Low Coherence Interferometry for the Inline Measurement of Translucent Multilayer Structures

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Abstract

In a joint national project with industrial partners in the sectors of sensor technology, mechanical engineering and plastic film production, the Fraunhofer Institute for Laser Technology (ILT) has developed a novel optical sensor to monitor the production of plastic films based on interferometric measurements with low coherent radiation [1]. This technique of Optical Coherence Tomography (OCT) is an imaging method generating high-resolution tomography scans. The sensor measures the thicknesses of single layers in multilayer films allowing for the first time inline process monitoring and efficient process guiding of flat-film and blow-film extrusion lines.

Multilayer plastic films

Today's plastic films are high-tech products specially engineered to exhibit specific properties In the food sector, in particular, ever greater requirements are being placed on plastic packaging [2-4]. Here, the trend is moving towards packaging that prolongs the shelf-life of fresh products and offers enhanced functionality. The fact that packaging films are expected to meet increasingly sophisticated requirements is technically reflected in the growing complexity of layer structures and a greater number of functional layers per film.

The application of inline measurement and control systems to determine total film thickness is already standard. However, there are currently no film inspection systems on the market that can measure the layer structure of multilayer films and the individual layer thicknesses during the production process with micrometer accuracy over a thickness range of several millimeters.

However, the task to measure the thicknesses of single layers is of high economical interest. Functional plastics are often made out of expensive materials, including plastics like ethylene vinyl alcohol (EVOH) or polyamide (PA). By acting as a diffusion barrier for oxygen and water vapor, EVOH ensures that food can be preserved longer. Due to their high price, plastics processors are striving to keep the proportion of these raw materials in the product to an absolute minimum, while retaining full functionality.

State-of-the-art sensors for thickness measurements of plastic films

Capacitive measurement systems are standard equipment for measuring thickness on cast- and blown-film plant installations. An open capacitor is used as a sensor, with its narrow insulated metallic core embedded in a larger metallic surface. If the sensor is held against a plastic film, the associated field lines run through the material under analysis, which in turn acts as a dielectric in the capacitor field. Any change in film thickness leads to a measurable change in the electric field. This capacitive measurement method can be used to measure relative changes in thickness with 0.1 µm precision within measuring ranges of up to several 100 µm [5, 6]. Capacitive sensors, however, can only determine the overall thickness of the film. The sensor electrode also makes direct contact with the film surface, causing scratch marks unless special mounting devices keep the sensor at a constant distance from the film.

Infrared spectroscopic processes utilize the fact that different plastics exhibit characteristic absorption lines at different wavelengths. Light of a defined wavelength from an infrared emitter is directed onto the film to be measured in order to determine the layer thickness. If the plastic layer absorbs the light at the input wavelength, then the residual intensity that can be measured on the back of the film varies as a function of the thickness of the transilluminated material. Typically, layer thicknesses from 10 µm to some millimeters can be measured [7]. One major drawback of this kind of setup is that the sensors can only detect a single thickness value, even when analyzing a film made up of multiple individual layers of the same material. Data on individual layer thicknesses can therefore only be obtained for simple systems in special cases. Compared to capacitive sensors the spatial separation of the infrared-radiation emitter and receiver makes it much more difficult to perform inline measurements.

Optical Coherence Tomography for industrial applications

Fraunhofer ILT has developed an optical sensor based on interferometry with low coherent radiation to measure single thicknesses of multilayer structures. Optical Coherence Tomography (OCT) is an imaging method to generate high-resolution tomography scans [8, 9]. As can be seen in Fig. 1, OCT is a recognized medical imaging method especially in clinical diagnostics of ophthalmic diseases for more than ten years.

However, the transfer of this measurement method to other fields, in particular industrial applications, was not in the focus up to now. In comparison to medical publications the activities in the subject areas like “Automation & Control” or “Polymer Science” outlined in Fig. 2 are currently negligible. However, OCT offers the potential for significant applications in industry. With regard to the measuring task in plastic processing stated above, ILT has designed an OCT sensor especially for this industrial application.

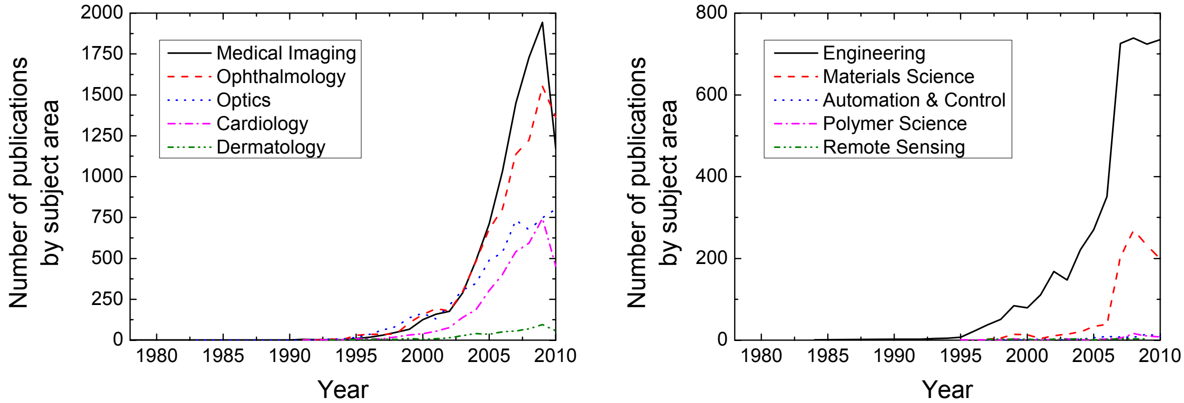
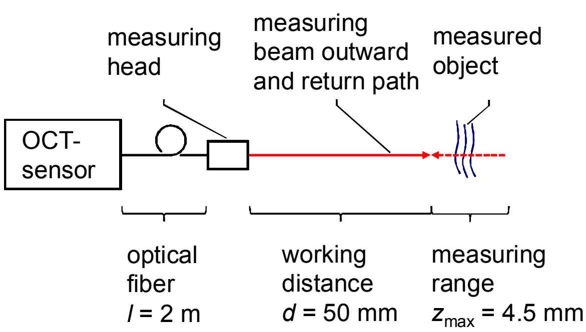


Fig. 1, 2: Publications in the field of “Coherence Tomography” by selected subject areas, multiple subject areas per publication possible (ISI Web of Knowledge, Thomson Reuters, May 2011)

The chosen method, known as Frequency Domain-OCT (FD-OCT) [8, 9], utilizes a superluminescent diode (SLD) emitting low-coherent light in the near-infrared range to optically measure individual layer thicknesses. The SLD spectrum follows a normal distribution with a center wavelength of $\lambda_0 = 860$ nm and a spectral bandwidth of $\Delta\lambda_{FWHM} = 50$ nm, the total emission power is $P = 5$ mW.



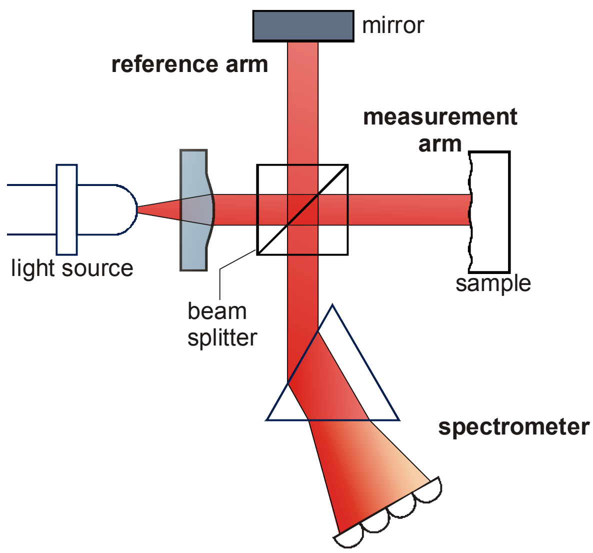


Fig. 3: Measurement set-up

Fig. 4: Principle of a Frequency Domain-OCT

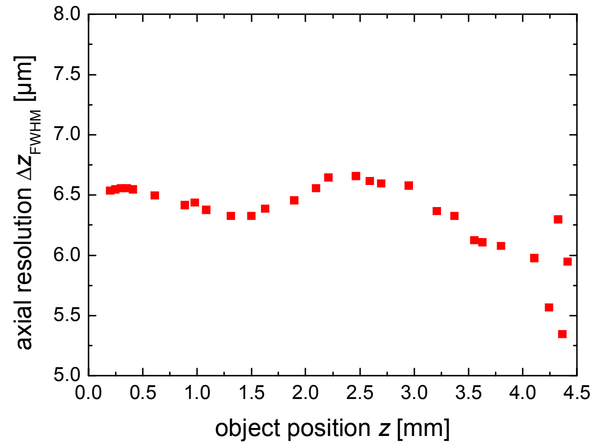
Fig. 3 shows a schematic of the measurement setup. An optical fiber and a compact measuring head focus the measurement radiation onto the film from a distance of a few centimeters. The light reflected from the measured object propagates backward to the sensor along the same path. Inside the sensor, this light interferes with radiation from the reference arm as illustrated in Fig. 4. The interference signal of the OCT sensor is detected by a spectrometer. A Fourier-Transform of the detected spectrum yields the depth structure of the sample measured. The OCT sensor performs these depth scans, called A-scans, at each measurement point of the film surface. Within its measuring range the sensor detects changes in the refractive index, such as the transition from air ($n = 1.0$) to the first film layer ($n \approx 1.5$).

By scanning the object laterally, the recorded A-scans can be combined to two-dimensional depth profiles (B-Scans) or three-dimensional tomograms (C-Scans). The expected measuring range of the setup is $z_{max} = 4.5$ mm with an axial resolution of $\Delta z_{FWHM} = 6.5$ µm. Typically, the signal at the boundary between two layers is relatively small, but thanks to the sensor's dynamic range of six orders of magnitude, even smallest changes in the refractive index are sufficient to detect the layer boundaries reliably.

Characterization of the OCT sensor

Measurement range and axial resolution of OCT systems are specified by manufacturers, however key metrological characteristics like linearity and temporal repeatability of OCT sensors for medical usage are often not declared. Because these specifications are essential for industrial applications, we have quantified these for the developed OCT sensor according to the standard for opto-electronic measurements [10]. Two high-reflectivity mirrors were placed in the measurement arm, of which one was displaced for the characterization procedure and the other was used as a reference signal to compensate thermal effects in the optical fiber. Experiments were performed with exposure time $t_e = 10$ µs and test frequency $f = 2$ kHz at a working distance of $d = 50$ mm.

Matching the theoretical values of the design, the measurement range amounts to $z_{max} = 4.5$ mm with an optical resolution of $\Delta z_{FWHM} = (6.5 \pm 0.2)$ µm, that is shown in Fig. 5. Consequently, the sensor has a measurement range to resolution ratio (MRR) of 690 :1, which is higher than the MRR of commercially available OCT devices. Without any kind of averaging the highest dynamic range of SNR = 61.0 dB is reached within the first millimeter of the measurement range, see Fig. 6. The signal roll-off amounts to -8.2 dB/mm, which is a consequence of the modulation transfer function (MTF) of the spectrometer set-up.



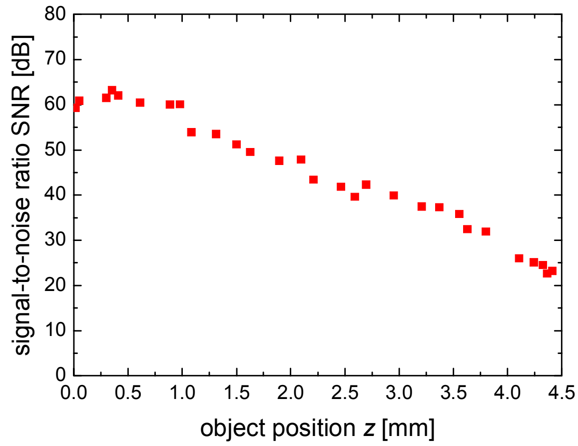
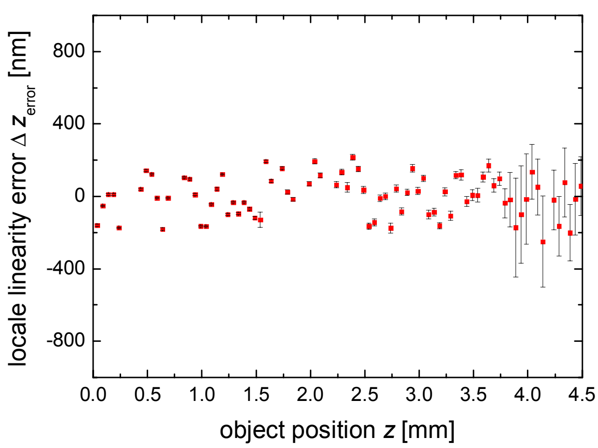


Fig. 5: Axial resolution of the OCT sensor as a function of the object position

Fig. 6: Dynamic range of the OCT sensor as a function of the object position

The measured linearity error is Δz_{error} = 0.25 µm corresponding to 0.006 % of the measurement range, Fig. 7. Compared to optical distance sensors such as laser triangulation, confocal or chromatic sensors a relative linearity error of less than 0.01 % is achieved for the first time. At the same time the temporal repeatability is better than <*s*> = 280 nm, even better than <*s*> = 50 nm within the first *z* = 3.5 mm as shown in Fig. 8.



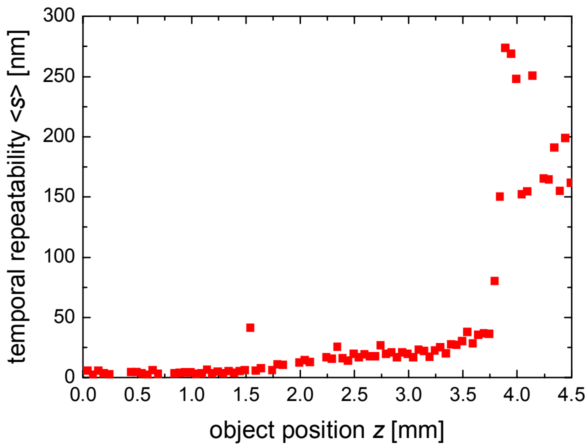


Fig. 7: Linearity error of the OCT sensor as a function of the object position

Fig. 8: Temporal repeatability of the OCT sensor as a function of the object position

The measurement of a single layer results in two signal peaks caused by the boundaries at both the front and the back side of a layer. The optical distance is calculated initially from the positions of the two signal peaks. Out of this value the geometric layer thickness is determined with the aid of the refractive index of the plastic. The refractive indices are measured in accordance with established standards [11].

OCT sensor for thickness measurements of single layers in multilayer films

In comparison to state-of-the-art plastic film thickness measurements, the OCT sensor is unidirectional and contactless. It can be used to measure multilayer systems where two or more individual layers are made out of the same material. In Fig. 9 a three-layer film with materials in the sequence 1 / 2 / 1 is illustrated. Fig. 10 shows the result of measurements on such a film, where material 1 is low density polyethylene (PE-LD) and material 2 is ethylene vinyl alcohol (EVOH). The thicknesses of the two PE-LD-layers can be measured separately and the OCT sensor provides three thickness measurement values.

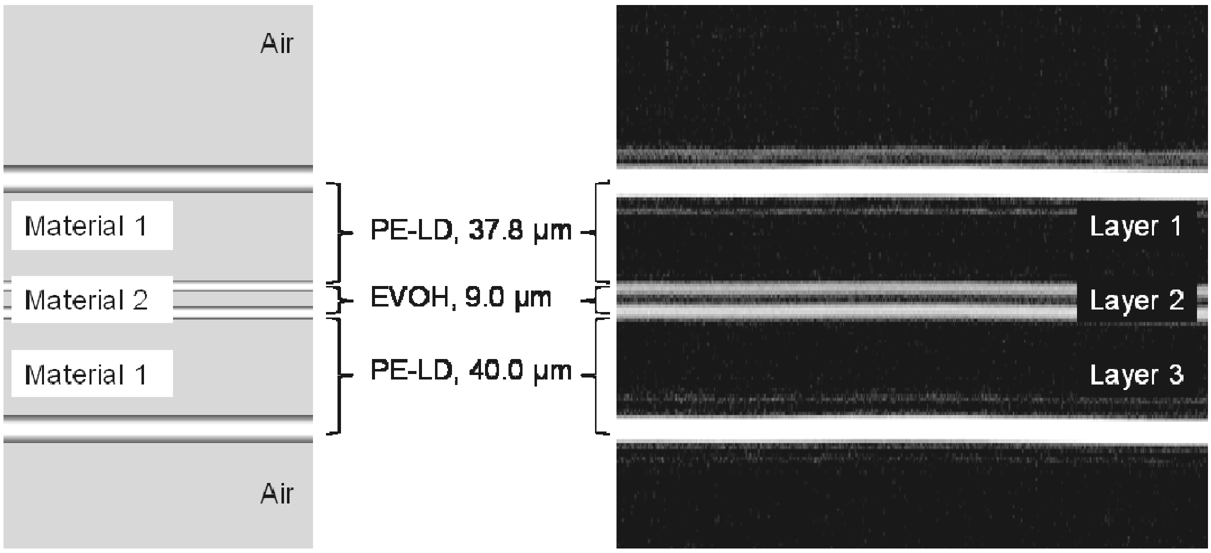


Fig. 9: Structure of a multilayer plastic film

Fig. 10: 1000 A-Scans of a multilayer plastic film measured with the OCT sensor

Guaranteeing an optimum barrier effect at all times requires constant monitoring to ensure that the functional layers are entirely intact and sufficiently thick. With the developed OCT sensor individual layers of a flat-film or blow-film extrusion line can therefore be measured directly during production. The high measurement frequency in the kilohertz range facilitates detailed high-resolution measurement of the layer structure along the multilayer film.

Summary

Fraunhofer ILT has developed an optical sensor to monitor the production of multilayer plastic films. Laboratory measurements on static samples have demonstrated that both the total thickness and the thicknesses of single layers can be measured with the OCT sensor. At present, the minimum measurable single layer thickness is ≥ 6.5 µm within a measurement range of 4.5 mm.

Outlook

In the next step, the OCT sensor will be integrated into a blow-film extrusion line at the plastic film manufacturer A+C-Plastic, in Eschweiler, Germany. Of interest is the ability of the OCT sensor to withstand harsh environmental conditions, in particular high temperature variations. Determining plastic layer combinations that can be measured inline is also the topic of further work.

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