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PRACTICAL CONSIDERATIONS FOR CHOOSING OPTICAL PROBE HEADS

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***Abstract* — we review properties of the optical probe heads used in combination with the low-coherence interferometer for thickness measurement applications. We describe practical aspects of the probe properties to help guide user through the selection process and to enable reliable and accurate measurements.**

***Index Terms* —non-contact metrology, material thickness, angular tolerance, working distance, working range, focal spot size, numerical aperture.**

I. Introduction

Optics- and light-based metrology tools have found increased popularity in the quality control labs around the world. Non-contact nature, reliability, and maintenance-free operation of the light-based technology are just some of the advantages over the mechanical counterparts.

Due to its novelty, this cutting-edge technology lacks the intuitive feel of the mechanical gauge. In many cases it requires advanced knowledge of physics and optics to develop robust understanding of the capabilities and limitations. Tool selection and decision-making presents a significant undertaking on the part of the quality engineer. Here we cover one important step during the purchasing process – selection of the optical probe head. While we target this discussion at the technology commercialized by Lumetrics, the general concepts are applicable to other similar metrology tools as well.

Lumetrics has developed the time-domain low-coherence interferometry (LCI), also sometimes referred to as partial coherence interferometry, for measuring thickness of various translucent materials. The LCI works by illuminating the sample with a beam of light and analyzing the relative time-delay of the reflected light. The reflections are created by the interfaces between different layers in the sample. The in-depth technical description of the LCI is widely available and can be found in literature [1, 2, 3, 4].

II. The concept of the optical probe head

Lumetrics LCI, marketed under the registered name of OptiGauge II consists of three main components: (1) interferometer box (2) optical probe head, and (3) optical fiber that connects the optical probe with the interferometer box. The optical fiber delivers the light from the interferometer probe to the optical probe, and guides the reflected light collected by the optical probe back to the interferometer box.

In theory, this measurement system can operate without the use of the probe. A bare fiber can be used to illuminate the sample with the light and to collect the reflected light. The efficiency of such approach is however exceedingly small – only tiny fraction of the reflected light enters the fiber. In most cases the amount of the reflected light collected in such fashion is insufficient to obtain the signal above the noise level.

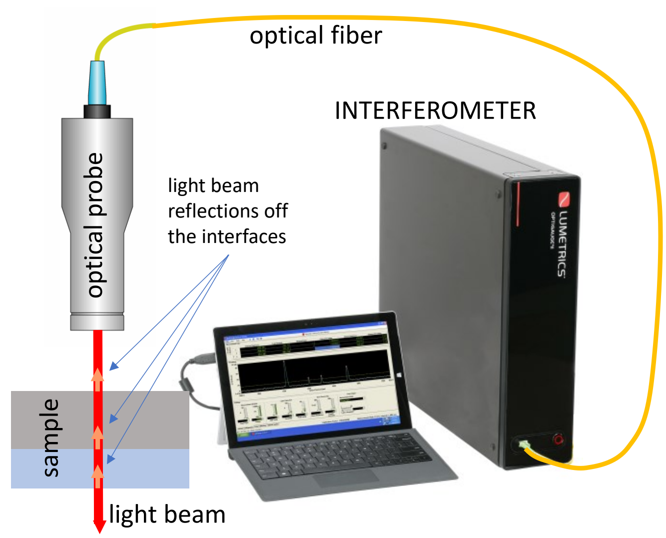

Figure 1: Basic components of the LCI measurements system.

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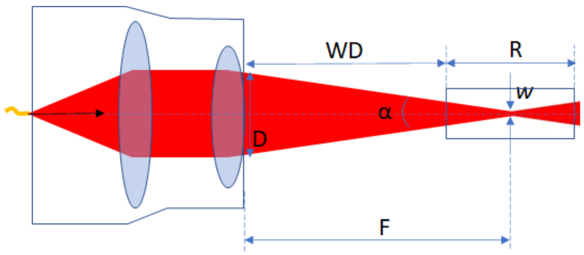

Figure 2: Conceptual schematic of an LCI optical probe. The cone of light (red) is emitted from the fiber and is refocused. R is measurement range, WD is working distance, α is a measure of the angular tolerance of the probe, F is the focal distance, w is the diameter of the beam at the focus, and D is the beam diameter at the output of the probe.

The primary role of the probe head is therefore to maximize the amount of the reflected light that travels back to the interferometer box. Figure 2 shows the conceptual schematic of the optical probe head. The light is emitted from the end of the optical fiber in a divergent cone. The optics inside the optical probe reshapes the divergent cone of light into the converging cone of light. The converging cone of light defines most of the parameters that are used to describe the properties of the measurement beam.

Beam focus: the location where the cone angle converges to its smallest size. Focal distance (F) is the distance from the front lens of the probe to the focus. If pure geometry guided the dimensions of the converging beam, the beam focus would have been a point. However, physics dictates that the beam does not converge into a point, but rather goes through a waist (see Figure 3).

Focus size (w): the diameter of the beam at the focus.

Angular tolerance: defined by the **cone angle** (α) of the converging beam. Sometimes it is also called **acceptance angle**. Angular tolerance, cone angle and acceptance angle all describe the same concept, and therefore can be used interchangeably for any qualitative description.

Measurement range (R): the area around the focus where the measurement sample should be placed to obtain the best reflected signal. This parameter can also be called a **working range**, and a **depth of focus**.

Beam diameter (D) at the output of the probe is self-explanatory.

Working distance (WD) is the distance between the body of the probe and closest boundary of the measurement range. That distance contains the “dead” space not needed for measurements. This space can be utilized when integrating the optical probe into an application-specific fixture. For example, the probe can be mounted outside of the vacuum chamber, measuring sample inside the chamber through a window.

We can group these parameters into two practical groups: the primary and secondary.

A. The primary parameters.

These parameters are angular tolerance (α), range (R) and the focus size (w). These parameters control the amount of reflected light that enters the optical fiber on the way back to the interferometer. Cone angle (angular tolerance) is the most intuitive beam parameter and therefore is commonly used when describing properties of the optical probe. The mathematical derivation of these parameters for probes offered at Lumetrics can be found in other publications [5, 6, 7].

These 3 parameters depend on each other. Changing one will necessarily change the other two. Table 1 shows the qualitative dependence of the other primary probe parameters on the cone angle.

Cone angle (α)	Meas. Range (R)	Focus size (w)
Smaller	Larger	Larger
Larger	Smaller	Smaller

Table 1: Relative dependence of the probe parameters on the cone angle

B. The secondary parameters

Parameters D and WD (parameter F is directly tied to WD, so for simplicity we will not consider it separately) do not control the amount of the reflected light, but a responsible for the dimensional properties of the probe. These parameters also depend on each other – changing one of them will change the other.

For example, for a given angular tolerance (α) the probe can be designed to have a specified working distance (WD). The selected WD will then define the beam diameter (D), and therefore the diameter of the probe – the longer is WD, the larger is the probe size.

III. THE STANDARD PROBES AND THE CONE ANGLE

Lumetrics offers 3 standard probes with three different values for the cone angle of the measurement beam. Table 2 shows qualitative values of the cone angle for the probes. The numbers in the probe names indicate the approximate value of the working distance. The exact working distance vary slightly from the numbers used in the name and can be found in [6].

Probe name	α	w, µm	R
50 mm probe	Small	40	Large
25 mm probe	Medium	20	Medium
25mm HNA probe	Large	10	Small

Table 2: Cone angles for the standard probes

Typically, any other probes are derived from these three probes. The variations come from the specific requirements for the probe size and the working distance, but the measurement capability is always reserved to finding the right cone angle.

IV. MEASUREMENT RANGE OF THE PROBE

When the sample is placed into the path of the measurement beam, the reflected light is converted into the electronic signal peak at the interferometer. Figure 3 illustrates this outcome by showing a glass window placed into the measurement beam – the reflections from the two sides of the window result in the signal peaks. The time-delay between these reflections is encoded as a distance by the interferometer, and the distance between the signal peaks corresponds to the thickness of the material.

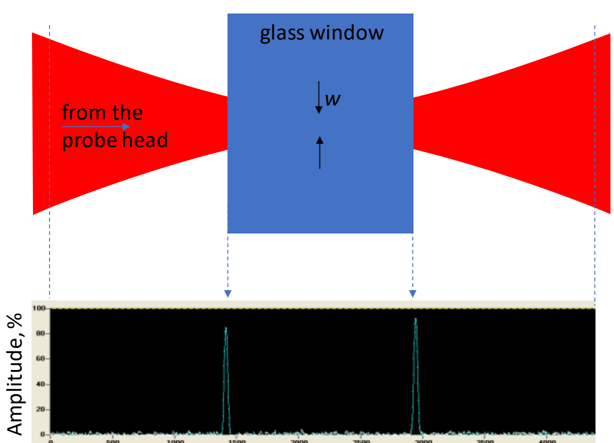

Figure 3: Schematic of the glass window placed into the focal region of the measurement beam, and the corresponding interferometric signal peaks.

Imagine moving the glass window from the left-hand side of the Figure 3 to the right-hand side, while at the same time monitoring the *amplitude of the first peak*. As we move the glass window, the amplitude of first peak amplitude will grow to the maximum and then decline (Figure 4). The maximum signal amplitude is achieved when the reflecting surface of the glass window is located at the focus of the probe. The peak amplitude is reduced when the reflecting surface is moved away from the focus. At some distance away from the focus (to the left or to the right of the focus), the signal amplitude becomes less than the noise floor. In the Figure 4 we labeled these locations as A and B. The overall distance between A and B is then equal the measurement range of the probe.

Publication [7] contains derived values for the measurement range of the standard probes (in the publication it is referred to as practical depth of focus).

V. OVERALL MEASUREMENT RANGE.

In addition to the measurement range of the probe, the interferometer also sets the measurement boundaries. The measurement range (or working range) of the interferometer is defined by the inner configuration of the interferometer. The working range of the interferometer also limits the maximum thickness of materials that can be measured.

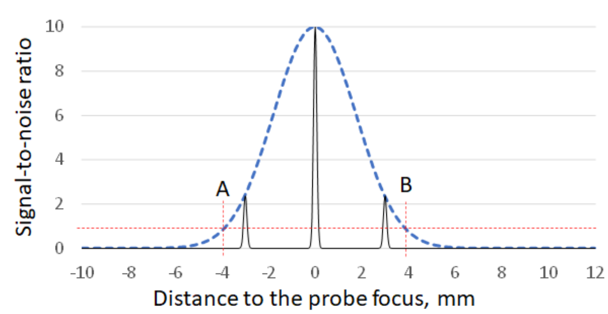

Figure 4: Change in the amplitudes (blue dashed line) of the interferometer signal peaks when the reflecting surface is placed at different locations with respect to the probe focus. Signal peak examples for 3 different locations are shown in solid black lines. Locations A and B correspond to the SNR=1. The distance between A and B corresponds to the working range of the probe.

In the software suite that accompanies the OptiGauge II measurement system (OptiGauge Control Center), this range is reflected in the size of the window that displays the interferometric signal. If the reflecting surface is located outside of that range, the reflected signal is not shown – it is outside of the capabilities of the interferometer. Figure 5 demonstrates the situation where the righthand side surface of the glass window is outside the working range of the interferometer.

The working range of the interferometer can be smaller or larger than the working range of the probe itself. For example, the working range of 50mm probe is 50mm, but is effectively truncated by the working range of the interferometer (which is equal to 16mm, nominally).

The working range of 25mm HNA probe (2 mm) is smaller than the working range of the interferometer. The complete rise and fall of the signal peaks amplitudes while changing the probe-sample distance can be fully observed on the software signal graph.

The measurement range of the overall system (interferometer plus the probe) is determined by the smallest of the probe and the interferometer measurement ranges.

VI. Signal quality and probe selection

The quality of the signal peak is defined by its signal-to-noise ratio (SNR), i.e. how much higher the amplitude of the signal peak is compared to the noise floor. The OCC shows the signal amplitudes as the percent of the maximum possible amplitude. Signal peaks with the amplitude above 60% are needed to obtain the specified measurement accuracy and repeatability, Peak amplitudes below that value start affecting measurement performance, with the lower SNR reducing the repeatability and accuracy.

The bottom graph in Figure 3 demonstrates an example of a good quality signal that corresponds to the reflections off the surfaces of a glass window. Both surfaces interface the air, resulting in strong reflections and good SNR. Such sample represents the best-case scenario of having highly reflective optical-grade surfaces.

In practice, however, many samples have a combination of well-reflecting interfaces and low-reflecting interfaces. As the result, the LCI signal contains a combination of peaks with vastly different amplitudes – some can be close to 100%, while others are just slightly above the noise.

For such samples, the probe selection and alignment are used as the tools for finding the best SNR configuration for all signal peaks. By selecting the right probe, and by properly aligning it with respect to the sample, it is possible to increase the strength of the low-amplitude peaks while maintaining the good quality (SNR>60%) of the high amplitude peaks.

The process of finding good quality peaks consists of these steps:

A. Start with the 50mm probe.

This probe offers the most versatile performance.

B. Tip-tilt alignment

Top-tilt angular probe alignment is used to orient the measurement beam perpendicularly to the sample interfaces.

For samples where interfaces are parallel to each other, changing angle of the measurement beam increases or decreases the amplitudes of all peaks. For sample where interfaces are not parallel to each other, the tip-tilt alignment offers opportunity to change the relative amplitudes of the signal peaks.

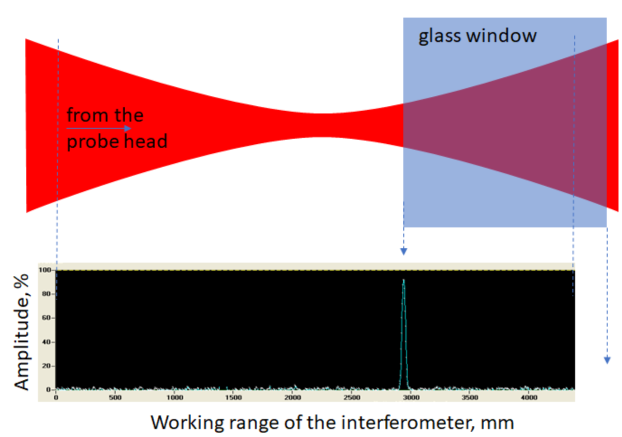

Figure 5: Schematic showing one of the reflecting surfaces of the glass window located outside of the interferometer working range. Compare to Figure 4 – signal peak for only one surface is visible in the software graph.

C. Probe-sample distance

Changing probe-sample distance means moving the location of the probe focus with respect to the interfaces. The interfaces located closer to the focus will result in more reflected light and therefore higher signal amplitude (according to the graph in Figure 4). The interfaces that are located further away from the focus result in lower collection efficiency of the reflected or scattered light.

In practical terms, changing the probe-sample distance means changing the relative amplitudes of the signal peaks.

The 50 mm probe has the smallest angular tolerance and therefore the largest working range. Therefore, changing the vertical position of the probe (i.e. changing the position of the focus with respect to the reflecting surface) may not be sufficient to obtain the good quality signal for all reflecting surfaces.

D. Switch to 25mm HNA probe

Opposite to the 50mm probe, the 25mm HNA probe, having the largest cone angle, results in a dramatic change in the signal amplitude as the probe is moved in the vertical direction. Use this probe for controlling signal peaks amplitudes by changing probe-sample distance.

E. Lateral sample alignment

In some cases, surface texture may add additional complexity to finding a good quality signal. In this case, move the sample laterally by small amounts (using micrometer-driven translation stage) to scan the measurement beam along the surface to evaluate the effects of the surface texture on the signal quality. Choose measurement location that increases the amplitude of the signal peaks.

F. Switch to 25mm probe

If using the 50mm and 25mm HNA probes does not result in the satisfactory signal quality, the 25mm probe offers a mid-way performance.

VII. Examples

The table below summarizes the typical samples and the corresponding probes that has been historically shown to be the most appropriate.

Examples	**Optimal probe**
Glass lens in air	50 mm
Polymer lens in air or liquid	50 mm
Polymer lens on a substrate	25 mm HNA
Single layer materials in air or liquid	50 mm
Silicon wafer (not doped)	50 mm
Silicon wafer (doped)	25 mm
Thick (>1 mm) multilayer materials	25 mm
Thin (< 1mm) multilayer materials	25mm HNA
Near-flat packaging	25 mm HNA

50mm probe can be used for any samples that contain:

- smooth surfaces,
- flat or curved,
- if curved, the measurements are taken at discreet points (do not require scanning)
- similar interfaces between materials (e.g. glass-air only, no glass-glass or glass-polymer)

25 mm HNA probe is used for samples that are:

- Near-flat (food packaging) but require scanning.
- Contain different material interfaces that result in strong and weak reflections (polymer lens resting on a wax substrate)
- Samples that are highly absorptive (silicon wafers with dopants)

The non-HNA 25 mm probe does not have a set of prescriptions that help identify it as the appropriate probe. It should be tested for given sample to assess the quality of the signal as compared to the other two probe types.

VIII. References

[1] M. R. Hee, "Optical coherence tomography: theory," in *Handbook of Optical Coherence*, New York, Marcel Dekker, 2002, pp. 41-66.

[2] S. Aumann, S. Donner, J. Fischer and F. Muller, "Optical Coherence Tomography (OCT): Principle and Technical Realization.," in *High Resolution Imaging in*

Microscopy and Ophthalmology., Cham, Springer, 2019, pp. 59-87.

[3] C. K. Hitzenberger, "Measurement of corneal thickness by low-coherence interferometry," *Applied Optics,* vol. 31, no. 31, pp. 6637-6642, 1992.

[4] V. G. Badami and T. Blalock, "Uncertainty evaluation of a fiber-based interferometer for the measurement of absolute dimensions," *Proceedings of SPIE,* p. 587903, 2005.

[5] F. Ignatovich, "WP-102 Angular tolerance for standard probes," Lumetrics, Inc, 2018.

[6] F. Ignatovich, "WP-103 Spot sizes for standard probes," Lumetrics, Inc, 2018.

[7] F. Ignatovich, "WP-104 Depth of focus for standard probes," Lumetrics, Inc, 2018.

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