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Fiber optic interferometry for industrial process monitoring and control applications

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ABSTRACT

Over the past few years we have been developing applications for a high-resolution (sub-micron accuracy) fiber optic coupled dual Michelson interferometer-based instrument. It is being utilized in a variety of applications including monitoring liquid layer thickness uniformity on coating hoppers, film base thickness uniformity measurement, digital camera focus assessment, optical cell path length assessment and imager and wafer surface profile mapping. The instrument includes both coherent and non-coherent light sources, custom application dependent optical probes and sample interfaces, a Michelson interferometer, custom electronics, a Pentium-based PC with data acquisition cards and LabWindows CVI or LabView based application specific software. This paper describes the development evolution of this instrument platform and applications highlighting robust instrument design, hardware, software, and user interfaces development. The talk concludes with a discussion of a new high-speed instrument configuration, which can be utilized for high speed surface profiling and as an on-line web thickness gauge.

Keywords: Low-coherence interferometry, fiber optic sensors, thickness, imager focus, surface profiling

1. BACKGROUND

This paper describes the design and development of a high-resolution (sub-micron accuracy) fiber optic coupled dual Michelson interferometer based instrument developed for use in a variety of process monitoring applications.[1-9.] Light from the non-coherent light source is sent to the sample under test through a single-mode fiber. Light reflected from the optical interfaces in the sample is sent into the interferometer and is used to determine sample dependent parameters, such as optical distances or sample thickness. The laser is used to monitor the distance, which the interferometer moves, and is used to trigger data acquisition of the non-coherent light interferometric data at constant distance intervals so that the calculated parameters are automatically calibrated by the instrument.

The measurement system includes both generic and application specific components. Generic components include the dual Michelson interferometer, interferometer control electronics, and Pentium computer with National Instruments data acquisition cards, LabWindows CVI and Visual Basic software for setting up and controlling the interferometer and quantitative interferometric peak locating analysis software. Application specific components include optical probes, optical multiplexers, sample and probe transport mechanisms, peak processing to provide sample information and user interfaces. Applications developed include measurement of film thickness profiles,[3-5] measurement of optical retardation in films,[6] measurement of liquid thickness distributions on coating hoppers,[1-2] optical cell path length calibration, digital camera imager focus assessment,[7-9] and surface profile measurements.

2. INSTRUMENT DESIGN AND PRINCIPLE OF OPERATION

Figure 1[1,2] shows a schematic of the instrument that includes a dual Michelson interferometer set up in an optical autocorrelation configuration. Light from a 1300-nm broadband light emitting diode (LED) is coupled into a single-mode optical fiber and passes through a 1 by 2 coupler. Light from the LED traveling in the single-mode optical fiber is focused onto the sample through an optical focusing probe, which includes a Gradient Index lens (GRIN) as the active focusing element. Some light is reflected off the front surface of the sample and some light reflects off each successive optical interface of the sample. All of these reflected light signals from the optical interfaces of the sample pass back through the optical focusing probe, are sent back down the same optical fiber, and introduced into the interferometer via a FC connector. The light from the sample is then collimated and sent to the beam splitter of the interferometer. A helium neon laser (HeNe) is also utilized to track the distance that the optical path of the interferometer changes as the optical head rotates.

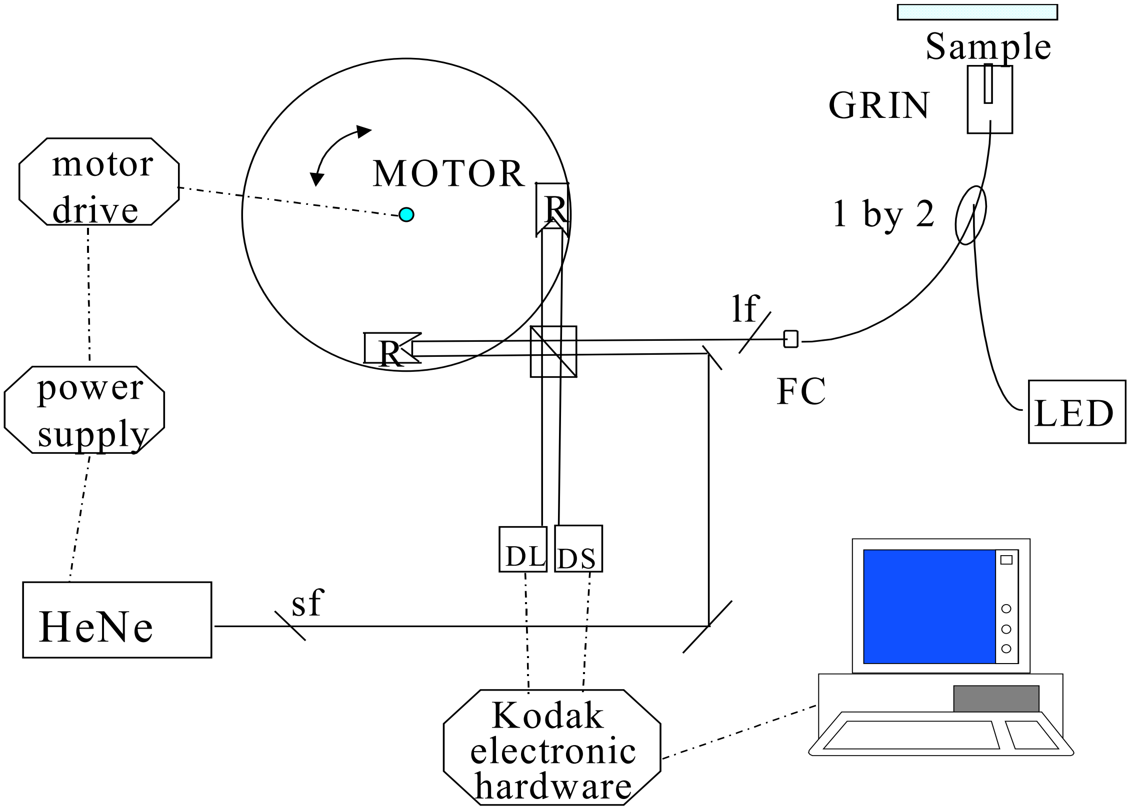


Figure 1. Low-coherence light interferometer schematic

These signals are introduced into the rotating head interferometer as the top beam on the right side of the beam splitter cube. The interferometer is set up in a bulk Michelson configuration. Solid lines in Figure 1 indicate the light paths. There is also a second light path for a HeNe reference beam ($\lambda_{HeNe} = 632.991 \pm 0.0005$ nm), which arrives at the beam splitter cube as the bottom beam on the right side. A pair of hollow-cube retroreflectors (R) are mounted 90^o apart on a ~87 mm diameter rotatable disc platform. The beam splitter cube divides the laser and LED beam into pairs of light beams directed toward the hollow retroreflectors. The hollow retroreflectors are pre-aligned to form the two reflective arms of the Michelson interferometer. Rotating the motor shaft causes the path length of one arm to increase while the path length of the other arm decreases by the same amount. A brushless DC motor attached to the center shaft of the platform and interfaced to the rotating element produces the rotation. The outputs of the interferometer go to a pair of detectors for the laser (DL) and the LED signal beam (DS). A band-pass filter (lf) is used to block the light from the laser from being incident on the sample. A second filter (sf) is used to prevent LED light, reflected from the sample, from entering the laser cavity. During operation, the rotating head motor is cycled continuously at a user-defined frequency and amplitude to alternately increase and decrease the optical path difference in the interferometer.

During the operation, light signals from both the laser and the sample light sources traverse the same optical path in the interferometer arms, but in reverse time order as they travel to and from the pair of retroreflectors. The stabilized HeNe laser interferometer is utilized to track the distance the optical path has changed during rotation of the optical head. The laser signal is utilized to provide data acquisition trigger signals, at constant distance intervals, for collecting interferometric data from the non-coherent light interferometer. Thus, the purpose of the laser interferometer is to track the distance the rotating optical head moves while the non-coherent light interferometer is collecting data from the sample.

For the non-coherent light source, constructive interference occurs when the pathlengths of the two arms in the interferometer are equal within a few coherence lengths. In order for constructive interference to occur, light must be reflected back into the interferometer from the sample. This will occur at each optical interface in the sample. The distance between adjacent interference peaks is the optical thickness (group index of refraction (n) times physical thickness) of the sample material. In air layers, the distance between the two adjacent surfaces is the thickness of the layer. Because the instrument uses a stabilized laser light source for providing constant distance interval measurements, the instrument measures absolute optical path distance defined as (n) times thickness.

The measurement configuration of the interferometer is the optical autocorrelation mode, in which light reflecting from the sample is input to both arms of the Michelson interferometer. In the autocorrelation mode, light reflecting from the sample is made to interfere with itself, and both arms of the interferometer see reflections from all of the optical interfaces in the sample (front and back surfaces of the web). As the path lengths of the two arms of the interferometer are changed, a series of interference peaks are observed, indicating the optical path differences between adjacent optical interfaces. The self-correlation condition occurs when the two path lengths of the Michelson interferometer are equal, in which case, all optical interfaces in the sample interfere constructively. The measured distance between the largest peak, at zero path length difference, and the first set of adjacent peaks is the shortest optical path difference in the sample (in our case, the optical thickness of the web).

Data acquisition and analysis is performed utilizing a Pentium computer and National Instrument data acquisition E series cards with a maximum data acquisition rate of about 1.25 MHz. The periodicity of the laser light is used to track distance that the non-coherent light interferometer moves. Because the laser light is coherent, zero crossings of the laser signal occur at every $\lambda/4$ of the laser wavelength. Kodak has designed and built custom electronics and Lab Windows CVI instrument control and developed data analysis routines[1-4,6] to analyze non-coherent light interferograms resulting from reflections at optical interfaces in the sample under investigation. The goal of the peak location analysis techniques is to find the true envelope center of an interferogram peak that to first approximation is a Gaussian times a cosine function. The peak location algorithms developed include moment calculations, Gaussian peak analysis and Fourier phase slope analysis[10,11]. They provide measurement repeatability better than 0.050 μm for samples with peak separations greater than 25 μm with a sampling interval of $3\lambda_{HeNe}/4$. Once the peak locations are calculated, the appropriate distances relevant to the measurements being performed must be computed. Distance calculations are based on acceptance ranges and thresholds.

3. ROBUST OPTICAL PROBE DEVELOPMENT

An angled fiber optic probe was developed as shown in Figure 2, which allows the user to disconnect the optical fiber cable connecting the instrument to the sample optical probe head. A Rifocs Diamond FC to Diamond APC-FC single-mode optical fiber is used with the FC side connected to the instrument and the APC-FC side and is attached to an angled FC receptacle (Rifocs DAK-13/FC). The APC-FC side has an 8^{o} cleave angle, which eliminates any back reflection from the fiber end that goes to the focusing GRIN lens. The APC-FC receptacle is attached to a mounting bracket with a 3.7^{o} offset angle onto a mount holding the GRIN lens. By rotating the optical fiber coupler 3.7^{o} clockwise, the output light exits normal to the plane of the GRIN lens. The entire assembly is placed into a 2 axis GIMBAL mount that allows varying the angles independently with respect to the x and y axes. Also shown in Figure 2 is a micrometer stage for adjusting the probe-to-sample spacing. This type of optical probe interface is used for on-line web and liquid layer thickness measurements, and for measuring web thickness offline. Figure 3 shows a schematic of an exact constraint design optical probe[12] with a custom chuck and a non-ferruled APC-FC connector on one end of the fiber cable. The probe is designed so that the APC-FC ferrule is centered in the chuck and that the light will come out parallel to the long axis of the chuck. The lens is inserted into a ridge from the other end of the chuck so that it will be at a known distance from the end of the APC-FC ferrule. The distance between the ferrule tip and the lens determines the focal length of the optical probe.

4. APPLICATIONS

A variety of process applications have been developed with the above interferometer configuration. We describe web thickness measurement for quality control, digital camera focus assessment and wafer and imager mapping here.

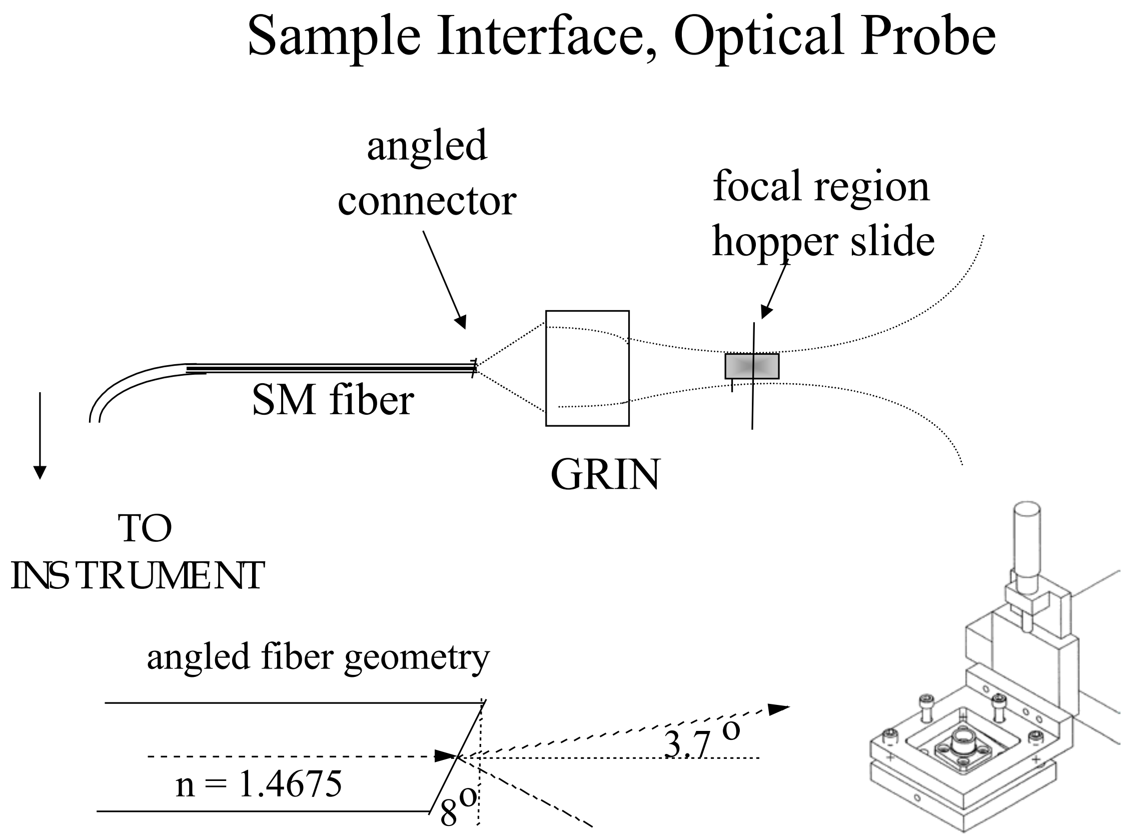


Figure 2. Optical probe schematic

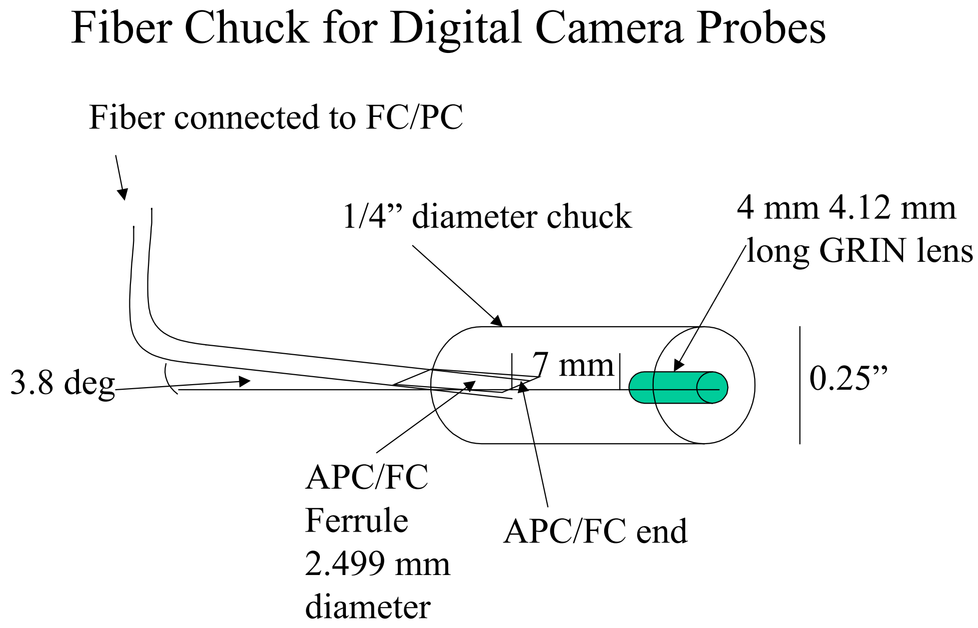
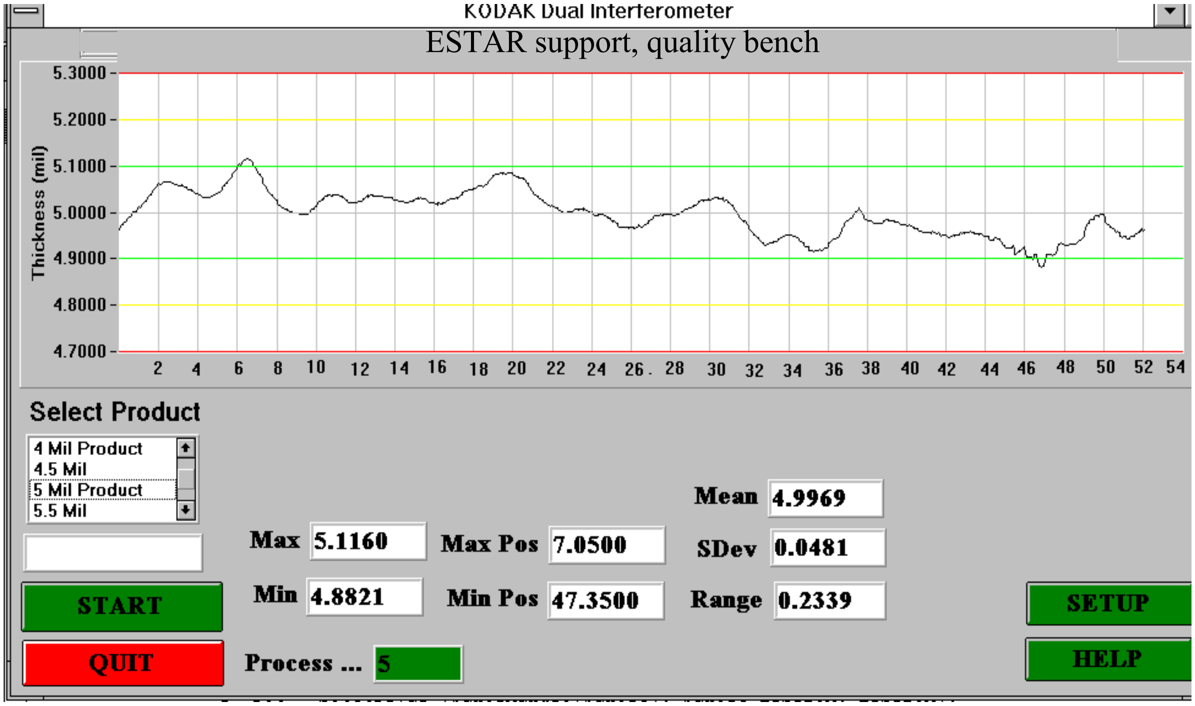


Figure 3. Fiber chuck for digital camera probe mounting

4.1. Measurement of Film Thickness Uniformity

The low coherence light interferometer has been adapted for use as an off-line assessment of widthwise thickness uniformity in polyester film manufacturing operations and is being used as a product certification tool[3-5]. A transport stage for moving 35-mm wide strips of film under an optical probe head at a constant rate was developed[3]. The optical probe uses the Gimbal Mount shown in Figure 2. A 3-mm diameter 0.11 pitch GRIN lens (NSG America Part # SLW 300 011 130 NCO) with a design focal length of 28.5 mm, angular acceptance cone of 0.85°, a depth of focus of 2.5 mm and a focused beam spot size of 47 mm is used. Figure 4 shows data obtained for a 35 mm strip of film sent through the transport stage moving at 2" across the measurement head. The interferometer motor scan rate is 10 Hz and data for both sides of the zero crossing are utilized to give 40 thickness measurements per second or a density of 20 points per inch. Before beginning the actual measurement, the operator uses a hand-held bar-code reader attached to the computer to scan a bar code supplied with the web. The PC uses this information to retrieve the desired measurement display parameters for the specific product code from its database. Over 200 different product codes are in the look up table database. The display automatically includes control limits for the product being tested. The setup screen is password protected and is used by product engineers to set up new product parameters. This instrument is being utilized as a tool to certify product release.



KODAK Dual Interferometer

ESTAR support, quality bench

Select Product

- 4 Mil Product
- 4.5 Mil
- 5 Mil Product
- 5.5 Mil

Max 5.1160

Min 4.8821

Max Pos 7.0500

Min Pos 47.3500

Mean 4.9969

SDev 0.0481

Range 0.2339

Process ... 5

Figure 4. Sample measurement screen for a web widthwise uniformity trace

4.2. Digital Camera Focus Assessment

In film-based 35 mm SLR cameras, the film rails determine the location of the film plane in the camera. In digital cameras, an accurate and repeatable method for determining the imager depth relative to the lens flange mount is needed in order to ensure that the digital imager is positioned at the proper focal depth. Focal position tolerances are about ±25 µm over the full dimensions of the imager. The measurement needs to be performed in a relatively short time interval in order to be utilized on a camera assembly production line. Since operators on the assembly floor will perform the measurement, it must be robust, easy to operate, and allow that camera certification occur based on the measurement results.

Optical probes have been developed that insert into the SLR camera's lens flange mounting ring, which enable accurate assessment of imager focus[8, 9,12]. Figure 5 shows two types of optical probes developed for this purpose that use the fiber chuck design of Figure 3. The optical probes include a reference optical flat surface near the end of the cylinder that is inserted into the camera body. The principle of the measurement[7] is summarized in Figure 6. The left side of Figure 6 shows the measurement relationships, while the right side shows a sample in the camera body interferogram along with the definitions of the relevant peak distances.

Figure 5. Optical probes for assessing imager focus in Canon EOS (left) and Nikon Pronea-based (right) camera bodies

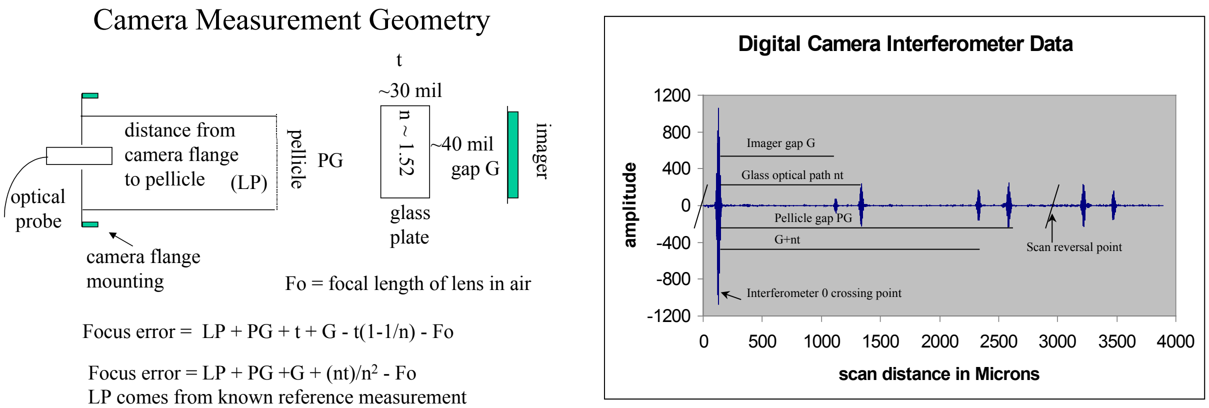


Figure 6. Focus assessment in the camera body measurement relationships (left) and sample interferogram (right)

The optical probes shown in Figure 5 have 5 measurement locations (Canon EOS) and 3 points (Nikon Pronea) respectively. In order to enable multi-point measurement capability an optical multiplexer is added between the interferometer and the optical probes. Multiple optical probes have been combined into a user-friendly measurement system enabling a variety of types of measurements to be made with a single interferometer. The program main menu screen allows the operator to select the type of measurement to be made and the camera model to be measured. Based on the selections, the multiplexer will automatically sequence to perform measurements with the appropriate optical probe and to perform the appropriate analysis for the selected measurement type.

During a measurement, the operator scans the barcode of the object being tested, inserts the probe or imager into the appropriate fixture, and presses start when ready. The interferometric measurement then proceeds and the appropriate calculations are performed based on the multiplexer positions and type of measurement indicated. Green lights are used to indicate that the measurement is OK (within specification limits), red lights are used to indicate that the measurement is out of specification and yellow lights indicate that the measurement may be out of specification if one of the other parameters is near a control limit. Numerical calculations of the values are shown underneath each of the measurement location colored indicators. The data is also automatically logged to a file using the camera barcode information as the file name. After the last probe position is measured, a measurement done indicator appears, and the operator can either measure the next camera as above or go back to the main menu screen.

In order to perform in camera focus assessment it is required to assemble the camera, operate the electronics and open up the shutter before inserting the optical probe into the camera body. When an out of focus condition occurs there is much rework needed and it is not known if the imager is improperly placed in the camera mounting plate or if the camera body has an out of specification lens flange mounting ring to film rail distance. As a result of this uncertainty two other types of measurements were developed, determining the film rail to lens flange mounting ring distance, and a die to plate measurement to assess the imager die to the camera mounting plate distance. Figure 7 describes the die to plate measurement system and shows the die to plate test fixture in use on the right.

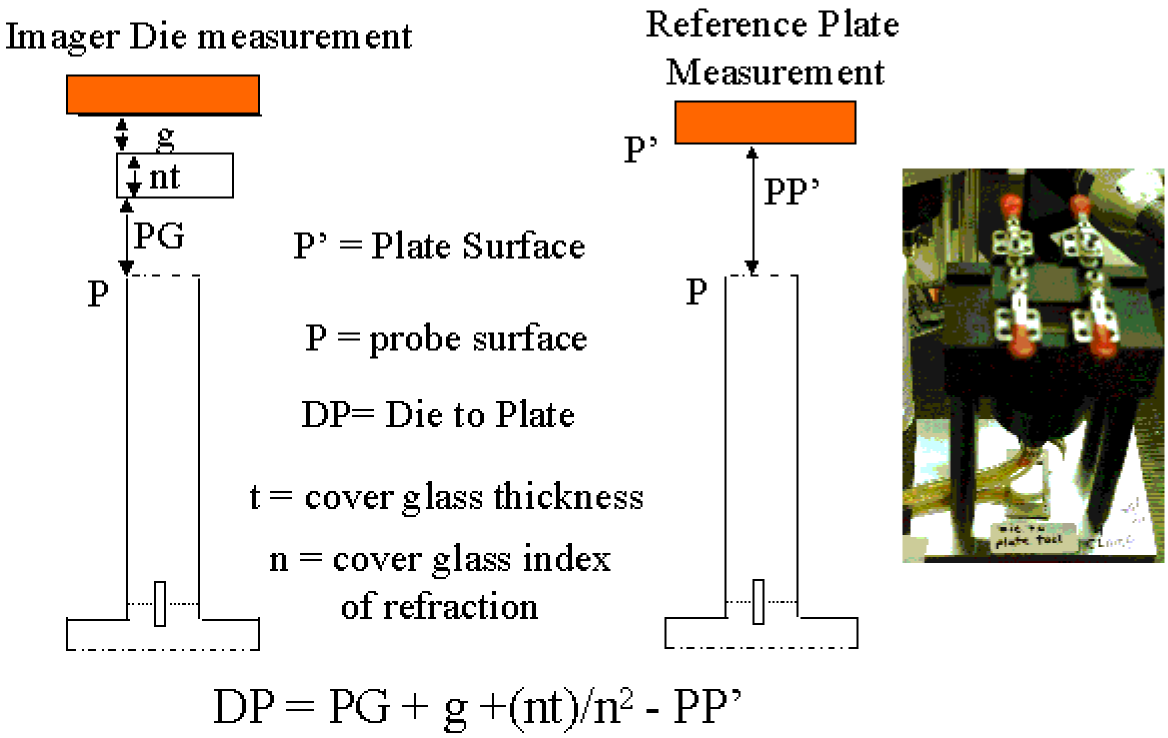


Figure 7. Die-to-plate measurement relationships (left) and test fixture (right)

The die-to-plate measurement fixture consists of an optical probe mounted into a camera body equivalent that includes the same imager mounting structure as the camera. During measurement, the camera mounting plate containing the imager is placed on the test fixture at the film rail equivalent facing down. A clamp table is placed on top of the imager mounting plate and contacts the imager at the locations that it is screwed into the camera body when mounted into a camera body. Toggle clamps are then tensioned to provide equivalent mounting pressure and to secure the imager and mounting plate in place. The fixture is calibrated by using a flat plate instead of the imager to calculate the value of PP'. The measurement repeatability of the die-to-plate distance using this fixture and the low-coherence light interferometer is better than 2 µm. Implementation of this new test has saved much testing time and has eliminated the normal in camera tests of focus.

4.3. Imager and Wafer Flatness Mapping

For this type of measurement an imager or wafer is placed in a measurement cell with an optical flat that is placed above the imager or wafer surface to be measured. The x-axis is scanned at 10 mm/sec with a 20 Hz measurement rate and the distance from the optical flat's flat surface to the imager or wafer surface is measured. At the end of a scan line 500-µm steps in the y-axis are taken. The output of the program is then analyzed with software developed in a Matlab platform. It presently takes about 20 minutes to perform a surface profile map of a 2" square imager, and example of which is shown in Figure 8.

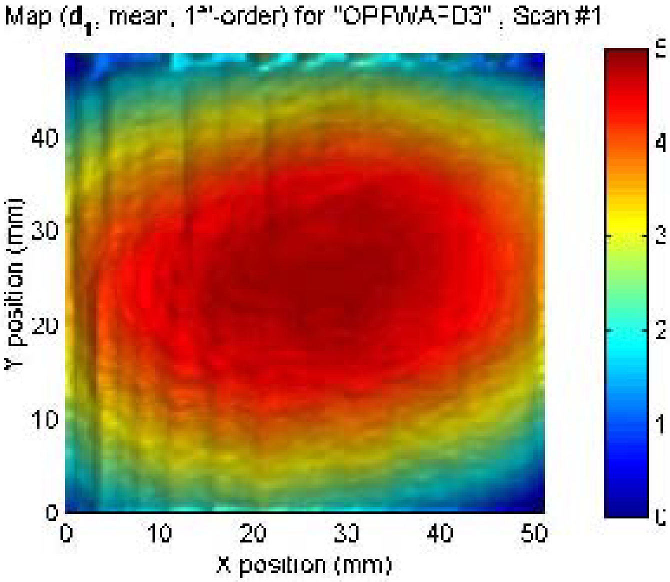


Figure 8. Flatness map for a 2" square imager

5. High Speed Measurement Platform

A high speed all fiber dual interferometer platform has been developed by a collaborative effort between Eastman Kodak Company and Optiphase, Inc[13]. A schematic of the instrument is shown in Figure 9. The measurement system utilizes long lengths of fibers wrapped around piezoelectric PZT cylinders to change the pathlengths of the two arms of the interferometer. A 1550 nm fiber Bragg grating stabilized diode laser with less than 5 ppm drift is being utilized as the coherent light source. Data acquisition is being performed utilizing a National Instruments PCI-6111 5 MHz, 12 bit A-D converter board. A 500 MHz Pentium III computer is being used as the processor operating in a Labview 6.0 environment with a Windows nt operating system. The low coherence light source is a 55 nm bandwidth ELED centered about 1310. Up to a 2.5 kHz measurement rate has been demonstrated utilizing $\lambda/4$ sampling intervals. Measured performance is similar to that obtained with the instrument based on the bulk Michelson interferometer shown in Figure 1.

4. Summary

A high-resolution low-coherence light interferometer has been developed, which uses a second laser interferometer to track path length changes in the low-coherence interferometer and to provide constant distance sampling intervals. Robust fiber optic probes have been developed that enables using this instrument in a variety of process measurement applications. The instrument utility has been demonstrated using examples of the measurement of, web thickness uniformity, the assessment of imager focus in digital cameras and imager and wafer mapping. A high speed platform utilizing an all fiber dual interferometer is under development which will allow data to be collected and analyzed up to 150 times faster than the bulk Michelson dual interferometer.

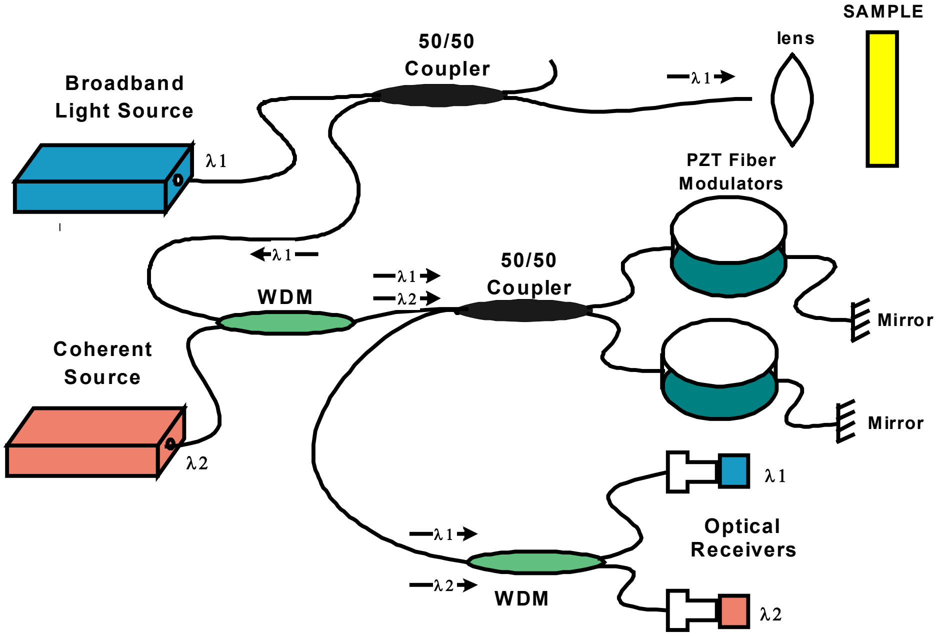


Figure 9. Schematic of a high speed interferometric measurement platform

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