Fiber-Based White-Light Interferometer With Improved Sensor Tip and Stepped Mirror

Frank Depiereux, Niels König, Tilo Pfeifer, and Robert Schmitt

***Abstract*—White-light interferometry has been a well-known and established measurement technique for years. However, in certain fields of production technology, such as microassembly or small-cavity inspection, there is a need for miniaturized metrology systems. This request can be answered, among other variants, with the use of fiber-based interferometry. The application of fibers enables, e.g., separation of a sensor (probe) from an optical receiver. The result is that the sensor probe can theoretically be miniaturized down to the curve diameter of the used fiber. On the one hand, this paper demonstrates how the use of a continuously improved miniaturized sensor probe can enable the application of such a measurement system in the mentioned technological fields. On the other hand, it describes the present state of a special mirror to increase the measuring range, frequency, and stability of the sensor system. This mirror replaces the moving reference mirror, which is commonly needed in an interferometer. It is designed with a certain number of steps to compensate the path difference between the object and reference beams. The fundamental aspects of white-light interferometry are presented and lead to the concept of a miniaturized fiber-based distance-measurement system.**

***Index Terms*—Graded index optics, microsensors, optical distance measurements, optical fiber measurements, optical interferometry.**

I. Introduction

LOW-COHERENCE interferometry is an established technique in metrology; it is used, e.g., for surface profiling of wafers. Systems for these purposes, such as white-light interference microscopes, are bulky stand-alone solutions and cannot be used for measurement tasks, such as small-cavity inspection. On the contrary, most existing systems for in-hole inspection are not applicable for hole-diameters below 1 mm and often have the disadvantage of using tactile measurement principles, which can cause damage to the (e.g., coated) surface of the measurement object. Fiber-based solutions have great potential to both provide highly accurate measurement results and, at the same time, allow flexible and miniaturized probe designs, like the commercially available ThetaForm system from Tropel, which is a fiber-optic dual-wavelength interferometer [1].

The presented system is based on fiber optical low-coherence interferometry. The necessary system miniaturization can then be realized with fibers which are used as sensing probes. In principle, the system is based on linking two interferometers: a measuring interferometer (the donor) and a receiving interferometer (the receiver) [2]. In the described system, the donor was miniaturized down to a fiber-based sensor probe. Consequently, the (short coherent) light source, which is a super luminescence diode (SLD), has to be capable of being coupled with minimal losses to a fiber. The signal coding in an optical spectrum permits measured values to be transmitted via optical fibers [3]. Influences such as dispersion, which are exerted on the signal by the fibers, can be ignored within certain limits (short fiber length).

A Michelson interferometer has been used as a receiver. Scanning of the measuring area in the time domain is replaced by a spatial projection of the interferogram onto a charge-coupled device (CCD), CMOS, or line detector, depending on the preferred measuring-frequency and measuring-range combination. The direct electronic measurement of the interferogram means that the measuring frequency is determined only by the frame or line rate of the chosen detector and by the downstream electronics.

A stepped oxygen-free aluminum reflector is used to expand the measuring range. The range of the system can be designed as required by selecting the number and height of steps [5]. The slight angularity of the mirror that is perpendicular to the direction of the incidence beam leads to a characteristic fringe pattern on the detector. The pattern depends on the characteristics of the light source and on the angle of the mirror.

II. Theoretical Background

In contrast to laser interferometry, white-light or low-coherence interferometry provides limited coherent areas in which interference is possible. They are obtained in dependence on the full width at half maximum (FWHM) and the central wavelength of the light source. Short coherent light sources allow an absolute distance measurement due to the existence of clear interference areas. The function of the sensor and the principle of the white-light interferometry can be developed in the frequency range by focusing on the transmission functions of the donor and the receiver, which are combined with the Gaussian power-density spectrum of the light source [6].

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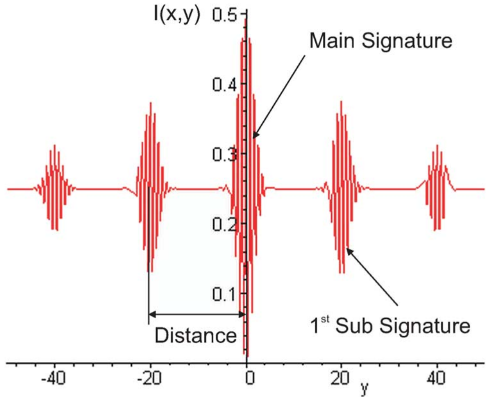

Fig. 1. Simulated detector signal.

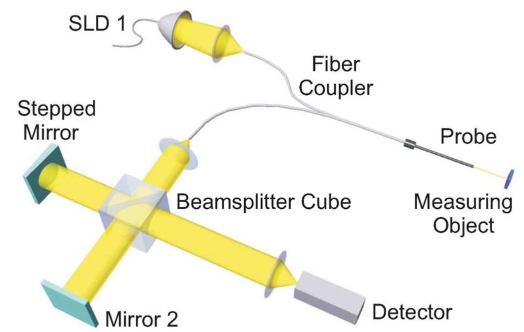

Fig. 2. Schematic system setup.

The signal intensity and position are the results of the path difference in the sensor and the receiver [5].

1) Power-density spectrum of the light source (Gaussian)

$$P(\lambda) = \sqrt{\frac{2}{\pi}} \frac{1}{\Delta\lambda} e^{-2\frac{(\lambda-\lambda_0)^2}{\Delta\lambda^2}}. \quad (1)$$

Here, λ_0 is the central wavelength, and $\Delta\lambda$ is the FWHM of the light source.

2) Transmission function for the sensor (airy function)

$$T_{\mathrm{G}}(x,k) = \frac{(r_1 - r_2)^2 + 4r_1 r_2 \sin^2 2\pi kx}{(1 - r_1 r_2)^2 + 4r_1 r_2 \sin^2 2\pi kx}. \quad (2)$$

Here, $k = 1/\lambda$ is the wavenumber, and r_1 and r_2 are the values of reflection of the Fizeau-like donor, where the first surface is equal to the end surface of the fiber and the second surface to the surface of the measurement object in a distance of x.

3) Transmission function for the receiver

$$T_{\mathrm{E}}(y,k) = \frac{1}{2}(1 + \cos 2\pi ky). \quad (3)$$

Here, y is the path difference between the mirrors in the receiving Michelson interferomter.

4) The signal intensity $U_x(y)$ is

$$U_x(y) = \int_{-\infty}^{\infty} P(\lambda) T_{\mathrm{G}}(x,k) T_{\mathrm{E}}(y,k) dk. \quad (4)$$

In order to simplify, differences in the running time of the waves due to changes in refractive indexes of the optical components are not taken into account. When the path-length differences in the donor and the receiver are the same $(x = y)$, signatures are obtained for these positions. There are redundant signatures which are $n4X = n(x+y) = n2x$ apart for a measured value of X, as long as the path difference can be compensated on the geometry of the stepped mirror, i.e., within the measuring range. Only the first pair of subsignatures is of interest for the detection because of the loss of intensity for the following subsignatures (Fig. 1). There is a further signature (the so-called main signature) for equal geometric path lengths in the receiver $(y = 0)$. It is sufficient for measurement evaluation to detect only the main signature and one subsignature because the distance between the center values of the signatures is exactly $x = 2X$. The signature width depends on the distribution of the light-source power density. A detailed mathematical description of (1)–(4) can be found in [4].

The signal described by (4) is shown in Fig. 1. Both the main and the first two pairs of subsignatures have been simulated.

The width of the theoretically developed signature relates to the used SLD. With the main wavelength $\lambda_0 = 846.9$ nm and the FWHM value $\Delta\lambda = 15.6$ nm, the coherence length of the SLD is given by the following.

5) Coherence length

$$l_{\mathrm{cSLD}} = \lambda_0^2/\Delta\lambda = 846.9^2\ \mathrm{nm}^2/15.6\ \mathrm{nm} \approx 46\ \mu\mathrm{m}. \quad (5)$$

III. System Description

The system setup (Fizeau donor/Michelson receiver) is shown in Fig. 2. When light is emitted from the source (SLD 1), a short coherent wave of light reaches the Fizeau donor via the single-mode fiber coupler. The reference wave, which develops at the end surface of the probe, is superimposed on the Michelson receiver with the measuring wave from the measuring object. The fiber-based Fizeau design also has the advantage that, as a result of the common-path design, almost no additional phase shifts occur due to temperature changes. When the paths are matching, they interfere. The interference signals can be detected by a CMOS, CCD, or line camera, depending on the desired measuring range and frequency.

The light source is an SLD with an average output power of ~3 mW and a central wavelength of 846.9 nm, which is already pigtailed to a single-mode fiber. This power output is necessary due to the optical losses which occur when a technical surface is measured. The light from the source is coupled into a single-mode fiber and transmitted to the Fizeau probe via the coupler. The single-mode fiber has a diameter of approximately 5 μm and a numerical aperture of 0.12, which, in conjunction with a collimating sensor probe, results in an almost collimated beam of approximately 40 μm along the complete measuring range. The use of a focusing sensor probe is also possible. The single-mode fibers have a further advantage: The fiber acts like a

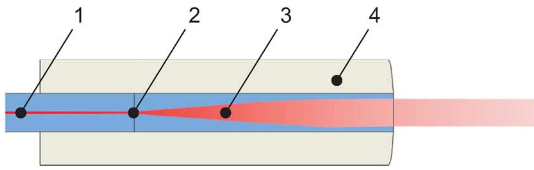

Fig. 3. Collimating connector in all-fiber design.

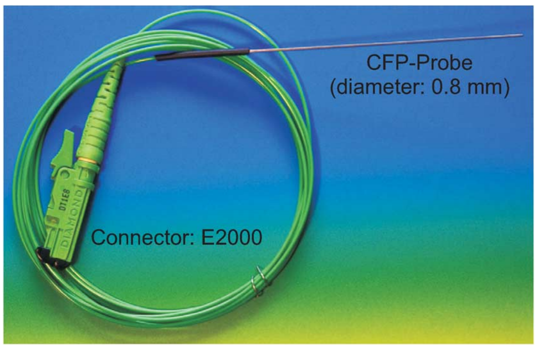

Fig. 4. CFP-probe prototype [10].

spatial mode filter; the spatial coherence is restored [6]. The receiver setup provides a collimated beam, which illuminates the reference (mirror 2) and the tilted stepped mirror. The stepped mirror replaces mechanical elements like Piezo actuators or linear stages.

A. Sensor Probe

When the system is used without a collimating sensor probe, the beam expands under the half-angle of $\theta = 6.8^\circ$. This results in a beam diameter of $d_\mathrm{M} \sim 358\ \mu$m in the measurement distance of 1.5 mm. A collimated beam can be provided by the use of a gradient-index fiber collimator [7], which is shown in Fig. 3.

A short piece of gradient-index fiber (3) is spliced (2) to the single-mode fiber (1) and glued into the ferrule (4) of a chosen connector. The GRIN fiber has then to be polished to a defined length to provide collimation [8].

The same technique was used for miniaturization of the sensor probe. To achieve an outer diameter of the sensor probe below 1 mm and a minimum of 50-mm sensor shaft length, a newly designed carbon-fiber-reinforced plastic (CFP) tube is used for the sensor probe [9]. For the optical signal transmission and beam shaping, the same concept as described above has been used. The integration of the spliced fiber led to a Fizeau probe with an outer diameter of 0.8 mm. A prototype of the sensor converted with an E2000 connector is shown in Fig. 4.

Compared to other materials, the main advantages of the CFP lie in its special mechanical properties. On the one hand, it is flexible to tolerate collisions in industrial handling, and on the other hand, it is robust and keeps its shape, which is elementary for measurement purposes. In the first attempts toward probe miniaturization, steel and glass ferrules were used; however, neither of them matched the desired handling properties, e.g., glass ferrules broke, and metal ferrules easily bend due to handling accidents.

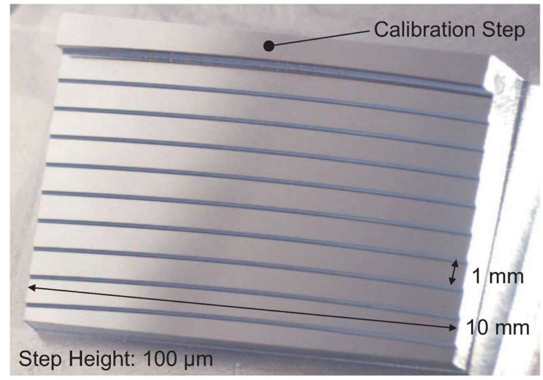

Fig. 5. Stepped mirror (design variant 2).

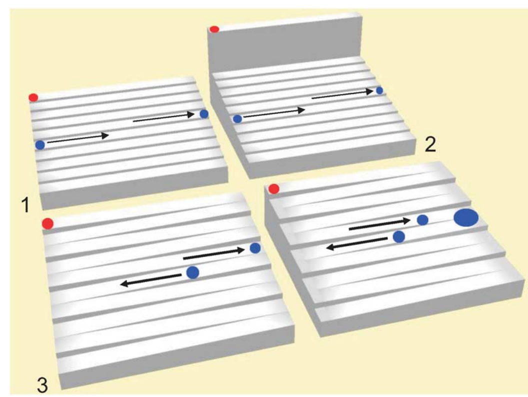

Fig. 6. Possible designs of the stepped mirror.

B. Stepped Mirror

As mentioned above, the sensor is connected to the Michelson receiver via the second coupler arm. The lens setup at the end of the fiber that leads to the receiver provides a collimated beam, which illuminates both the reference and the stepped mirror. The stepped mirror provides a measuring range that depends on the dimensions, number of steps, and angle of the mirror. A mirror with ten steps, where each is 100-μm high, was used in the setup shown in Fig. 5. To ensure a continuous measuring range, the required angle of incidence is $\sim 0.6^\circ$. This angle is a result of the selected step dimensions (step length multiplied by height). The visibility of the interference continually diminishes as the incidence angle increases [5], [11].

Tests with the stepped mirror delivered an important information about improving its design. Different design variants of the stepped mirror are shown in Fig. 6. Main (red) and subsignatures (blue) are added, and movement directions of the subsignatures are indicated. In order to increase the measuring distance by simultaneously detecting both the main and subsignatures, a stepped mirror (2) with a so-called "calibration step" was designed. The advantage of this design is that the mirror always shows the main signature on the first step. The working distance of the sensor system depends on the height of the calibration step. The mirror shown in Fig. 5 provides a working distance of 1.5 mm and a measuring range of ± 0.5 mm. The main signature is important not only for signal processing but also for monitoring the receiver condition.

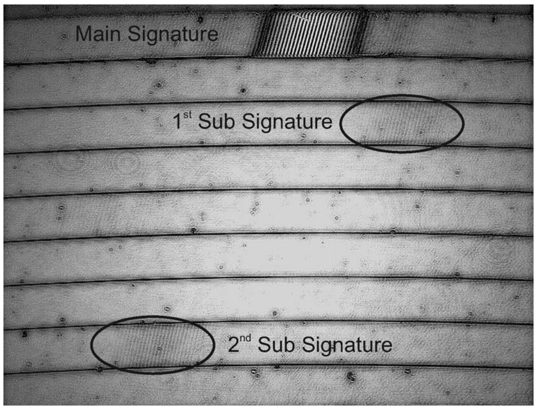

Fig. 7. Detector image with main signature (above) and subsignatures (encircled).

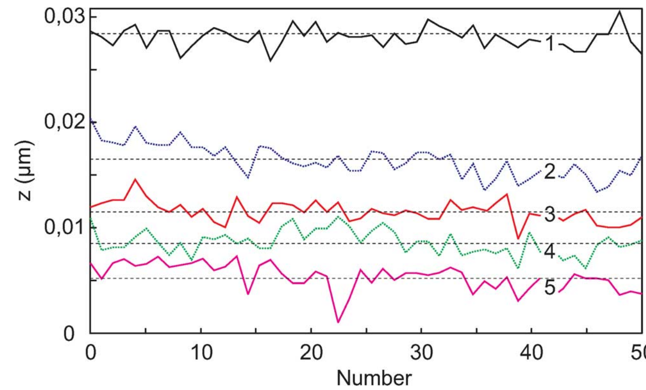

Fig. 8. Results of distance measurements.

The resulting signal processing for a mirror with planar steps is quite intensive because of the "signature jump" at the end of each step. Design variants 3 and 4 show improved mirrors with a serpentine structure. This structure enables continuous signal detection without jumps. Design 4 shows a further improved serpentine structure with a common plateau at the end of each incline. These plateaus show the signature for both the ending and the starting inclines. It has to be made clear that these mirrors are far more difficult to manufacture than the stepped variants 1 and 2.

IV. Results

The combination of the stepped mirror and the light source results in signatures which are laterally spread across regions of the mirror, with maximum intensity in the middle of the signature. This behavior is shown in Fig. 7.

The detector image shows the stepped mirror with signatures on different steps. The signature on the first step is the main signature. It certainly has a higher intensity compared to the others. To explain the two subsignatures (ellipses), it has to be mentioned that the measured object was a thin slice of a transparent material. When measuring such an object, reflections from both the front and backsides of the surface are obtained (as in OCT measurements). These reflections interfere within the receiving interferometer on different steps. In addition to the distance, the thickness of the test sample can be measured as well. In this particular case, the result of the measurement would give a measuring distance to the object of approximately 1180 μm and a measured thickness of approximately 450 μm.

A. Test Measurements

The fiber-optic system has thoroughly been investigated in different tests. The tests were performed with a slightly different sensor setup than that described in Fig. 2. We used a CCD-line as detector and a focusing probe attached to the "Nano measuring and positioning machine" (NMM-1) from Sios GmbH, Ilmenau, Germany. The machine provides a positioning range of 25 $\times$ 25 $\times$ 5 mm and a resolution of 0.1 nm for each axis [12].

TABLE I
Mean Values and Standard Deviations

Series	Mean Value	Std. Deviation
1	0.0284	1.0 nm
2	0.0165	1.6 nm
3	0.0115	1.1 nm
4	0.0085	1.2 nm
5	0.0052	1.3 nm

The goal of the test series was to evaluate the standard deviation of the system. Five test series with 50 point measurements on a polished glass surface were carried out. A random point on the surface was chosen, and then, the distance to this point was measured. The test object was laterally moved in one direction and, afterward, was moved back to the initial point to perform the second measurement, and so on. The series have been taken at different locations on the test object; therefore, different distances were measured. The results of the test series are shown in Fig. 8.

Table I gives the calculated standard deviations for the five measurement series showing the accuracy in the nanometer range.

V. Conclusion

Fiber-based sensors and measuring systems have the great potential to substitute or enhance existing measurement and detection systems. In particular, requirements on miniaturization and the need for distributed sensors or probes, even in harsh environments, is perfectly matched by fiber optical solutions.

We demonstrated the concept and realization of a fiber optical measurement system based on low-coherence interferometry. In this context, we presented a miniaturized Fizeau probe with beam-shaping properties in all-fiber design. Furthermore, we presented a stepped mirror that was used to replace the mechanical scanning elements within the Michelson receiver. We investigated the standard deviation of distance measurements gathered with our system. The results could prove the high potential of fiber-based interferometry, as it is used in our system, for further applications in different industrial fields, like MEMS-testing or in-hole inspections.

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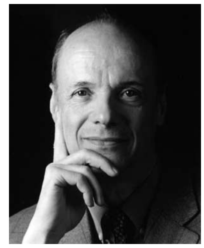

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