L3. Accordingly, light scattered from a point on the ground glass is collimated by lens L3. A beam splitter BS separates the light into two beams of which one is directed to test mirror M1 and the other to reference mirror M2. The test and reference beams are reflected by mirrors M1 and M2, respectively, and interfere on CCD. Lens L4 images mirror surface M1 on CCD.

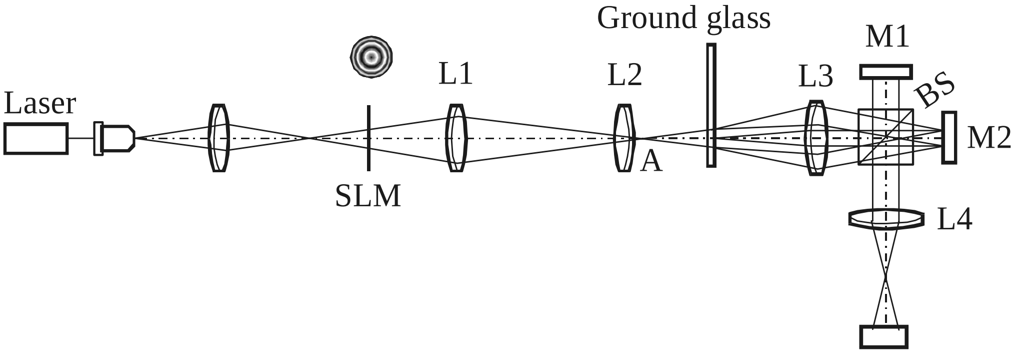

Figure4 Coherence controlled interferometer

In this experiment, the zone-plate-like source shape displayed on SLM was adjusted such that the longitudinal coherence function has a high peak when the axial distance between mirror M1 and mirror M2 is t~2.5mm. This was done by setting the number of zone-plate rings *N*=20. In this particular condition, light from an arbitrary point in the bright zone rings generates a fringe pattern with the same phase when mirror M1 and M2 is separated by 2.5mm. Consequently, the size of the zone-plate-like pattern on the rotating ground glass should be

$$Size_{ZP} = 2f\,\tan\left[\arccos\left(1-\frac{N\lambda}{2t}\right)\right] = 11.54mm\,. \qquad (8)$$

In our system, the diameter of lens L3 is $Aper = 48mm$, and the distance from the point A to SLM is $Dis_{A-S} = 111.2mm$. Therefore, the measurement area of the test surface is limited to

$$d = 2\left(\frac{Aper}{2} - \frac{Dis_{A-S}+f}{Dis_{A-S}}\frac{Size_{ZP}}{2}\right) = 28.0mm \qquad (9)$$

We shifted mirror M2 in such a way that the axial distance between mirror M2 and the virtual image of mirror M1 varies from –4mm to 4mm. We measured the fringe contrast of the interferogram at each mirror position; the result is shown in Fig.5, together with the coherence function predicted by theory. For the comparison of performance, we shifted the location of the point source A so that the illumination system is made to deviate from the prescribed condition; this resulted in the shift of point B by 120mm from mirror M1. The coherence function in this case is also measured and shown in Fig. 5.

For the illumination system optimally designed according to our theory, the longitudinal coherence function has high peaks when the test and reference mirror is separated 2.5mm as shown by the triangles in Fig.5. The coherence peak height becomes lower when the point B is shifted from mirror M1, and the prescribed illumination condition is not satisfied. This result demonstrates the importance of our illumination condition.

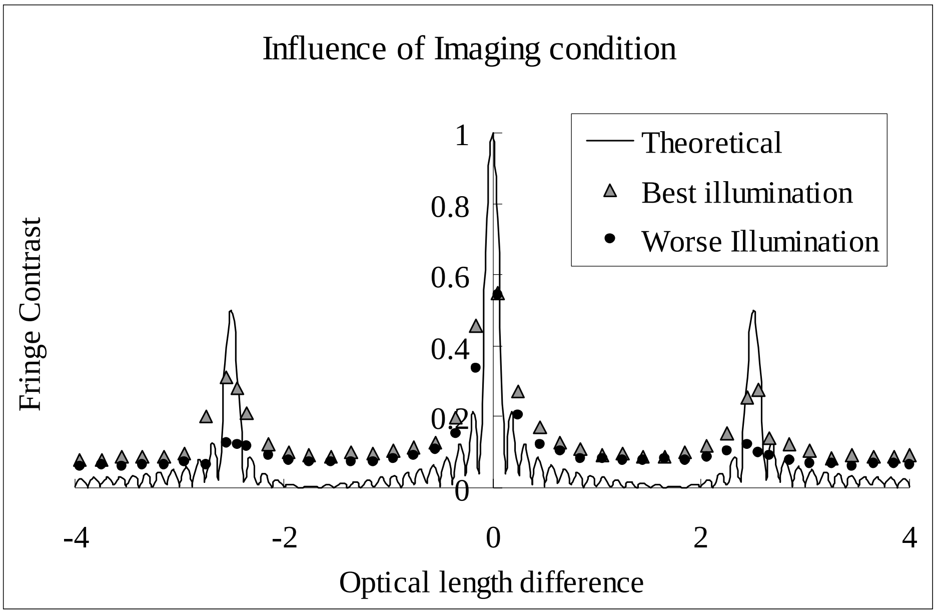

Figure5 Longitudinal spatial coherence function.

Even in the best illumination, the peak height of the coherence function is lower than that predicted by theory. This may be caused by the non-uniform illumination of the SLM and the aberrations of the illumination system.

4. Conclusions

To improve the performance of the coherence control technique, we proposed a new design principle for the illumination system. The new design can reduce the influence of the scattering directivity of the ground glass. We carried out an experiment and demonstrated the advantage of our illumination system. For the better control of the coherence function, the aberration of the illumination system and the non-uniform illumination of SLM must be reduced.

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