White-light interferometer with dispersion: an accurate fiber-optic sensor for the measurement of distance

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We present a fiber-optical sensor for distance measurement of smooth and rough surfaces that is based on white-light interferometry; the sensor measures the distance from the sample surface to the sensor head. Because white light is used, the measurement is absolute. The measurement uncertainty depends not on the aperture of the optical system but only on the properties of the rough surface and is commonly ~1 µm. The measurement range is approximately 1 mm. The sensor includes no mechanical moving parts; mechanical movement is replaced by the spectral decomposition of light at the interferometer output. The absence of mechanical moving parts enables a high measuring rate to be reached. © 2005 Optical Society of America

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1. Introduction

White-light interferometry is an established method for the measurement of topographical features of sample surfaces. The measured surface is illuminated by a broadband light source and the reflected wave interferes on the detector with the wave reflected from the reference mirror. The intensity of light on the detector is maximum if the optical path lengths of the two interferometer arms are equal. One performs the topography measurement by scanning the measured sample along the optical axis. In this way the mutual coherence function is measured as a function of optical path difference. The maximum of the envelope of the mutual coherence function indicates the position where the optical path difference is equal to zero.

The main drawback of this method is that the measured sample must be moved mechanically. Scanning in the depth direction is time consuming and permits only stationary objects to be measured. This drawback can be overcome by introduction of a dispersive element into one arm of the interferometer and by spectral decomposition of the light at the detector. An interferometer with a dispersive element in one arm can be balanced for only one wavelength. When this wavelength is found, the length of the object arm of the interferometer can be determined and therefore also the location of the sample surface.

Because of spectral decomposition, such a sensor can be achieved only as a point or line sensor. We propose a point sensor for fiber-optic implementation. This sensor utilizes the dispersion of the optical fiber and measures the distance between a small sensor head and one point of the measured surface. Thus this sensor is an optical equivalent of the mechanical stylus sensor. We emphasize that the sensor does not suffer from the limitations of triangulation sensors, which include autofocus sensors.

The sensor described is a modification of a spectral interferometer. In the spectral interferometry described in Ref. 6 and referred to as as well as spectral radar or as a channeled spectrum technique, the optical path difference is determined from the period of the spectral modulation. In our method the optical path difference is determined from knowledge of the wavelength for which the interferometer is balanced. We should add that there are interferometric methods that vary the spectral features of the light source and that do not need any depth scanning. These methods exploit variation of the spectral amplitude.
 orc of the spectral phase\(^3\) of the mutual coherence function.

The basic idea of the sensor described here as a modification of spectral radar was described in Refs. 2 and 10. In this paper we present the theory of fiber-optic implementation of the sensor and show the results of measurements of distance. Finally we discuss the parameters of the sensor.

2. Theory

A schematic of our proposed system appears as Fig. 1. A Michelson interferometer is illuminated by a broadband light source. A dispersive element is placed in the reference arm, and the measured surface is part of the object arm. The light at the output of the interferometer is spectrally decomposed by a spectrometer.

We assume that refractive index \(n\) of the dispersive element depends linearly on wave number \(k = 2\pi/\lambda\) in the interval given by the spectral width of the light source:

\[
n(k) = n(k_0) + \alpha(k - k_0),
\]

(1)

where \(k_0\) is the central wave number of the light source and \(\alpha\) is a dispersion parameter. This assumption is justified because the refractive index of common optical glass depends almost linearly\(^1\) on the wave number in the range 700–900 nm. The spectral intensity at the output of the interferometer is given by

\[
I_k = 1/2 I_s [1 + \cos \phi(k)],
\]

(2)

where \(I_s\) is the spectral intensity of the light source and \(\phi(k)\) is the phase difference between the two interferometer arms. For the phase difference, the following equation holds:

\[
\phi(k) = 2kz - d[n(k) - 1] = 2k[z - d[n(k_0) + \alpha(k - k_0) - 1]],
\]

(3)

where \(z\) is the distance of the sample surface from the reference plane and \(d\) is the thickness of the dispersive element as plotted in Fig. 1.

Phase difference \(\phi(k)\) is, according to Eq. (3), a square function of \(k\), and it is graphed in Fig. 2(a). The behavior of spectral intensity \(I_k\) as a function of \(k\) is given by Eq. (2) and is illustrated in Fig. 2(b). Apparently, a symmetric interference pattern with a distinct center appears in the spectrum of the interferometer output. The position of this symmetry center is calculated as the vertex of the parabola given by Eq. (3) and illustrated in Fig. 2(a):

\[
k_c = \frac{z}{2ad} \left[ \frac{n(k_0) - \alpha k_0 - 1}{2ad} \right].
\]

(4)

The physical meaning of wave number \(k_c\) becomes apparent if we express distance \(z\) obtained from Eq. (4):

\[
z = [n(k_0) + 2ak_c - \alpha k_0 - 1]d = [N(k_c) - 1]d,
\]

(5)

where \(N(k) = n(k) + kdn/dk\) is the group refractive index.\(^\text{12}\) Equation (5) is the condition of the balance of the interferometer with a dispersive element in one arm. Because of the dispersion, the interferometer is balanced only for one wave number, namely, \(k_c\). The refractive index and the group refractive index of common optical materials such as glass and silica are greater than 1; then, according to Eq. (5), distance \(z\) is always positive, which means that the object arm is longer than the reference arm.

We define a distance \(z_0\), which is the difference between the length of the object arm and the length of the reference arm if the interferometer is balanced for...
central wave number $k_0$ of the light source. According to Eq. (5), $z_0$ takes the value

$$z_0 = [n(k_0) + \alpha k_0 - 1]d = [N(k_0) - 1]d.$$  \hspace{1cm} (6)

Substituting for $[n(k_0) - 1]d$ from Eq. (6) into Eq. (4), we obtain

$$k_C - k_0 = \frac{z - z_0}{2ad}.$$  \hspace{1cm} (7)

It follows from Eq. (7) that distance $z$ is related to the position of the symmetry center of interference pattern $k_C$. Distance $z$ can be determined when one knows wave number $k_C$. This is the underlying principle of the sensor described here. Product $2ad$ acts as a scaling factor between the distance and the wave number. As the constants $k_0$, $z_0$, $\alpha$, and $d$ are given by the experimental arrangement, the relationship between $k_C$ and $z$ is constant, which means that distance $z$ is measured absolutely.

The measurement range of the sensor described here is restricted by the spectral width of the light source and the factor $2ad$. According to Eq. (7) we can estimate the measurement range:

$$\Delta z = 2ad\Delta k,$$  \hspace{1cm} (8)

where $\Delta k$ is the spectral width (FWHM) of the light source.

The theory described is valid also if the interferometer is built from fiber-optic components. The chromatic dispersion of optical fibers is determined by fiber dispersion parameter $D$, whose unit is ps/(nm km). From this parameter a fiber parameter $\alpha_f$ can be calculated that is defined in analogy to parameter $\alpha$ of optical materials. In the wavelength interval 700–900 nm the material dispersion is the most significant dispersion effect, and the refractive index of the fiber material depends almost linearly on wave number $k$. Then it holds that

$$\alpha_f \equiv -\frac{c\lambda_0^2}{4\pi} D,$$  \hspace{1cm} (9)

where $\lambda_0$ is the central wavelength of the light source and $c$ is the speed of light. Because in the fiber-optic implementation there are optical fibers in both interferometer arms, one must use an optical fiber with a higher dispersion parameter $\alpha_f$ in one interferometer arm to be able to utilize the dispersion effect. Provided that the fiber with the higher dispersion parameter is introduced into the reference arm, Eq. (7) takes the form

$$k_C - k_0 = \frac{z - z_0}{2(\alpha_f - \alpha)L}.$$  \hspace{1cm} (10)

where $L$ is the length of the optical fiber with the higher dispersion parameter. Comparing Eqs. (7) and (10), we can see that the expression $2(\alpha_f - \alpha)L$ is now the scaling factor between the measured distance and the wave number. Similarly, according to expression (8), the measurement range is given by

$$\Delta z = 2(\alpha_f - \alpha)L\Delta k.$$  \hspace{1cm} (11)

If the dispersion parameters of the optical fibers $\alpha_f$ and $\alpha$ are provided, one can adjust the measurement range by choosing a suitable fiber length $L$.

3. Construction of the Sensor

We built the sensor by the use of fiber-optic elements. Thus the sensor head can be small. It is connected to the spectrometer and a light source by a single-mode optical fiber. The optical fiber also serves as the dispersive element, providing the correct functionality of the sensor. The optical setup of this sensor is illustrated in Fig. 3.

A fiber-optical Michelson interferometer is fed by a superluminescent diode with central wavelength $\lambda_0 = 815$ nm and a spectral width (FWHM) of 20 nm. The sensor head in the object arm includes an optical system that focuses the light from the fiber onto the sample surface and collects the scattered light back into the interferometer. The light in the reference arm is reflected by a mirror placed at the end of the reference arm. The spectrometer at the output of the interferometer registers the spectrum with an interference pattern.

To utilize the dispersion effect described, we use an optical fiber with higher dispersion in the reference arm. We utilize a single-mode fiber with fiber dispersion parameter $D = -129$ ps/(nm km) (at $\lambda = 815$ nm) for the reference arm. The single-mode fiber...
in the object arm has fiber dispersion parameter $D = -113 \text{ ps/(nm km)}$ (at $\lambda = 815 \text{ nm}$). According to expression (9), the corresponding values of the dispersion parameters are $\alpha_\lambda = 2.05 \text{ nm}$ and $\alpha_f = 1.79 \text{ nm}$.

The measurement range can be adjusted according to expression (11) by choice of an appropriate length of optical fiber. On the other hand, the measurement range is limited by the depth of focus of the optical system in the sensor head.

The depth of focus of an optical system consisting of two lenses as illustrated in Fig. 3 is given by

$$s = \frac{f_1}{f_2} \cdot 1.22 \lambda \cdot \frac{\text{NA}^2}{L},$$

where $f_1$ and $f_2$ are the focal lengths of lenses $L_1$ and $L_2$, respectively, and NA is the numerical aperture of the optical fiber. Two of these quantities are given: wavelength $\lambda = 815 \text{ nm}$ and numerical aperture NA = 0.11. The two focal lengths $f_1$ and $f_2$ must be chosen such that depth of focus $s$ is as large as the desired measurement range. It is possible to increase the depth of focus by increasing the ratio $f_1/f_2$, but we must keep in mind that the numerical aperture of the optical system will decrease and the light intensity in the object arm will dip. Moreover, lateral resolution will decrease with increasing ratio $f_1/f_2$. Therefore a compromise must be made. We chose the measuring range $\Delta s = 0.9 \text{ mm}$, which is sufficient for many applications. The size of the point-spread function is 30 $\mu\text{m}$. With $\Delta s = 20 \text{ nm}$ given, it follows from expression (11) that the length of the optical fiber with higher dispersion is $L = 9350 \text{ mm}$. Because the light from the superluminescent diode is partly polarized, a polarization controller is introduced into the reference arm to guarantee high contrast of the interference pattern.

4. Evaluation of the Interference Pattern and Calibration of the Sensor

Measured distance $z$ is determined from the position of symmetry center $k_0$ according to Eq. (10). The task of the evaluation procedure is to find the symmetry center of the interference pattern in the spectrum of the interferometer output. An established search method for the symmetry center of a pattern is autoconvolution. The autoconvolution of a symmetric function shows a maximum at the symmetry center of the function. Before the autoconvolution is applied to the spectrum of the interferometer output, the shape of the spectrum of the light source is filtered off by a digital filter. The individual steps in the evaluation procedure are illustrated in Fig. 4. The spectrometer measures the spectrum in wavelength units and not in wave-number units. Provided that the spectral width of the light source is much less than the source's central wavelength, the search for the symmetry center can yet be performed in a spectrum expressed in wavelength units. The maximum of the autoconvolution is evaluated with subpixel accuracy of the spectrometer CCD array.

Because the factor $2(\alpha_\lambda - \alpha_f)L$ in Eq. (10) is not known exactly, the sensor has to be calibrated. A roughness standard with a lapped surface that is close to an ideal diffusor is used as a calibration sample. The object is moved by means of a translation stage along the optical axis. The whole measurement range is scanned in $5\mu\text{m}$ steps, and the corresponding value of $k_0$ is acquired at each position $z$ of the object. The scaling factor between the distance and the wave number is obtained from the measured values by linear regression. One also uses the roughness standard with the lapped surface to determine the repeatability and the measuring uncertainty of the sensor. To determine the repeatability, we repeatedly measured the distance of one point on the object's surface to the sensor head and the root-mean-square deviation of the measured values was calculated. The measured repeatability amounts to $0.05 \mu\text{m}$ in the center of the measurement range and to $0.11 \mu\text{m}$ at its margin. More important is the measuring uncertainty on rough surfaces. The basic principle of the sensor is white-light interferometry on rough surfaces. The physically achievable longitudinal measurement uncertainty is equivalent to the roughness of the measured surface. This longitudinal measurement uncertainty depends not on the aperture of the observation optical system but only on the surface roughness.

The measuring rate of the sensor is given primarily by the integration time of the spectrometer. This time in our case amounts to 12.5 ms. The time required for the execution of the evaluation algorithm is less than 0.2 ms. Thus the measuring rate of the sensor is ap-
proximately 80 measurements per second, limited only by the spectrometer. There is room to speed up the measurement rate to 10 kHz or more.

5. Experimental Results
The sensor described is a point sensor, but it can also measure the height profile of an object by scanning the object in the lateral direction. The distance between the object and the sensor head is measured after each scanning step to measure the height profile of the object along a given line. Examples of measurements are presented in Figs. 5–7.

Figure 5 displays the measured height profile of a spark-eroded surface (Rugotest number N6 A). The arithmetic mean deviation of the surface is given by the manufacturer as \( R_a = 0.8 \, \mu \text{m} \). The measured value \( R_a' \) amounts to \( 0.76 \pm 0.19 \, \mu \text{m} \). In Fig. 6 the measured height profile of a roughness standard (Rugotest number N7 A) is displayed. This roughness standard has the arithmetic mean deviation \( R_a = 1.6 \, \mu \text{m} \) given by the manufacturer, and the measured value \( R_a' \) amounts to \( 1.53 \pm 0.20 \, \mu \text{m} \). The height profiles are measured at lateral positions every \( 5 \, \mu \text{m} \). The results confirm that the sensor can also be used for the measurement of roughness.

Figure 7 shows the measured height profile of a finish-turned surface (roughness standard Leitz). The height profile in Fig. 7(a) measured every \( 5 \, \mu \text{m} \) is compared with the height profile in Fig. 7(b) measured every \( 1 \, \mu \text{m} \). The measurements display no significant difference. The depth of the turning grooves amounts to \( 12 \, \mu \text{m} \), and their pitch is equal to \( 160 \, \mu \text{m} \).

As the profile height \((z)\) is measured by the calibrated sensor and the shift in the lateral direction is performed by an accurate translation stage, the height profile shows high precision in both coordinates.

6. Conclusions
A new fiber-optic sensor for noncontact measurement of distance based on white-light interferometry has been introduced. White-light interferometry combined with dispersion permits the sensor to measure absolutely distance. The measured surface can be smooth or rough. The longitudinal measurement uncertainty depends on the surface roughness and is independent of the observation aperture. The sensor needs no mechanical moving depth scan and provides a high measuring rate. The bulky parts of the sensor are separate from a remote small-sized sensor head.

We conclude by noting that the test samples are optically rough surfaces with the effect that the signal generation is completely different from the standard white-light interferometry at smooth surfaces. For completeness we briefly mention that our sensor can measure smooth surfaces as well. There are a couple of commercial sensors that measure the point distance by using different principles such as shearing interferometry of the scattered wave front or autofocus with variation in chromatic focal length. We emphasize that the underlying physical principle of these sensors is triangulation. The measuring uncertainty of a triangulation system is severely affected by speckle noise and cannot compete with white-light interferometry, which is the underlying principle of our sensor.

References
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