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Fiber profilometer for measurement of hard-to-access areas

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ABSTRACT

A fiber profilometer is developed to measure hard-to-access areas. This system utilizes low coherence light interferometry technique to detect profiles of internal surfaces of samples. A differentiation method is employed to enhance vertical resolutions of imaging results. An auto-focusing scheme is proposed to obtain an optimized lateral resolution. The performance of the profilometer system is demonstrated by experimental studies.

Keywords: hard-to-access area measurement, profilometer

1. INTRODUCTION

In many laser processing and cleaning applications, it is required to measure profiles of internal surfaces of work pieces or components, such as diesel injectors, gear boxes and bladed disks. These structures have small opening holes, inner cavities or high-aspect ratio channels. Thermal and mechanical stretching and chemical corrosion may create micro-crackers on internal surfaces. The micro-crackers do cause failures to the components. Quantitative roughness measurement is critical for evaluation of machining quality for the components. Traditionally, people utilize replication method to duplicate features of internal surfaces.¹ The replication is an indirect way for measurement, and it could be destructive to samples. Optical probe-based methods are invented as alternative solutions for measurements of hard-to-access areas due to its nature of direct measurement and nondestructiveness.²⁻⁸ In 1987, Gilbert *et al* first invented a radial profilometer using a panoramic doughnut lens-based probe, which was able to perform wide-view measurement.^{2,3} In 1998, Alayli *et al* proposed a fiber profilometer for high accuracy profiling.⁴ This method makes use of a calibrated relationship between the amounts of reflected light and sample-probe distance to identify the surface displacement values. Sub- μm accuracy is achieved. Later, in a commercial product of STIL company, chromatic confocal technique is applied to build up a portable profilometer.⁵ A vertical resolution of 20 nm can be obtained. In addition, time-domain and spectrum-domain low-coherence light interferometries (LCI) are adopted on fiber probe profilometers respectively, and broad industrial and research applications are demonstrated.^{6,7} Recently, Necsoiu *et al* obtained a patent that measures the complex surfaces by using white light fringe interferometry with a specially designed measuring head containing a Michelson objective and a fiber optic bundle.⁸ The above methods operate based on different principles, but common performance parameters are concerned, including achievable lateral and vertical resolutions, sensitivity, speed and cost. Usually, compromises have to be done between different parameters. Amongst these methods, the time-domain LCI technique is superior due to its high vertical and lateral resolutions, shot-noise limited detection sensitivity, and kHz data acquisition speed, low cost, and broad applicable materials. Thus, the time-domain LCI technique is a promising solution for profile measurement of hard-to-reach areas.

However, there are some limitations on the performance of state-of-the-art LCI fiber profilometer. First of all, the fiber configuration is vulnerable to mechanical vibrations and thermal variations, which introduce instability to signals. Common-path interferometry method is employed in the profilometer systems to compensate the disturbances on the fiber. Compared to normal interferometer, an additional analyzing interferometer is incorporated to obtain the interference signal patterns in the common-path interferometer setup. The inclusion of extra fiber components inevitably introduce more disturbances. As a result, vertical resolution of current fiber LCI profilometer is restricted to 1 μm , which is much worse than the theoretical value. Further, the best

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achievable lateral resolution of the system is determined by the focal beam size of the probe, when the sample is placed on focus of the probe. In practice, the initial working distance is manually set before sample scanning. It is likely that the sample surface is not properly placed on focal position because of imprecise visualization. Even if the sample is placed on correct position, it can also go out of focus during the scanning. Such mismatches degrade lateral resolution in the results. Thus, an improved interferometric scheme with auto-focusing function is needed to yield desired high vertical and lateral resolutions.

In this paper, we built up a high resolution fiber profilometer for the hard-to-access area measurements. An interferometric differentiation method is presented to enhance measurement stability. The fiber profilometer uses time-domain LCI technique. Two interference correlograms are recorded by modulating the length of reference arm. One is interference between beam reflected from sample surface and reference beam. The other corresponds to interference between internally reflected beam at the probe end surface and reference beam. The positions of sample and probe surfaces could be reconstructed from the correlograms, respectively. The absolute distance between sample and probe end surfaces is then calculated from difference between the two positions. Disturbances on fibers could be significantly suppressed through signal differentiation. The system setup is simpler compared to the common-path interferometry, and more robust to disturbances. Further, automatic adjustment of focus could be achieved by setting the distance between the sample and probe surfaces at focal length of the probe to achieve an optimized lateral resolution. Experiments are performed on calibrated samples and industrial work piece to verify the performance of the proposed fiber-based profilometer. A vertical resolution beyond 200 nm and a lateral resolution of 12 μm are demonstrated in experiments.

Figure 1. Schematic of interferometer configuration. Inset: interference correlograms.

2. INTERFEROMETER DESIGN AND PRINCIPLE

The system is established on the configuration of a Mach-Zehnder interferometer. The setup schematic is shown in Fig. 1. The output beam from a broadband light source is coupled into port P_1 of the coupler. The light power is equally split into ports P_3 and P_4 on the other side of the coupler. Light in P_3 is shined on, and reflected by a mirror as the reference beam (E_R). Light in P_4 is directed into a fiber probe. One portion of light in the probe is focused on sample surface, reflected by the surface, and collected by the probe as the signal beam (E_{S1}). Another portion of light is internally reflected by the end surface of probe (E_{S2}), due to Fresnel reflection at glass-air interface. The two portions of light interfere with reference beam, respectively. The resulting interference light is measured by a photo-detector at port P_2 . Through modulation of the length of reference arm, we can record

the interference correlograms. Area measurement of the sample is accomplished by raster scanning the probe over sample surface.

The optical signal at the photo-detector is super-position of E_{S1} , E_{S2} , and E_R , which is expressed as:

$$\mathbf{E}_{Det} = \frac{1}{2}[\mathbf{E}_{S1}(z_0) + \mathbf{E}_{S2}(z_0 + z_S) + \mathbf{E}_R(z)], \quad (1)$$

where z_S is the optical path length (OPL) in the fiber probe, and z_0 is OPL between the probe end surface and the mirror surface, which is tunable by a motorized stage or a PZT fiber stretcher.

If we express the output electric current of the square-law photo-detector with respect to length of reference arm, the current signal can be written as:

$$\begin{aligned} \mathbf{I}(z) &\propto |\mathbf{E}_{Det}|^2 \\ &= \frac{1}{4} |\mathbf{E}_{S2}(z_0) + \mathbf{E}_{S1}(z_0 + z_S) + \mathbf{E}_R(z)|^2. \end{aligned} \quad (2)$$

If the absolute distance between the probe end surface and sample surface is larger than coherence length of light source, the AC component of the current is given by:

$$\mathbf{I}_{AC}(\tau) \propto \text{Re}\{\mathbf{E}_{S2}(z_0)\mathbf{E}_R^*(z) + \mathbf{E}_{S1}(z_0 + z_S)\mathbf{E}_R^*(z)\}. \quad (3)$$

The interference signal is shown in the inset plot of Fig. 1. When $z = z_0$, the OPL of reference beam $\mathbf{E}_R$ is equal to that of the probe reflection beam $\mathbf{E}_{S2}$, and it corresponds to peak of envelope of the first correlogram. While if $z = z_0 + z_S$, the envelope peak of the second correlogram is seen. From gap between the two peaks $(z_0 + z_S) - z_0 = z_S$, we can obtain the absolute distance between the probe end surface and the sample surface. In the presence of disturbance Δz on the fiber, differentiation operation $(z_0 + z_S + \Delta z) - (z_0 + \Delta z) = z_S$ can eliminate the effect of disturbance. Compared to the common-path interferometer configuration, this design incorporates only one time delay line mechanism (fiber stretcher) instead of an auto-correlator interferometer. There is no need to use a circulator.^{6,9} Thus, cost and possible error sources are reduced.

2.1 Probe design

Miniaturized fiber probes have been widely utilized in OCT and endoscope applications.^{10–13} We adopted a similar probe design. The probe involves a piece of single-mode fiber (SMF), and a small gradient-index (GRIN) lens. A mirror attached on the lens can provide right angle inspection capability. The fiber and optics are encapsulated in a metal or glass tube for protection. It is noticed that in the side-view configuration, the end surface of the probe is one cathetus of the prism. The working distance of a probe is defined by the difference between its focal length and the optical path that light travels within the prism. In our application, an intermediate focal length larger than 3 mm is desired, while the focal beam size is kept below 15 μm . Such parameters are attained through tuning the spacer length S and pitch number of the GRIN lens.

2.2 Auto-focusing scheme

In a probe-based profilometer, manual adjustment of the probe position is relatively imprecise. Deviation from focus results in a deteriorated lateral resolution. Auto-focusing techniques have been applied to white light interferometry and OCT imaging systems,^{13,14} which are similar to those employed in digital cameras. But these schemes are not suitable for the point-by-point probe scanning. Alternatively, we make use of the result of interferometric differentiation. In the measurement of fiber profilometer, z_S indicates the absolute distance between the sample surface and probe end surface. The strategy is to set this distance as focal length of the probe. The position of the probe is first manually adjusted above the sample surface such that the interference correlograms of the sample and probe reflected beams can both be detected. The distance between sample and probe surfaces are reconstructed from the two correlograms. If the measured distance z_S is not equal to the preset focal length z_f , we move the reference mirror to compensate the gap between z_S and z_f . The measurement and comparison processes are repeated until the gap goes to zero. Now the sample surface is considered located at the focus of the probe. The sample scanning can start. During the scanning process, the distance z_S keeps changing. The probe is possible to go out of depth of focus region. The solution is to regulate z_S at the preset z_f through a close-loop control. But it will reduce the scanning speed. Trade-off have to be made between the imaging resolution and the speed.

Figure 2. Schematic of (a) a semiconductor sample with square features, and (b) its AFM line-scan result. And (c) the line-scan results recorded by the fiber profilometer.

3. EXPERIMENTS

Experiments are carried out to demonstrate the performance of the developed fiber profilometer system. A superluminescence light-emitting diode (SLED) (DL-CS50778 from Denselight Semiconductor) at the wavelength of 1550 nm is used as light source. The photo-receiver is Model OE-200-IN2 from Femto with a variable gain from 10^3 to 10^{11} V/W, and its upper cut-off frequency is 500 kHz at 1550 nm. The scanning mechanism of probe is constructed on motorized translational stages (MAX604M from Thorlabs) for Cartesian coordinates, and a rotary motor stage (T-RS60C from Zebra) for cylindrical coordinate. A PZT fiber stretcher (FST-001-B from General Photonics) is employed to modulate the OPL of reference arm. The probe is integrated by mounting a standard GRIN lens and a SMF pigtailed ferrule in a ferrule sleeve. The air gap between the GRIN lens and pigtailed ferrule works as the spacer. The length of the spacer is tunable.

In order to examine the vertical resolution of the system, a semiconductor sample is scanned by using the fiber profilometer. Square features are deposited on wafer surface. The microscope image is shown in Fig. 2(a). The length of sides of squares is about 100 μm , and the gap between two squares is about 50 μm . We further characterize the sample with an atomic force microscope (AFM). The line-scan curve is shown in Fig. 2(b). It is observed that the average step height is 156 nm. We carried out a line-scan across the sample surface by using the fiber profilometer system. The calculated results are plotted in Fig. 2(c). It is seen that the measured average step height is 185 nm, which is quite closed to the AFM result. The precision of measurement is limited by signal sampling error, which is about 40 nm. The width of the feature is 112 μm . Thus, it is claimed that the fiber profilometer system can yield a vertical resolution of beyond 200 nm.

Next, we carried out scanning on a calibrated sample. The sample has a 30 μm -deep, 250 μm -wide groove on the surface. The sample-probe distance is first automatically adjusted to focal length of the probe. A raster scan is performed over an area of 1 mm $\times$ 1 mm on the sample surface. The area-scan result is shown in Fig. 3(a). It is observed that the profile of the groove is clearly resolved. The measured width and height of the feature are consistent with the nominal values. A line-scan curve is plotted in Fig. 3(b). The 10%-to-90% transition

Figure 3. Schematic of (a) area-scan, and (b) line-scan results of a calibrated sample by using auto-focusing technique, and (c) area-scan and (d) line-scan results under out-of-focus setting.

at the edge is about $12\ \mu\text{m}$. So we can claim that achievable lateral resolution is $12\ \mu\text{m}$. As a comparison, the sample is scanned under out-of-focus condition. The probe is placed at a position which is 1 mm away from the focus of the probe. The area-scan and line-scan images are shown in Fig. 3(c) and Fig. 3(d), respectively. It is observed that the resulting lateral resolution is about $45\ \mu\text{m}$, which is much worse than the one obtained using auto-focusing.

Figure 4. Schematic of (a) a metallic cylinder sample, and (b) fiber profilometer scanning image of the area around the screw.

A metallic cylinder component is then measured. As shown in Fig. 4(a), there is a cylindrical hole inside the sample, which is hard-to-access for measurement. The diameter of the hole is 25 mm. There is an M3 screw attached on the wall of the cylinder. We performed scanning over an area circled by the red rectangle. The scanning image is shown in Fig. 4(b). We can see that there is a hole indicating the existence of the screw. The diameter of the hole is 3.2 mm. According to the ISO standard, the M3 screw has a 3 mm internal diameter. The measurement result is close to the standard dimension. The gap between internal and external threads is 0.2 mm. It is proved that the fiber profilometer can be applied for measurements of hard-to-access areas.

4. CONCLUSION

In conclusion, a fiber-based profilometer is established for measurements of hard-to-access areas based on low-coherence light interferometry. Two interference correlograms are observed in the recorded signal. One correlogram is due to light reflected from probe end surface, and the other due to reflection on sample surface. The absolute distance between the two surfaces is calculated from the difference between peak positions of the two correlograms. The differentiation operation significantly reduces disturbances on the signal, and thus improves the vertical resolution of imaging. Additionally, an auto-focusing scheme is proposed. An optimized lateral resolution is obtained through the auto-focusing. Experiments are carried out on calibrated and industrial samples. A lateral resolution of 12 μm and a vertical resolution of 200 nm are achieved.

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