

Optical Instrument for Thickness Measurement

Alessandro Pesatori
Dipartimento di Elettronica,
Informazione e Bioingegneria
Politecnico di Milano
Milano, Italy

<https://orcid.org/0000-0002-6751-5709>

Michele Norgia
Dipartimento di Elettronica,
Informazione e Bioingegneria
Politecnico di Milano
Milano, Italy

<https://orcid.org/0000-0002-6751-5709>

Federico Cavedo
Dipartimento di Elettronica,
Informazione e Bioingegneria
Politecnico di Milano
Milano, Italy
federico.cavedo@polimi.it

Abstract— In modern metrology it is increasingly common to find the importance of thickness measurements in the production processes of compact materials (metals, plastics, paper, rubber, etc.). A quick and timely measurement is indispensable in those automated industrial processes capable of modifying the production parameters in real time in order to have the characteristics exactly suitable for the needs. The idea of the development of this kind of instrumentation it is starting from this. The requirements that the system will have to respect, including the importance of having a meter that must not be in contact with the plastic film and that can only be positioned on one side of it. These restrictions require the choice of a measurement methodology to be sought mainly in the optical field.

Keywords—*Optical interferometry, Thickness measurement, Optical coherence tomography, Plastics industry*

I. INTRODUCTION

As part of the measurement of physical quantities such as thicknesses (Fig.1), it is necessary to acquire measurements with micrometers order of accuracy, thus encountering a series of problems that are often difficult to overcome. Modern market needs, in fact, require that measurements be taken quickly, without repeated calibrations and, if possible, without touching physically the product.



Fig. 1. Typical industrial setup of a plastic sheet plant.

There are many different methods to measure the thickness, here are briefly resumed:

A. Capacitive method

The most commonly used method is the capacitive type [1]. It exploits the variations in capacitance or induced currents (impedance) caused by the presence of the sample under examination within a suitably created field, for example the dispersion field of a capacitor. The film influences the strength of the electric field with each variation of its thickness. This variation is received and retransmitted as a thickness value. This technology guarantees precision of 0.1-0.01 μm , but has the disadvantage of being rather expensive and, above all, of requiring a specific calibration for each material to be measured, as well as being particularly sensitive to the vibrations of the plastic film. Another big issue is the fact that the capacitive head used to make the measurement, is getting worn by the passage of the plastic film during the measurement and it has to be replaced after some month of usage.

B. Ultrasonic method

Another widely used method is the one that uses ultrasound waves reading their reflections due to refraction index variations [2-3]. Their interesting use consists in accurately measuring the time that elapses between the emission of the ultrasonic pulse and the instant of return of the reflected echo. When the sound signal is directed towards a sheet, a part of the signal is reflected from the external surface while a part manages to penetrate the material until it meets the back surface, where it is also partly reflected. The transducer, after the emission of the impulse, carries out the function of receiver and converts the echo signals into electrical signals that can be easily acquired. The time measured between the emission of the impulse and the reception of the first echo is proportional to the distance between the probe and the external surface of the material. The time measured between the first echo and the second echo is instead proportional to the thickness of the material crossed by the signal.

However, this technique is not applicable to the measurement system in question since the distance between the receiver and the plastic film, constantly subjected to vibrations, does not remain constant. Furthermore, it is necessary to know for each material the speed of sound propagation to calibrate the instrument.

C. Absorption method

The absorption measurement allows to obtain the thickness of the plastic films knowing the specific absorption coefficient of the material and measuring the ratio between the incident intensity and that transmitted by the material [4]. Despite its simplicity it has not been possible to apply this technique since it is necessary that the light source and the photodetector are positioned on the two sides of the measurand. Due to the bubble shape of the plastic film it was not possible to exploit a configuration based on mirrors so as to be able to position the source and the detector on the same side of the object of measurement.

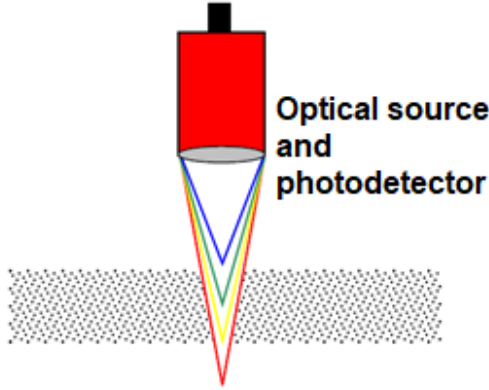


Fig. 2. Confocal chromatic dispersion setup

D. Optical confocal method

The confocal chromatic dispersion, instead, exploits broad-spectrum sources; an appropriate optical focuses the different wavelengths at different distances along the focal axis [4]. In this way, only the peaks corresponding to the wavelengths that have the focal point at the air-plastic and plastic-air interfaces are detected, as shown in Fig. 2. From the difference in wavelength it is possible to derive the difference between the two foci that corresponds to the thickness of the film. This technique allows to have source and detector on the same side of the plastic film, but the low intensity with which the beam focused on the second interface reaches the photodetector does not allow to distinguish the signal from the noise of the measurement system.

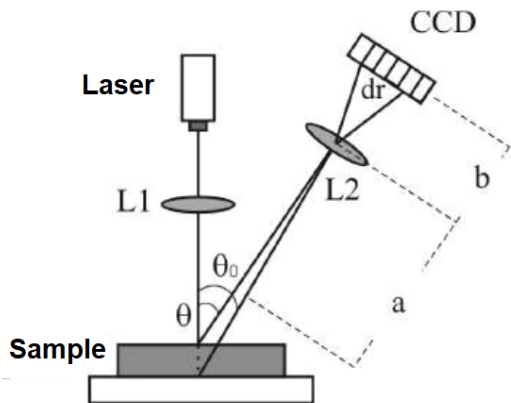


Fig. 3. Laser triangulation

E. Laser triangulation method

Laser triangulation [4] focuses a laser beam on the film and a lens diverges the reflected rays from the two interfaces on different points of the photodetector, as shown in Fig. 3. Given the geometry of the system it is possible to derive the relationship that links the thickness of the film under examination with the distance between the rays incident on the photodetector. Despite the simplicity of the system, this technique has been discarded since the absorption of the materials to be measured requires the use of infrared sources, a region in which the CCD detectors available on the market do not have satisfactory performance.

F. Incident angle variation method

Incident angle variation interferometry [4] uses instead a monochromatic source whose orientation towards the film surface is continuously changed in order to obtain interference figures from which to extrapolate the information on the thickness as shown in Fig. 4. However, preliminary experimental measurements have shown an excessive sensitivity of this technique to the transparency of the sample to be measured, making it impossible to measure some opaque and colored samples.

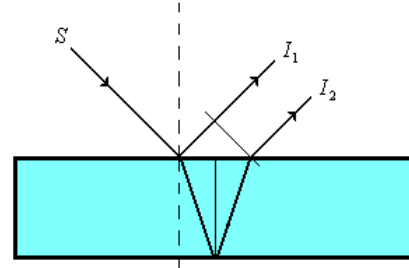


Fig. 4. Reflected beams in thin sheet

G. Low coherence method

Low coherence interferometry [4-10] does not present the problems that degrade the interference figures of the two previous techniques; this makes it possible to carry out measurements on every type of sample, both transparent and colored and also on multilayer ones.

If two wavelengths λ_1 and λ_2 are considered close to each other, the phase difference between them after traveling a distance L will be equal to:

$$\Delta\phi = \frac{2\pi}{\lambda_1}L - \frac{2\pi}{\lambda_2}L = 2\pi \cdot L \cdot \frac{\lambda_1 - \lambda_2}{\lambda_1\lambda_2} \simeq 2\pi \cdot L \cdot \frac{\Delta\lambda}{\lambda_0^2} \quad (1)$$

where $\Delta\lambda$ is the difference between the wavelengths and $\lambda_0 = (\lambda_1 + \lambda_2) / 2$. In general, the sources with extended spectrum from $\lambda_0 - \Delta\lambda/2$ to $\lambda_0 + \Delta\lambda/2$ are characterized by the coherence length:

$$L_c = \frac{\Delta\phi \lambda_0^2}{2\pi \Delta\lambda} \quad (2)$$

defined as the distance from the central fringe to which the introduced phase shift $\Delta\phi$ determines an intensity of the envelope of the established interference figure. In general, the shape of the interference figure depends on the spectrum of the source used and for sources with the Gaussian spectrum there is an envelope of the gaussian interference, as shown in

Fig. 5. By convention [8, 9] these sources have a coherence length of:

$$L_C = \frac{2 \ln(2)}{\pi} \left(\frac{\lambda_0^2}{\Delta \lambda} \right) = 0.441 \left(\frac{\lambda_0^2}{\Delta \lambda} \right) \quad (3)$$

The coherence length gives the order of magnitude of the maximum difference between the optical paths of the reference branches and the measurement of an interferometer in a Michelson within which interference is observed.

Figure 5 shows the intensity as a function of time at the receiver of the output branch of a Michelson interferometer when a source with coherence length L_C is used to measure the thickness d of a plastic film with refractive index n . As you can see the low coherence of the source allows the interference figures due to the two reflections of the measurand do not overlap and it is therefore possible to measure the delay between the central fringes that coincide with the maxima of the two Gaussian envelopes. The measure of the delay between the maxima of the Gaussian envelopes allows to obtain the thickness of the plastic films through equation 2.28:

$$d = \frac{v}{n} \bar{t} \quad (4)$$

In principle the spatial resolution of the device is equal to the coherence length of the source used. In fact, if the thickness of the plastic film were lower than L_C the interference figures corresponding to the two interfaces would overlap, making the measurement difficult. In reality the resolution is smaller, in fact, the exponential envelope of the interference figures decays very quickly, making the maxima distinguishable from the rest of the signal and as long as the maxima of the two interference figures are distinct it is possible to carry out the measurement.

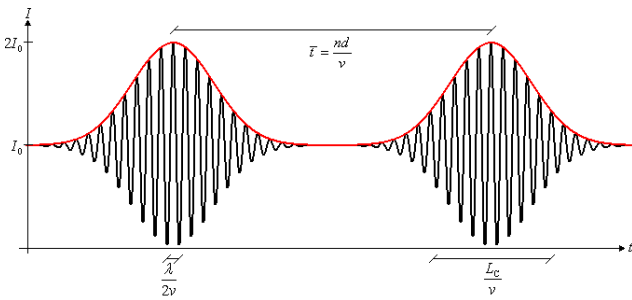


Fig. 5. Plastic colored film transmittance of different thickness.

The L_C coherence length, defined in equation (3), is however used de facto as a standard to give the order of magnitude of the resolution obtainable with a given source in interferometric systems.

The number of fringes (Fig. 6) contained in the envelope can be calculated knowing the central wavelength λ_0 and the L_C coherence length:

$$N = 2 \frac{L_C}{\lambda_0} \quad (5)$$

This information will be used to quantify the frequency of the envelope and will therefore allow the size of the envelope detector downstream of the photodetector.

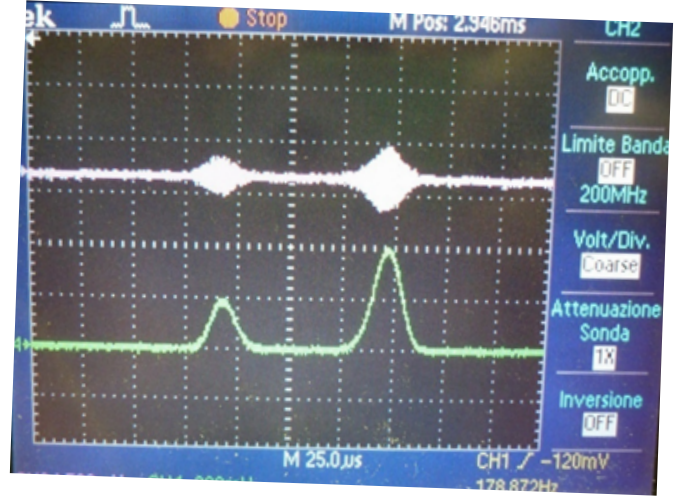


Fig. 6. Reflected signal read by interferometer due to refraction index variation of the plastic film.

II. SYSTEM OF MEASUREMENT SETUP

Figure 7 shows the complete scheme of the system. The source was a superluminescent laser diode (SLED) EXALOS model 1320-2111 of 20 mW with the related control electronics. Note the fiber optic output that allows direct interfacing with the interferometric system via FC/APC connectors. The classical configuration of a Michelson interferometer uses a beam splitter to equally separate the beam coming from the source in the reference arm and the measurement arm. The beam splitter also recombines the beams coming from the two paths so that the resultant in turn divides equally between the optical output and the source. The simplicity of this configuration is paid with the loss of most of the useful signal: only 25% of the power generated contributes to generating the useful signal.

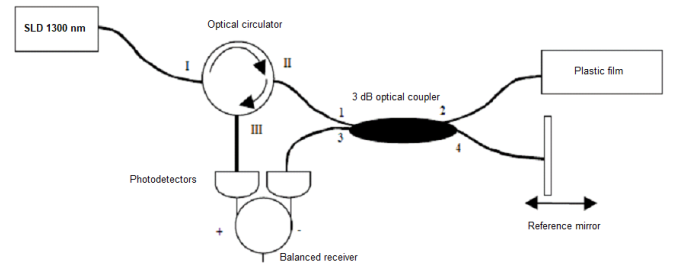


Fig. 7. Setup of the low coherence interferometer

The fact that a part of the optical power returns to the source does not only imply a decrease in the performance of the system, but also represents a potential risk for the functioning of the super-luminescent diode. The return of optical power to the SLED, in fact, can trigger LASER action in cavities and this would considerably reduce the life time of the device. To overcome both these problems a Michelson interferometer in fiber is used, in the so-called power conservation configuration where the splitter element of the bundle consists of a 2x2 coupler. The model utilized is the module INT-MSI-1300 produced by THORLABS. The

Michelson interferometer whose measurement and reference branches are in fiber and two fiber stretchers to modulate the length of the optical paths so as to perform a spatial scan along the axis of the measurement branch without having to physically move the mirror of the reference branch. In order to have a quite wide range of measurement, we used two OPTIPAHSE PZ2 – High-efficiency Fiber Stretcher, with an elongation factor of $3.8 \mu\text{m}/\text{V}$, powered between $\pm 260 \text{ V}$ for a $\sim 2 \text{ mm}$ of range measurement. They are controlled by two triangular waves in high voltage counterphase. To improve the measurement, polarization controllers have been inserted in the two branches in order to obtain the maximum output signal from the system. While the reference arm ends with a fixed fiber mirror, the measurement branch has an appropriate optic for collimating and focusing the beam towards the measurand. The signal from the interferometric system is suitably filtered by an envelope detector before being acquired and processed by a PC through a LabVIEW program written specifically for this project.

III. PLASTIC FILM CHARACTERIZATION

In order to test the performances of the designed prototype the industrial partner has provided some transparent and colored plastic samples on which transmittance measurements have been carried out for different wavelengths of the incident radiation. This allowed us to better characterize the samples themselves and to study their optical properties. Moreover, on the basis of the results of this analysis the central wavelength of the low coherence source spectrum was chosen. The following figures show the graphs related to these measurements for each sample supplied. For the sake of simplicity, the transparent samples were named with the letter T and the colored ones with the letter C; the nominal thickness is also indicated.

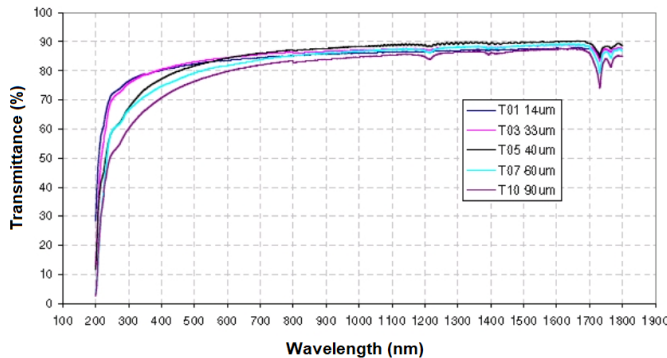


Fig. 8. Different thickness plastic transparent film transmittance

As can be seen from Figure 8, transparent samples have similar behaviors and in the visible spectrum (400 nm – 700 nm) absorb less than in the near infrared. For ultraviolet radiation with wavelengths inferior to 400 nm the transmittance decreases and the samples become completely opaque for wavelengths less than 200 nm. In the infrared, instead, the transmittance increases and for all the samples for wavelengths over 1000 nm values between 85% and 90% are obtained.

The colored samples instead do not offer unambiguous answers and the behaviors vary a lot between them because of the different types of dyes used that greatly influence the absorption coefficient of the films as can be seen in Fig. 9. It is not possible to choose a wavelength for which the transmittance is satisfactory for all samples.

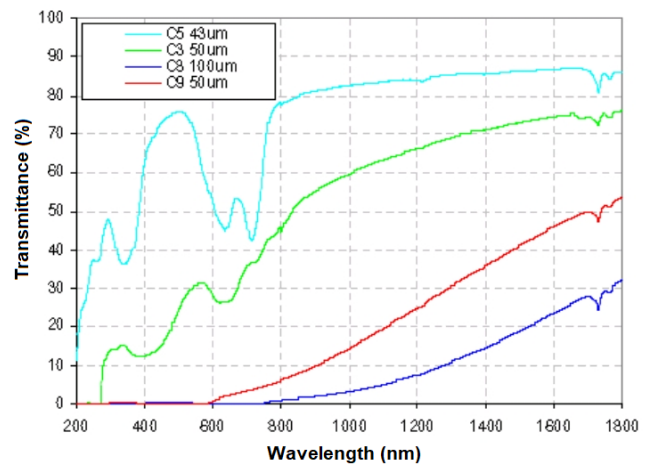


Fig. 9. Different thickness plastic colored film transmittance.

Looking at Fig. 10 which represents the measurements relating to the samples C1, C4 and C7 it can be seen that their transmittance is practically zero for wavelengths lower than 1000 nm while it increases (even if only slightly) at wavelengths larger. These results allowed to establish a minimum threshold for the central wavelength of the low coherence source in order to obtain at least a minimum of transmittance for the samples taken into consideration.

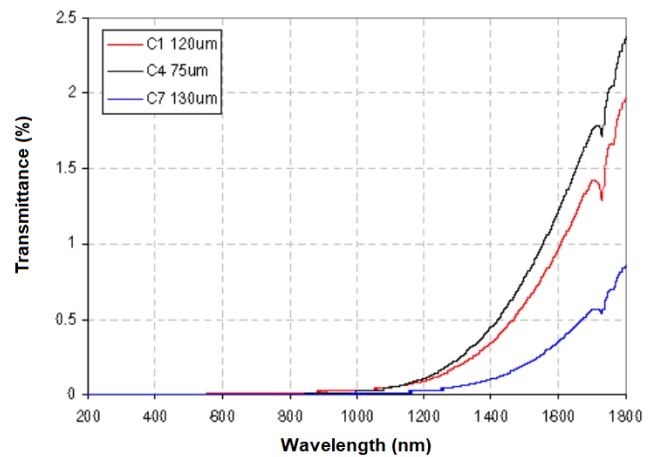


Fig. 10. Plastic colored film transmittance

IV. MEASUREMENTS

The colored samples instead do not offer unambiguous Laboratory measurements were initially performed on transparent samples. After having stretched them thanks to special supports, measurements were taken in 5 different points of the film and mean and variance were obtained. In the following figures the results of these measurements are shown. The gray signals represent the individual measurements, the red one represents the average of the 5 measurements and the blue dotted line represents the nominal value of the sample thickness provided by the manufacturer. The producer in providing the nominal values of the samples specified that these are only references and the actual thickness can vary up to 5% even between points of the same sample. The averages of the measurements as can be seen from figures 11 to 13 are all between 1 and 5% of the nominal value. The sample material PE-TI-EVOH-TL-PE is the lightest and therefore, although it is not the thinnest, it has proved to be the most sensitive to air currents and therefore its

relative variance was found to be the greatest among the samples examined.

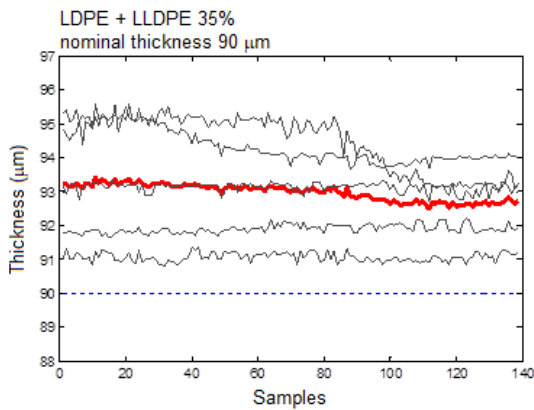


Fig. 11. Measurements of a transparent plastic film of 90 μm of nominal thickness performed by the instrument.

The drifts that are noticed in some 90 μm measurements of the samples are due to the fact that the measurand has detached from the support. However, these measurements are exposed because they demonstrate how the system is able to obtain the thickness of plastic films even when they are out of the beam focus point. The variations in thickness measured in these cases is due to the fact that the beam does not affect the film perpendicularly but at a certain angle and therefore the approximation of equation (4) is no longer valid.

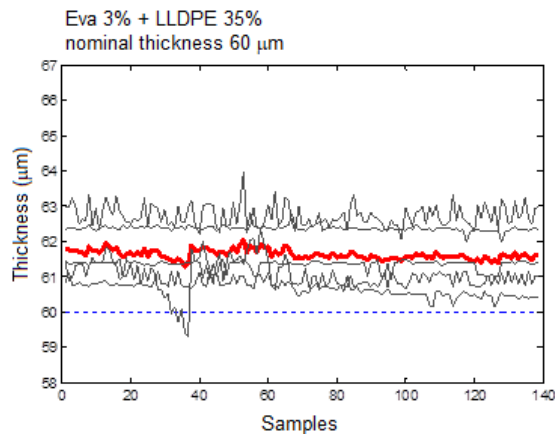


Fig. 12. Measurements of a transparent plastic film of 60 μm of nominal thickness performed by the instrument.

V. CONCLUSION

In this work a prototype of a system capable of measuring the thickness of plastic films during their production was designed and built. Nowadays, in factories are installed systems that can perform these measurements only if they are in contact with the plastic film. This inevitably changes the thickness of the plastic films which in some cases are also deformed. Using an optical system, on the other hand, the interaction between the system and the target is eliminated, making the measurement more accurate. The realized system is based on the Michelson interferometer and uses a low coherence source to obtain two interference figures separated by the rays reflected by the plastic film. From the distance

between the figures of interference it is possible to obtain the thickness of the plastic films.

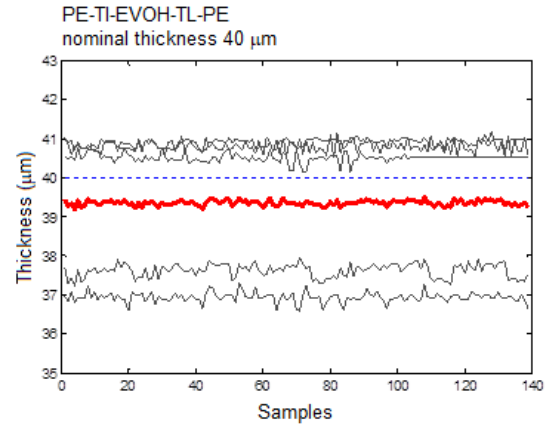


Fig. 13. Setup Measurements of a transparent plastic film of 40 μm of nominal thickness performed by the instrument.

Once assembled, the system was calibrated and tested in the laboratory by performing preliminary measurements on some transparent samples. For the measurement of colored samples, it will be necessary to introduce a polarization beam splitter cube in the optical head and modify the LABVIEW program to correctly process the interferometric signal of these samples.

ACKNOWLEDGMENT

The authors want to thank all the master and bachelor degree students that has worked on this project.

REFERENCES

- [1] Ren-jie Zhang, Shu-guang Dai and Ping-an Mu, "A spherical capacitive probe for measuring the thickness of coatings on metals," *Measurement Science and Technology*, vol. 8, pp. 1028–1033, September 1997.
- [2] Bhowmick, Saswata, "Ultrasonic Inspection for Wall Thickness Measurement at Thermal Power Stations" *International Journal of Engineering Research & Technology*, vol. 1, pp. 89-107, January, 2011.
- [3] M. Norgia, M. Annoni, A. Pesatori, C. Svelto, "Dedicated optical instruments for ultrasonic welder inspection and control," *Measurement*, vol. 43, pp. 39–45, January 2010.
- [4] S. Donati, *Electro-Optical Instrumentation: Sensing and Measuring With Lasers*, 1st ed., Prentice Hall, 2004.
- [5] D. Melchionni, A. Magnani, A. Pesatori, M., Norgia, "Development of a design tool for closed-loop digital vibrometer," *Applied Optics*, vol. 54(32), pp. 9637-9643, November 2015.
- [6] A. Pesatori, M. Norgia, C. Svelto, M. Zucco, M. Stupka, A. De Marchi, "A High-resolution mode-locked laser rangefinder with harmonic downconversion," *IEEE Transactions on Instrumentation and Measurement*, vol. 61, pp. 1536–1542, May 2012.
- [7] M. Born, E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*, 7th ed., Cambridge University Press, 1999.
- [8] B. E. Bouma, G. J. Tearney, *Handbook of Optical Coherence Tomography*, 1st ed., CRC Press, 2001.
- [9] W. Drexler, J. G. Fujimoto, *Optical Coherence Tomography*, 2nd ed., Springer Verlag, 2015.
- [10] W. Drexler, "Optical coherence tomography: Technology and applications," 2013 Conference on Lasers & Electro-Optics Europe & International Quantum Electronics Conference CLEO EUROPE/IQEC, Munich, 2013, pp. 1-1.