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High resolution optical thickness measurement based on electro-optic dual-optical frequency comb sources

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Abstract— **We propose an optical thickness measurement device based on electro-optic dual-optical frequency combs (dual-OFCs). Optical frequency combs (OFCs) are light sources that provide an optical signal consisting of many equidistant monochromatic tones. In this paper we present an agile dual-OFC architecture with adjustable frequency separation of the comb modes and total frequency span, allowing high resolution measurements of the thickness of transparent thick samples. This architecture is based on a single continuous-wave laser diode and external electro-optic devices to implement the dual-comb sensor, allowing easy control of the optical spectrum of the interrogation source (dual-OFC). As it is characteristic of dual-OFC systems, the optical transmittance function of the sample (etalon) is directly translated to the Radiofrequency (RF) domain, where detection, demodulation and processing of signals are performed. The shift in the complexity of implementation from the optical to the electronic domain yields many advantages, as acquisition and signal processing are made independently on the optical characteristics of the sample (thickness).**

Index Terms— **Dual-Optical Frequency Comb, Fabry-Perot Etalon, Optical Interferometry, Thickness Measurement.**

I. INTRODUCTION

Traditional spectroscopic methods for transparent object thickness estimation involves the illumination of the sample with a white light source and the analysis of the reflected or transmitted spectrum. The measurement principle is based on the fact that interference between the multiple reflections that occur when light strikes at a normal angle of incidence an etalon produces an interference pattern in the reflectance and the transmittance of the sample. When the incident wavelength is such that the reflected optical waves are in phase, constructive interference occurs, and a transmission maximum appears. In the same way, destructive interference produces transmission minimums. Given that the separation between these interference fringes depends on the optical path length of the sample, the etalon effect has been long used for the measurement of the thickness of single and multiple-layer materials. As the separation between the interference fringes is inversely proportional to the etalon thickness, the analysis of thin materials is far less challenging that the characterization of thicker samples. As a reference, submicrometer thicknesses generate separations between optical transmission maximums of up to hundreds of nanometers. Therefore, even very low resolution spectrometers can resolve thin film interference fringes to accurately obtain the thickness of a certain material. Thin film thickness measurement systems are widely employed in the semiconductor and industrial sectors, and these instruments are essential components in processes like film deposition or hard, anti-reflection or medical coating applications. In front of this, the analysis of thicker samples (in the millimeter range), that is of use for example for the fabrication of glass and plastic sheets or optical windows and lenses, requires a spectrometer with an optical resolution of few picometers, that only high-end and, generally, bulky and expensive setups can reach.

The use of interferometric techniques provides other alternatives for the measurement of thick transparent samples. Here, knowing the mean refractive index of the test object, and through the measurement of the optical phase of the transmitted signal via an interferometer, it is possible to calculate the mean thickness of test objects [1]. However, some of these systems have the disadvantage of being sensitive to alignment and vibrations, and it is necessary to make further corrections to obtain the measurement.

In this paper, we propose a new, high resolution, optical thickness measurement device for thick samples based on an electro-optic dual-optical frequency comb arrangement that can be adjusted to provide the optimal optical spectral resolution according to the requirements of the sample's the thickness. Optical frequency combs (OFCs) are light sources that provide an optical signal consisting of up to tens of thousands of equidistant monochromatic tones and are used as optical frequency rulers in spectroscopy and metrology [2][3].

Traditionally, OFCs are generated by two different methods. The first one relays on the generation of ultra-short pulses, being mode-locking the technique more frequently used [4]. However, the demands in terms of complexity of implementation and operation of OFC generated from mode-

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locked pulsed lasers are remarkably high in terms of stability and environment control, complexity and cost. This factor restricts the applicability of this type of sources beyond laboratory demonstrations, and their use in the implementation of optical sensors in industrial, biomedical or environmental applications [5]. On top of that, there is a final limitation if we want to use such powerful sources for thickness measurements, and it is that in order to cover the wider possible range of operation with maximum accuracy, the control and adjustment of the repetition frequency of the comb should be as flexible as possible, something that it is very difficult if mode-locking sources are used.

The second method typically used for OFCs generation relays on the external modulation of a continuous wave laser using amplitude or phase modulators, known as electro-optic OFCs [6][7]. Although of less quality of mode locked OFC sources (in terms of optical span, signal quality and power), there is, in fact, a good number of additional gains that electro-optic OFCs can provide, from the simpler design, to the inexpensive implementation, or the higher power per spectral element [8]. Even the traditional major constraint of electro-optic combs, i.e. the lower spectral coverage, has been very recently overcome with the demonstration of an octave spanning setup [9].

Although different detection schemes for OFCs have been proposed when used in spectroscopic and instrumentation systems, dual-comb detection [10] is the preferred option as it allows one-to-one mapping each mode of the measurement OFC into the radio-frequency (RF) domain by heterodyning with a second (reference) local oscillator (LO) comb slightly detuned from the measurement OFC [11]. The resulting Radio Frequency (RF) comb can therefore be electronically acquired and processed to obtain the amplitude and the (optical) phase of each tooth of the original comb [11].

As mentioned before, in this paper, we demonstrate for the first time the use of a dual-OFC for thickness measurement applications. In this sense we will take advantage of the ability of electro-optics dual-OFCs to adjust the span and the optical mode resolution (mode separation) for thick sample measurements without any moving part in the optical system. Additionally, the dual-comb architecture we present provides with a sensor interrogation mechanism and subsequent signal processing completely automatized and independent on the sample characteristics.

This paper is organized as follows. In section II the sensing device principle of operation and implementation is described. Section III describes the experimental results obtained that validate the approach and confirms the expected performances of the system. We end the paper in Section IV with the conclusions.

II. SENSING DEVICE

A. Fabry-Perot etalons and OFC sources.

The theoretical bases of the measurement method are presented here. When light enters an etalon, undergoes multiple internal reflections. These reflections depend on the wavelength (λ) of the light (in vacuum), the angle the light travels through the etalon (θ), the thickness of the etalon (l) and the refractive index of the material between the reflecting surfaces (n).

The transmittance T of an ideal lossless etalon is given by (1):

$$\mathrm{T}(\lambda) = {}^{1}\!/_{1 + \mathrm{F}\sin^2(\delta(\lambda)/2)} \tag{1}$$

where F is the Finesse Coefficient

$$\mathrm{F} = {}^{4\mathrm{R}}\!/_{(1-\mathrm{R})^2} \tag{2}$$

and δ is the phase difference between optical beams

$$\delta(\lambda) = {}^{4\pi\,\mathrm{n}\,\mathrm{l}\cos\theta}\!/_{\lambda} \tag{3}$$

being R the Fresnel reflection coefficient (that is assumed to be equal for both surfaces. In the optical set-up we consider normal incidence ($\cos\theta = 1$), so the free spectral range (FSR) of the etalon, Δf_{FSR}, is given by

$$\Delta f_{\mathrm{FSR}} = c/2n\,l \tag{4}$$

where Δf_{FSR} is the optical frequency separation between adjacent transmission peaks. Therefore, if the transmittance of the etalon is measured at several known frequencies within the FSR, it is possible to directly calculate the thickness of the etalon.

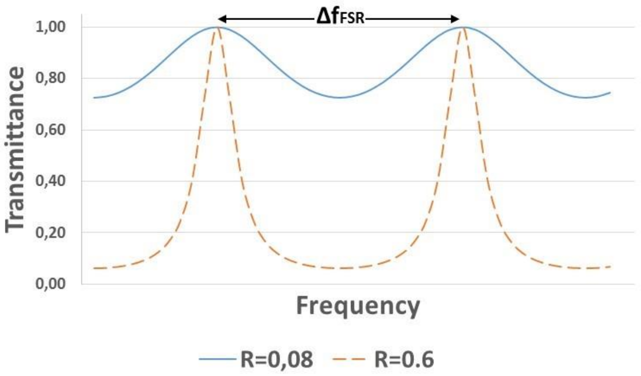

Fig. 1. Description of the behavior of a Fabry-Perot etalon.

The representation of the transmission function of an etalon for two different values of the reflection coefficient R is show in Fig.1. (dependent on the refractive index of the sample n). Let’s now consider what happens when we illuminate and etalon with an OFC. In this situation, we will be interrogating the sample with many optical frequencies at the same time, performing a parallel measurement. Moreover, as the number of modes inside the FSR and the optical separation between them can be changed with a simple variation of the repetition frequency of electro-optic OFCs (See section II.B), we can adjust the optical source to the actual characteristics (thickness) of the sample. This is especially important for high resolution thickness measurements.

As an example, whereas the free spectral range (separations between transmission maximums) at 1550 nm for a 10 mm etalon is approximately 10 GHz (a spectral width approximately of 83 pm in wavelength), the separation is 1000 GHz (83 nm) for a 10 um thick sample. Thus, in spite of the wide availability of reasonably inexpensive thin film thickness optical instruments, the optical assessment of the thickness of millimeter range etalons still remains very challenging. Nevertheless, and as it was previously stated, the limitations in the optical resolution achievable by traditional spectrometer designs are overcome by OFCs-based architectures. In this case, and to continue with the example, the repetition frequency can be changed to obtain the best resolution and the optical range necessary to measure different sample thickness. Repetition frequencies between 100 MHz and 1 GHz can be used as input to the modulators, allowing the measurement of samples between 2 mm and 12 mm thickness approximately.

The measurement set-up is represented in Fig. 2. It consists of a dual-OFC, (section II.B) whose repetition frequency f_{OFC} can be adjusted for high resolution measurement. The light from the source is divided into a measurement arm and a reference arm. The reference arm provides the information of the optical spectrum of the comb source while the spectrum of the measurement arm is modified by the sample object. As it is explained in section II.C reference arm is fiber guided while free space optics is used to interrogate the sample in transmission.

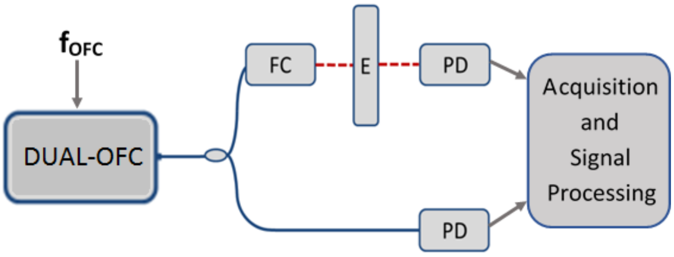

Fig. 2. Block diagram of the measurement set-up, where E represent the sample object as an etalon; PD are photodetectors; FC fiber collimator. Guided optics is represented in a blue continous line while free space propagation is displayed as a red dashed line. The repetition frequency of the comb source is f_{OFC} which is configurable parameter on the measurement set-up.

B. Optical Frequency Combs detection: Dual-OFC

To take advantage of the full optical resolution of OFCs, as it is imperative for the measurement of thick samples, dual-comb detection is employed. This technique, that is based on the heterodyning of the measurement comb with a local oscillator comb, allows the one-to-one mapping of each tone of the optical measurement comb into the RF domain, where can be digitized an easily processed. This technique was firstly proposed for high resolution spectroscopy by Schiller in 2002 [10], and first demonstrated by Keilmann et al. [12]. When using external modulation, the possibility of generating the two combs from a single laser removes the need of combs synchronization and, in addition, amplitude and phase fluctuations of the laser are self-compensated [13] making possible the implementation of high stability and robust dual-comb sources. On top of that, electro-optic dual-combs are not based on mechanical components and therefore can be operated at ultra-fast speeds [14], [15].

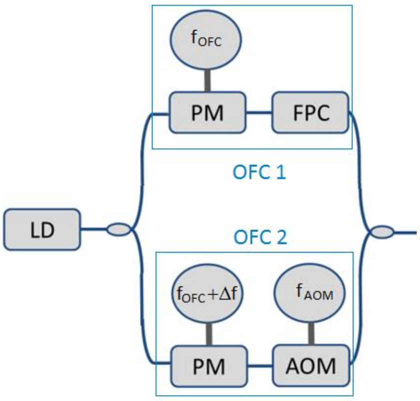

Fig. 3. Block diagram of the electro-optic dual-comb instrument. LD, Laser source; PM, Phase Modulator; FPC, Fiber polarization controller; AOM, Acousto-optic modulator.

The basic setup of a dual-comb system is shown in Fig. 3, where the OFC 1 (top) and OFC 2 (bottom) have a slightly different repetition frequency. In a standard configuration, both optical combs would be heterodyned on a photodiode, and this results in a comb of radio frequency beat notes that can be digitized. In this way, each of the optical modes is individually mapped into the RF domain where high performance signal processing tools and methods are available [8]. It is then possible to obtain the amplitude and phase of each of the optical teeth of the comb that have travelled through the sample referenced to the local oscillator, obtaining thus the spectral response of the sample. A second detector is sometimes included to obtain a reference measurement that is mainly used for amplitude and phase normalization, allowing compensating for any fluctuations in the spectral shape of the combs.

The one-to-one frequency mapping property of dual-comb spectroscopy is illustrated in Fig. 4. The two optical combs must have the same offset frequency and marginally different repetition rates. This condition is met in the electro-optic dual-comb architecture represented in Fig. 3 as the same laser diode is used to create both combs by external modulation. An additional external modulator, in this case an acousto-optic modulator is introduced to the OFC 2, which introduces an additional optical frequency shift to this comb. In this way, when the combs are combined and heterodyned on a square law detector, a set of beat notes is generated with the resultant one-to-one frequency downshifting. The most extended approach is to directly digitize the radio frequency comb before performing a Fourier transformation, that yields the amplitudes and phases of each of the teeth of the measurement comb.

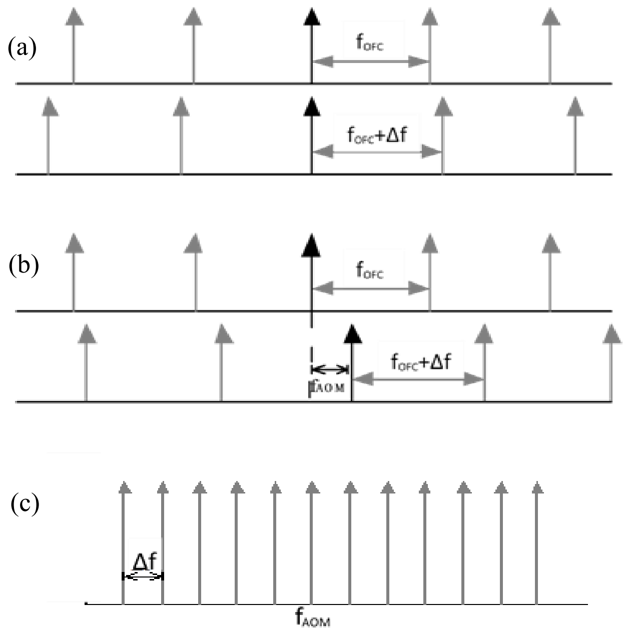

Fig. 4. Frequency mapping between the optical and radio frequency domains in dual-OFCs: (a) optical spectra at the output of each phase modulator, (b) optical spectra of OFC 1 (top) and OFC 2 with acousto-optic modulator (bottom), (c) A RF comb is generated as a result of the heterodyning between OFC 1 and OFC 2.

C. Optical Thickness measurement using dual-OFCs

The basic block diagram of the Optical thickness measurement architecture for thick samples based on an electro-optic dual-OFC source proposed in this paper was already shown in Fig. 2. As we can see in this diagram, the output from the dual-OFC source is used to interrogate the sample in transmission, while a second, reference, path is used to obtain the reference signal.

A more detailed scheme of the measurement system is shown in Fig. 5. The light source employed in the experimental validation of the architecture is a discrete mode laser (EP 1550-DM-HAA, Eblana Photonics Ltd., Dublin, Ireland), emitting 7 mW of optical power, connected to two optical phase modulators that generate the combs (Fig. 5). Two low-loss LiNbO3 phase modulators (PM-5S4-10-PFA-PFA-UV, EOSPACE Inc., Washington, USA) with an external load connection enabling high modulation voltages were selected for the setup. A RF power of approximately 33 dBm was used to drive the modulators. The two PMs modulation frequencies were always offset by $\Delta f = 100$ kHz for dual-OFC operation, while the center frequency of each of them was adjusted for optimum performance of the measurement (see below). After that, one of the combs is shifted in frequency by a 40 MHz acousto-optic modulator (T-M040-0.5C8J-3-F2S, Gooch and Housego PLC, Ilminster, United Kingdom), driven at 20 dBm, before recombination with the other comb. The optical signal is then amplified by an Erbium Doped Fiber Amplifier (EDFA) and launched into a Highly Non-Linear Fiber (HNLF; Length: 204 m - D=1.88 ps nm^{-1} km^{-1} @ 1550 nm - S=a.019 ps nm^{-2} km^{-1} - Non linear coefficient 11.3 W^{-1} km^{-1}, OFS company, Denmark). The optical amplification, even though it is not necessary most of the times, is convenient for obtaining a good sensitivity in open path operation. The addition of the HNLF roughly doubles the number of spectral lines available for spectral interrogation [16][17]. For this particular application, this provides the ability of doubling the optical resolution of the spectrometer, increasing thus the accuracy in the estimation of the interference period.

The signal is divided again (Fig. 5), and while one of the fibers is carried to a reference detector, the other one is connected to an optical fiber collimator (F810FC-1550, Thorlabs Inc., New Jersey, USA). The collimated dual-OFC beam travels through the etalon and it is detected by the measurement photodetector (PDA10CF, Thorlabs Inc., New Jersey, USA). The signals from the two detectors are synchronously subsampled (PDA14, Signatec Inc., California, USA) and processed in real-time using LabView (National Instruments Inc., Texas, USA).

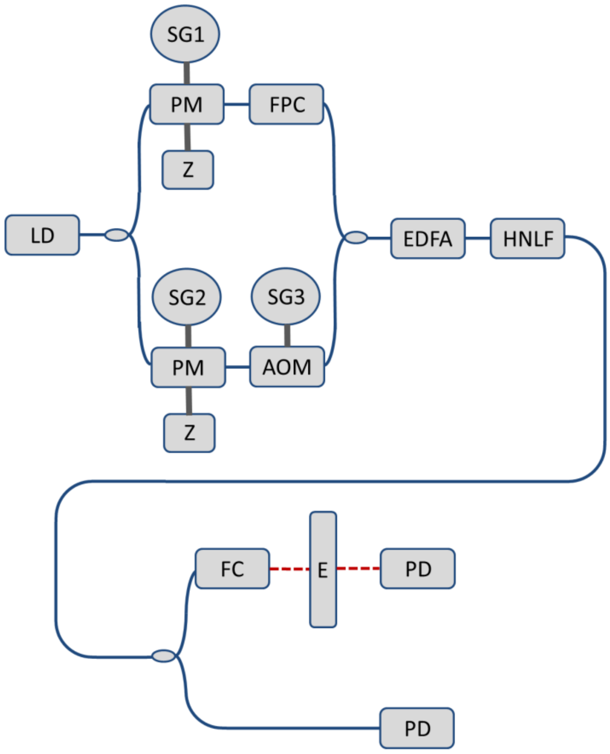

Fig. 5. Block diagram of the electro-optic dual-OFC instrument. LD, Laser source; PM, Phase Modulator; SG, Signal Generator; Z, RF Load; FPC, Fiber polarization controller; AOM, Acousto-optic modulator; EDFA, Erbium doped fiber amplifier; HNLF, Highly non-linear fiber; FC, Fiber collimator; E, Etalon; PD, Detector.

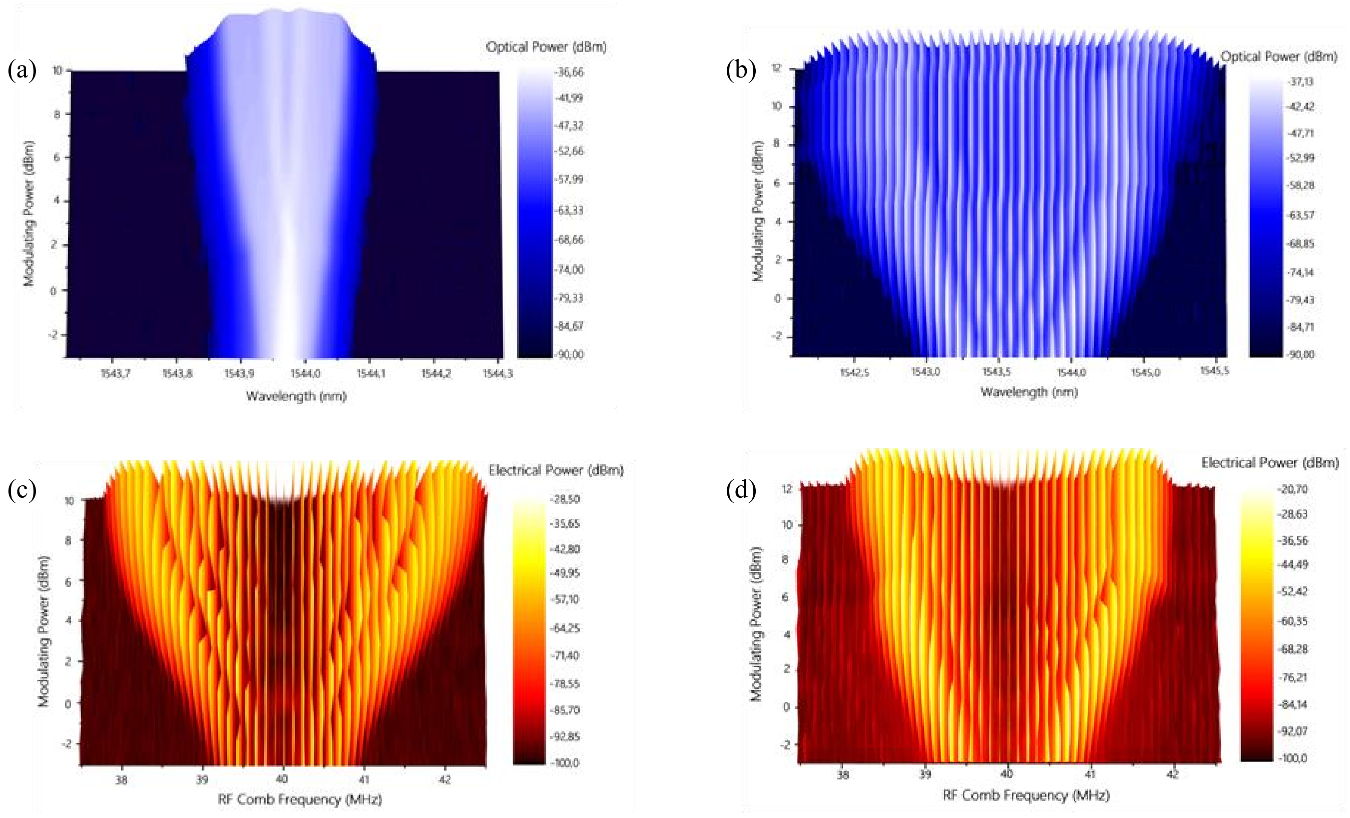

Figure 6. Characterization of the dual-OFC optical and RF spectra for different modulation frequencies and as a function of the power applied to the phase modulators.

In Fig. 6, optical and electronic spectra of the dual-OFC source with different repetition frequencies are shown. This figure corresponds to the characterization of the dual-OFC source, before the amplifier and the non-linear fiber. Fig. 6.a shows the optical spectra of one OFC when the modulation frequency of the phase modulator is f_{OFC} = 500 MHz, and Fig. 6.b shows the OFC spectra with modulation frequency of f_{OFC} = 8 GHz. It can be seen that the optical span, for a given RF power, depends on the modulation frequency as the number of modes is similar in both cases. The number of useful modes is increased as the RF power applied to phase modulators increases up to a limit. Also, it can be seen that the Optical Spectrum Analyzer is not able to resolve independent modes if lower modulation frequencies are used. Lower modulation frequencies are needed as the sample thickness is higher. Fig. 6.c and Fig. 6.d show the RF comb for modulation frequencies of 500 MHz and 8 GHz respectively. It can be seen that the RF spacing is the same in both cases as it only depends on the frequency difference of the dual-OFC which is always set to 100 kHz. This characteristic is a great advantage from the point of view of data acquisition and signal processing.

For illustration of the increase of the dual comb span due to the introduction of a non-linear fiber in the architecture, the spectrum of the RF comb for a repetition frequency of 100 MHz and an optical power of 25 dBm at the input of the HNLF is shown in Fig.7. Useful modes for thickness measurement are those within a 20 dBm bandwidth, so it can be seen in the figure that the HNLF doubles the number of modes and thus the measurement resolution.

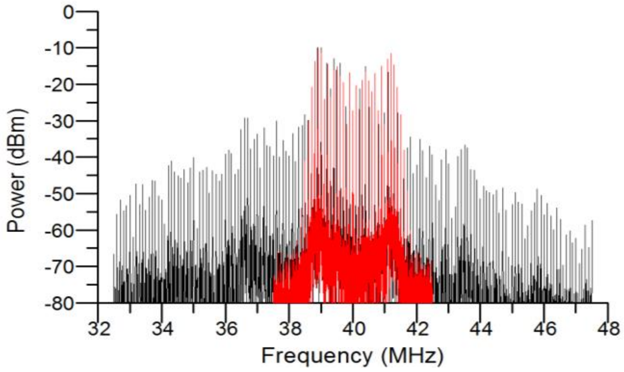

Fig. 7. Spectrum of the RF comb. **Without HNLF (red) and with HNLF (black).**

D. Data acquisition and processing

The signals from the two detectors are digitalized using a dual channel PCI data acquisition board with a 14-bit resolution ADC (PDA14, Signatec Inc., California, USA). These signals are processed in real-time using LabView (National Instruments Inc., Texas, USA).

The RF and electronic subsystem of the sensing architecture has been designed to synchronize the frequency of the phase modulators of the two OFC, the frequency of the acousto-optic modulator for RF frequency shifting to 40 MHz and the reference clock for data acquisition. The sampling frequency has been set to 36 MHz so output and reference signals are sub-sampled. The acquisition time is two miliseconds to guarantee that a high number of interferograms are acquired and processed in parallel [15]. Data processing is based on the Fourier transformation of the average of a given number of interferograms. Then, the amplitudes of corresponding modes of the measurement and reference receivers are divided, obtaining the transmittance of the sample with-in the comb span. After calibration, using the transmittance function of the etalon as a reference, the thickness of the sample can be obtained.

As signals are subsampled, the center frequency of the RF comb fixed by the frequency of the acousto-optic modulator to 40 MHz is aliased to 4 MHz. Subsampling limits the bandwidth of the RF comb to approximately 8MHz. Being the frequency difference of the dual-OFC equal to 100 kHz, this limit the number of the comb tones to one hundred.

III. EXPERIMENTAL RESULT

The experimental validation of the setup was performed by measuring the thickness of two optical samples, a 5 mm thick UV Fused Silica window (WG41050, Thorlabs Inc., New Jersey, USA) and a 12 mm thick N-BK7 High Precision window (WG12012, Thorlabs Inc., New Jersey, USA). Due to the versatility of the device, it was possible to vary the optical spectral resolution changing the repetition frequency of the dual-OFC to obtain the data, without any further change in the set-up. Measurements (together with the results of the fitting using equation (1)) are shown in Fig. 8 and Fig. 9 for the 5 mm and 12 mm windows respectively, in which the measurements have been box-smoothed to filter out high frequency noise. With respect to the fit, a complete freedom has been given to the absolute values of the Finesse Coefficient and the maximum transmittance to deal with changes in the reflectivity of the targets and the angle of incidence. The results of the fitting provide a thickness of 4.895 mm with a standard deviation of 22 µm (calculated from the confidence interval of the fit) for the 5 mm window, a value that it is well under specifications (5 ± 0.3 mm). In the same way, the characterization of the 12 mm window yielded a thickness of 12.121 ± 0.064 mm, being the specifications of the manufacturer 12 ± 0.3 mm.

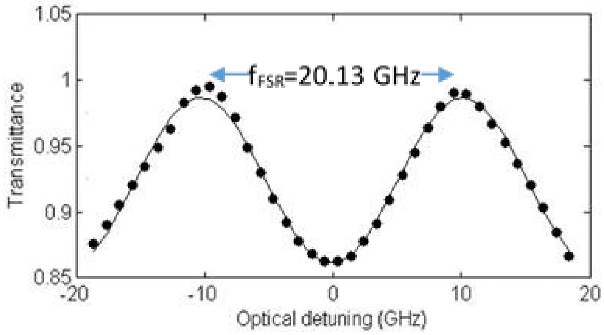

Fig. 8. Measurements carried out with a 5 mm thick optical window (dots) together with the fit of the results (continuous line). The repetition frequency of the dual-OFC was adjusted to 1 GHz, **obtaining a FSR=20.13 GHz (or 169.5 pm in wavelength).**

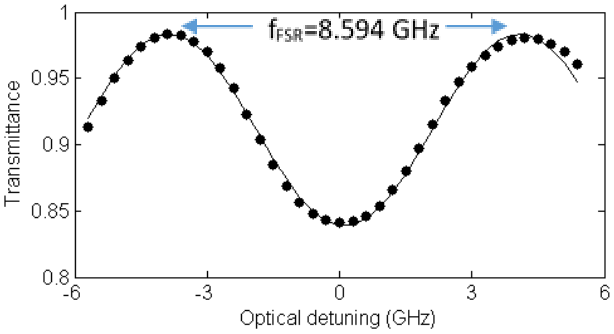

Fig. 9. Measurements carried out with a 12 mm thick optical window (dots) together with the fit of the results (continuous line). The repetition frequency of the dual-OFC was adjusted to 300 MHz, **obtaining a FSR=8,594 GHz (or 68.5 pm in wavelength).**

IV. CONCLUSIONS

In this paper, an optical thickness measurement architecture for thick samples based on an electro-optic dual-optical frequency comb has been presented. The setup has been experimentally validated by the determination of the thickness of two optical windows of different materials. The dual-OFC source enables the instrument to take full advantage of the optical resolution provided by the combs, being possible to dynamically adjust its value for maximizing the accuracy in the characterization of a sample. Additional advantages of the electro-optic dual-OFC approach are the high speed (the integration time employed was 2 ms) that allows real-time operation, the high power per spectral element, and the simplicity of the setup.

The presented architecture and experimental arrangement show that the practical unlimited optical resolution of these sources is a powerful tool for dynamic adaptation of the spectral coverage, which can be employed for the obtaining of systems that cannot be matched nowadays with any other available technology. Moreover, the shift in the complexity of implementation from the optical to the electronic domain that electro-optic OFCs provide over traditional combs, yields many advantages that can be fully exploited in thickness measurements as acquisition and signal processing is made independent on the optical characteristics of the comb.

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Borja Jerez received his BSc on Industrial Electronics and Automation in 2013 and his MSc on Industrial Engineering in 2015 from Universidad Carlos III Madrid, both with honors.

To date, he has been involved in research work specializing in the analysis and design of advanced multimode optical sources (Optical Frequency Comb Generators and Dual Optical Frequency Comb Generators) for spectroscopic applications. Since October 2015, he has been performing his Ph.D aimed at the development of optical sources in different regions of the electromagnetic spectrum.

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Pablo Acedo (M’00) received his bachelor degree on Telecommunication Engineering in 1993 from the Universidad Politécnica de Madrid, and his Doctorate (with honors) from the Universidad Carlos III de Madrid in 2000 for his work on heterodyne two color laser interferometry for fusion plasma diagnostics.

In 2002 he was appointed as Assistant Professor by Universidad Carlos III de Madrid where he continued with the development of scientific instrumentation systems for fusion plasma diagnostics and biomedical applications, leading national projects and contracts on these fields. Starting 2009 his research interests also focused on the development of multimode laser sources (Optical Frequency combs) and their applications in photonic signal synthesis, spectroscopy and other applications, leading several research projects and contracts in this field. He has been also very active in technology transfer through R&D contracts with different companies as well as with the creation of the spin-off company Luzwavelabs (www.luzwavelabs.com).

Prof. Acedo has published more than 80 contributions in journals and international conferences, including invited conferences and seminars.