Qualification of superpolished substrates for laser-gyro by surface integrated scatter measurement

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Received August 15, 2009

Integrated scatterometer for qualification of superpolished substrates for laser-gyro by surface scatter loss measurement is constructed. Different from the qualification of substrate by surface roughness, the scatterometer measures the forward surface scatter loss to check whether the mirror made of the substrate will be suitable for the required laser-gyro lock-in specification. The scatterometer utilizes convex lens instead of integrating sphere to collect scatter light. Special sample support and baffle are designed to block unwanted light. The result of stability test is given, which is about 0.4% over 10 h.

OCIS codes: 120.5820, 290.2558, 310.3840, 120.4640.

doi: 10.3788/COL20100802.0181.

Scatter light of coated mirrors has great influence on ring-laser-gyro (RLG) lock-in effect. The magnitude of random walk is proportional to mirror scatter loss[1], and weak scatter loss brings low-level lock-in. Scatter light in RLG comes from deposited coats and underlying superpolished substrate of coated mirrors. With the development of optical coating technique, scatter light added by coat is inconspicuous compared with that of substrate. Qualifying substrates to select those of less scatter loss for coating is important to RLG quality control.

Instruments and methods for qualification of superpolished substrates that have root mean square (RMS) roughness of about 0.1 nm can be sorted by whether they measure altitude distribution or scatter loss distribution of substrate surface. Among instruments measuring altitude distribution, no matter noncontact instruments like Nomarski microscope[2] and WYKO profiler, or contact instruments like atomic force microscope (AFM)[3], they all qualify substrate by surface RMS roughness. Although surface altitude distribution can be converted to scatter loss distribution according to surface scatter theory, each instrument has its own measurable spatial wavelength range, which corresponds to the angle range of surface scatter[4]. These instruments do not always reflect the scatter related to RLG lock-in.

Instruments which measure scatter loss can be sorted by whether they measure surface angle-resolved scattering (ARS) or total integrated scattering (TIS). ARS scatterometer measures the scatter light power at a series of angles over substrate surface, while TIS scatterometer use integrating sphere or Coblentz sphere[5] to integrate (or gather) a fraction of light scattered into the hemisphere in front of the substrate. Both scatterometers normalize scattered power by reflected specular power and the ratio is defined as bidirectional scatter distribution function (BSDF) and TIS, respectively. Scatterometer avoids conversion between altitude and scatter loss, so its result is correlated with RLG lock-in more directly.

Scatterometers, especially TIS, have been widely accepted as valuable tools for evaluating the opaque surface quality[6]. As for transparent surface such as uncoated substrate, it is trouble that the light such as rear surface scatter and volume scatter disturbs the qualification of forward surface, which should be eliminated[7]. Applying special designed structure and apparatuses, the integrated scatterometer described in this letter measures partial integrated scatter loss of transparent substrate surface to qualify whether it can be used to manufacture laser-gyro.

The principle of the integrated scatterometer developed in this letter is not complicated. A convex lens over the sample substrate surface focuses the scatter light onto a photo multiplier tube (PMT), and a photodiode measures the reflected specular light, as shown in Fig. 1.

ISL is defined as the ratio of integrated scatter power to reflected specular light, which is written as

$$\mathrm{ISL} = \frac{P_\mathrm{s}}{P_\mathrm{r}}, \tag{1}$$

where P_s is the integrated scatter power and P_r is the reflected specular power. While performing a measurement, the sample is scanned across its surface by a positioning system, thus yielding either one- or two-dimensional (2D) ISL diagrams. A substrate satisfying required laser-gyro lock-in specification is measured to define its ISL level as the qualification standard of the instrument.

Only scatter light in a cone is focused by convex lens. The half-angle of the cone is 23° in this instrument which

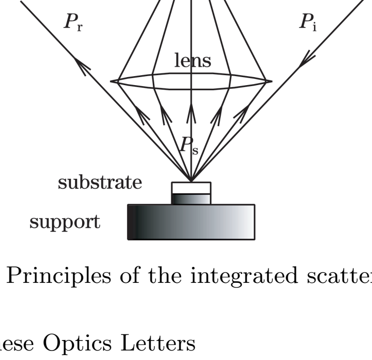

Fig. 1. Principles of the integrated scatterometer.

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employs a 50.8-mm diameter lens at a distance of 60 mm from the substrate forward surface. It can be seen that substrate surface light spot is imaged on the photosurface of PMT. The focal length of the lens is 38.1 mm, so the distance of PMT photosurface to lens is about 104 mm according to Gaussian imaging formula. While assembling the instrument, PMT is adjusted before fixed to yield the maximum output to ensure its photosurface is on the image plane.

Optical noise is of great concern when measuring small optical signals. One method to discriminate small signals from noise is to modulate the laser and use frequency-selective electronics such as lock-in amplifier.

Figure 2(a) shows the schematic of the integrated scatterometer. The beam preparation system and all detectors are fixed along an optical rail that is suspended to a cantilever. After optically cemented with support, the substrate is fixed on motorized assembly stages, which is mounted over the optical flat. These two independent parts can be aligned through motorized vertical translation stage and manual translation stages.

Light source is a stabilized He-Ne laser made of a rectangular ZERODUR$^{\text{TM}}$ glass tube with the power monitor and the frequency controller, which make the laser work at 633 nm and 1.26 mW stably, and the laser is p-polarized. After choppered, spatial filtered, and deflected, the incident light hits the sample surface at 45°. The scatter power is measured by PMT. The reflected specular light hits the photodiode, which records the specular power and reflects light to a 2D position sensitive detector (PSD). Then the residual stray light enters into a light trap.

Spatial filter is a microscope objective with a pinhole, and is arranged that it can be moved parallel to the beam to focus the spot on the sample surface to about 0.3-mm diameter. When chopper blade passes laser beam edge, straight edge diffraction makes the light spot lengthened and the baffle illuminated, yielding stronger scatter light than sample surface. The spatial filter and aperture stop should be adjusted to eliminate the straight edge diffraction of chopper.

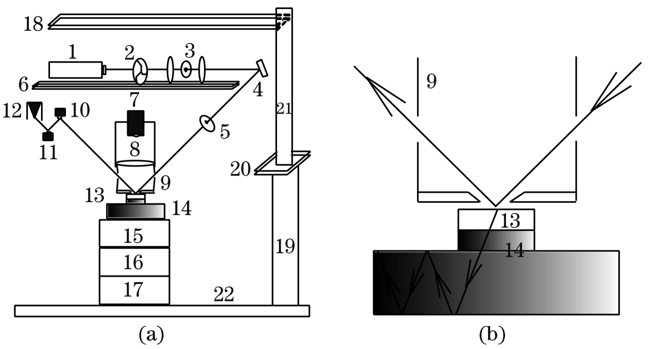

Fig. 2. (a) Schematic diagram of the integrated scatterometer; (b) beam path at the sample support. 1: laser, 2: chopper, 3: spatial filter, 4: deflection mirror, 5: aperture stop, 6: optical rail, 7: PMT, 8: convex lens, 9: baffle, 10: photodiode, 11: PSD, 12: light trap, 13: substrate sample, 14: sample support, 15: 2D motorized goniometers, 16: 2D motorized translation stages, 17: motorized rotation stage, 18: cantilever, 19: upright stanchion, 20: 2D manual translation stages, 21: motorized vertical translation stage, 22: optical flat.

The substrate is not opaque, thus most (about 99% for fused silica substrate) incident beam enters its inside, then reflects and scatters on its rear surface, making noise light much more than the signal light. Sample support shown in Fig. 2(b) is made of the same material as the substrate. All surfaces of support are polished, and then blackened with absorbing material except forward surface. When the substrate is to be measured, its rear surface is optically cemented with the forward surface of the support, so that the inside light reflects and scatters on support rear surface rather than substrate rear surface. Selecting suitable diameter and thickness for support can make the inside light reflected several (3–5) times by the upper, lower, and lateral surfaces of the support as the ray trace shown in Fig. 2(b), and absorbed by the black materials every time. So the reflected and scattered light of the rear surface is almost eliminated. Actually, from the direction of the detector we cannot see light spot on the rear surface in the experiment.

For superpolished surface scatter measurement, another noise light source is volume scatter light from the substrate inside, which is produced by the substrate material heterogeneity. The volume scatter light radiates in all directions, and a baffle with wedge aperture of 3-mm diameter shown in Fig. 2(b) can block part of it from entering the detector. The volume scatter light is weakened so that we can see the light trace inside the substrate is dim compared with scatter spot on substrate forward surface in our experiment.

2D PSD is used to supply position reference for adjusting sample height and attitude so that all sample substrates are located at the same distance from the convex lens when measured. This ensures the same integrating angles for all sample substrates. Positioning system contains 2D motorized goniometers to level sample substrate, 2D motorized translation stages to make orthogonal coordinate scan test, motorized rotation stage to make polar coordinate scan test, motorized vertical translation stage to adjust sample substrate height, and 2D manual translation stages for initial alignment of instrument. All motorized stages are equipped with stepper motors and drivers.

All detector signals are acquired by a multifunctional data acquisition (DAQ) card, which also controls all stepper motors. In other words, the DAQ card is the system bus between computer and hardware. A software lock-in amplifier system processes all detectors signals, which is to differentiate the small photoelectric signals from noise in the detectors, especially for scatter light.

Most parts of the measurement process are under software control and require little operator action. A typical measurement session would process as follows. Firstly, the sample substrate is optically cemented with support. Secondly, software coarse adjustment menu is selected to drive the motorized vertical translation stage to raise sample substrate to a height, so that light beam can hit the PSD. Thirdly, software fine adjustment menu is selected to drive the motorized goniometers to level sample substrate according to the output of PSD, and drive motorized vertical translation stage to raise sample substrate to the fixed height. Finally, software mesurement menu is selected to scan substrate surface and measure ISL, yielding a diagram and qualification of the

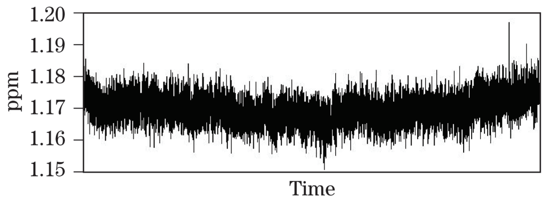

Fig. 3. Stability test of fixed point ISL.

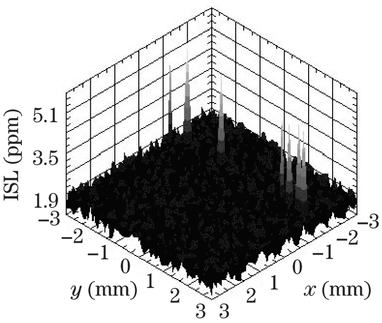

Fig. 4. 2D-ISL diagram.

substrate.

To make sure succeeding measurement credible, when the instrument is constructed, its stability of measuring substrate surface fixed point ISL is tested firstly. A fused silica substrate with forward surface of about 0.1-nm RMS (measured by AFM) roughness is optically cemented with the support and adjusted to measurement preparation position. Then, the instrument measured ISL of the fixed point for a period. Figure 3 shows the result, and the fluctuation of the instrument is 0.4% over 10 h.

The result of 2D-ISL measurement is shown in Fig. 4. Most of the surface has low-level scatter loss of about 2 ppm, except that several tiny zones have scatter loss about three times more than that of other area, which may be caused by the residual marks of chemical cleaning or defects.

In conclusion, the integrated scatterometer that is used to qualify the superpolished substrate by measuring surface integrated scatter loss is reviewed in detail. Each element comprising the instrument is described, as well as its operation. The measurement process is described to show the convenience of operation. The stability test result shows the instrument is reliable.

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