Non-destructive characterization of multilayer structures by low-coherence interferometry

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Abstract

We present here a non-destructive technique for characterization of multilayer structures based on low-coherence interferometry. This technique is capable to give information of physical thickness and index of refraction of the subjected sample regardless of how many different layers exist along the optical trip. The main limitation is if the investigated materials are transparent for the used optical wavelength. We performed sensing set up in the form of single-mode fiber-optic Michelson interferometer composed of one 2×2 optical coupler. There were tested three and five layers foils composed of sandwich structure made by alternation of polyarilate (PAR) and glue layer. We achieved a success discriminate the interface between the two different materials with accuracy of about 40 nm by analyzing low-coherence interferograms.

Keywords: thickness measurement, index of refraction measurement, interferometry, fiber optic sensor

1. Introduction

Non-destructive characterization of multilayer structures is a frequent task in a broad range of disciplines, equally in science and engineering. For example, in optical industry for characterization of antireflection technical glasses, in semiconductor industry for thickness measurement of oxides layers, in polymer industry for thin foil and glue thickness measurement, etc.

Thickness measurement of multilayer thin films in a submicron range is rather challenging task. There is a list of different techniques currently in use [1-6] such as ellipsometry, ultrasonic technique, surface plasmon resonance, white-light interferomety, capacitance measurements and mechanical profilometry, X-ray diffraction, atomic force microscope (AFM). Some of them are very complex and require specific and expensive measuring set up that can not be used for in-line measurement such as elipsometry or X-ray diffraction.

White light interferometry (WLI) or low-coherence interferometry (LCI) has been successfully used for absolute thickness measurement. In this paper we present a non-destructive optical technique [6-9] for characterization of multilayer structures based on low-coherence interferometry. This technique is capable to give information of physical thickness and index of refraction of the subjected sample regardless of how many different layers exist along the optical trip. The main limitation is if the investigated materials are transparent for the used optical wavelength. We performed sensing set up in the form of single-mode fiber-optic Michelson interferometer composed of one 2×2 optical coupler.

There were tested singular, three and five layers foils aimed for loudspeaker production. These foils are composed of sandwich structure made by alternation of polymer (PAR) and glue layer. It appears that uniformity of the layers, particularly of the interfacial glue can strongly affect the sound characteristic of the loudspeakers. We achieved a success to discriminate the interface between the two different materials with accuracy of about 40 nm by analyzing low-coherence interferograms. This result is comparable or even better than the newest result of authors in [3] that report on WLI accuracy of ±100 µm for thickness measurement.

2. Principle of Operation

The presented technique is based on low-coherence interferometry performed in “all-fiber” Michelson interferometer shown in Fig. 1.

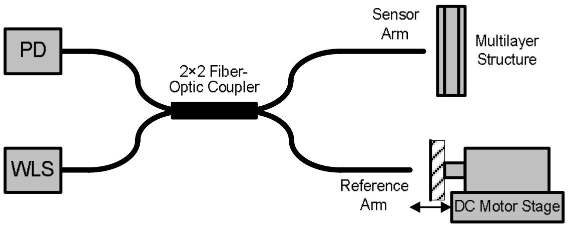


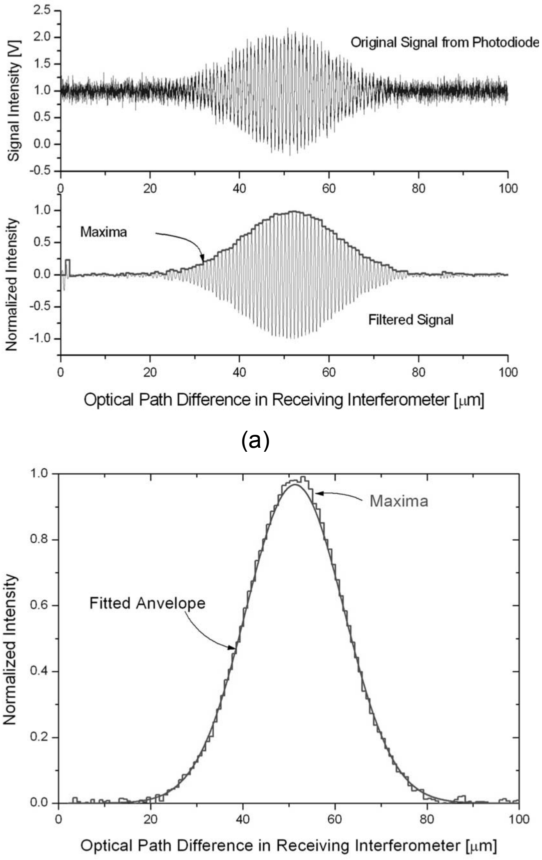
Fig. 1 Schematic presentation of “all-fiber” Michelson interferometer

Basically this is a fused 2×2 single mode (5/125 µm) optical coupler connected with a low-coherence light source at one input arm and photodetector at the other input arm. The outlet arms are directed to the target (sensing arm) and to the mirror (reference arm). Back reflected optical beams from the target and reference mirror make an interferometric pattern that is captured by photodetector. The current signal i, captured by photodiode has the following shape:

$$i = I_0 \left\{ 1 + V \exp\left[-\left(2\Delta x / L_C \right)^2 \right] \cos\left(k\Delta x \right) \right\} \tag{1}$$

where I_0 is the maximum photodiode current, V is the fringe visibility, Δx is the optical path difference, L_C is coherence length of the used white-light source (WLS) and k=2π/λ, where λ is the wavelength of WLS.

This pattern has a characteristic bell-shape form that can be described by Gaussian function. Our task in this technique is to find zero optical path difference (OPD) between the sensing and referencing optical paths which corresponds with position of the central fringe in the interferogram. In Fig. 2 we present an algorithm that we used for determination of position of central interferometric fringe. It is based on fitting of raw photodiode signal by Gaussian function following up with finding of maximum of this function.



(a)

(b)

Fig. 2. (a) Raw photodiode signal (above) and filtered signal (below); (b) fitted envelope for central fringe maximum

In case of single layer target we have two surfaces that reflect the input optical beam. The first one is the front and the second is the back surface. Back reflected beams from these two surfaces make an interferometric pattern. The only condition is that the layer is transparent for the used wavelength light source. In case of the three layers sample, schematically shown in Fig. 3, the number of back reflected surfaces are four. The number of interferometric patterns is also four. In case of five layers it is five patterns, etc.

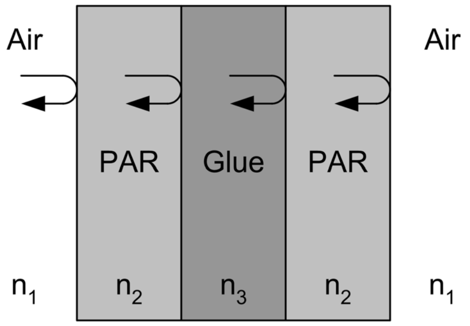


Fig. 3 Schematic presentation of the cross-section of the three-layer foil

3. Experiment

Experimental set up, schematically presented in Fig. 1, is composed of 2×2 fiber-optic coupler as a core sensing part and a superluminescent diode (WLS) of 850 nm of light wavelength having coherence length of about 30 μm and silicon photodiode (PD) at the input side of the coupler. The WLS is driven with DC current at 80 mA emitting optical light power of 460 μW at the outlet of the pig-tailed source. It means that we have had about 200 μW at the end of the sensing fiber. The sensing output arm is directed to the multilayer foil as a target and referencing fiber is directed toward the aluminium mirror. This mirror is mounted and firmly fixed to the movable stage having a high resolution encoder that provides position with accuracy of about 40 nm.

The lateral resolution is limited by the fiber core dimension (a=5 μm) and its angular spread, because we used bare fiber end directed to the multilayer foil without any collimating optics. The overall lateral resolution R_L is given by diameter of the light spot impinging the foil and is given by:

$$R_L = a + NA \cdot d \tag{2}$$

where NA is numerical aperture of the fiber (in our case NA=0.12) and d is the distance between the fiber end and foil. In our case the distance is d≈50 μm, and is measured by our sytem using interference of the beams back reflected from the fiber end and from the foil. Using these data we found the light spot diameter of about 10 μm. This is practically the lateral resolution of our sensing system. However we could enchance the lateral resolution using one fine scaning system such as the same one that we use for scanning of optical path difference in receiving interferometer. The resolution of this system is defined by reading encoder that is accompained by the mechanical scanner. We already said above that this resolution is about 40 nm.

We used single and multilayer plastic foil, aimed for loudspeaker production, as a target. The three and five layers foils were made by gluing of sheets. Index of refraction of polyarilate (PAR) is 1.61. Before characterisation we checked the transmitivity of the foil at light wavelength of 850 nm by an optical power meter. We found some degree of attenuation of the input optical power. It was about 10 times for the three layers foil. The outcom optical power from the fiber end was about 200 μW, but after passing through the foil we measured about 20 μW. This is still enough to be measurable in interferometric set up. This attenuation was induced by light scattering at the roughness of the foil surface as well as by material absorption.

The characterization procedure consists of fixation of a piece of the foil on a stable frame perpendicularly against sensing fiber. The target (foil)-sensing fiber separation was set to be of about 50 µm. Using a Thorlabs DC movable stage at the reference arm we have been scanned across the foil. Scanning procedure begins from the tip of the reference fiber till to 400 µm away. During scanning the photodiode signal has been acquired by NI 16 bit card.

4. Results and discussion

In Fig. 4 we present the raw signal of the photodiode that we got during testing of single layer of the PAR foil. We can see two interferometric patterns. Central interferometric fringes are separated of 58 µm and this value actually corresponds to the optical path (OP) of the beam traveling through the subjected foil. Taking into account index of refraction of the PAR (n=1.61) we can calculate the physical thickness (PT) of the foil using simple relation: PT=OP/n. The physical thickness of this sample is 36 µm. This value is also obtained by mechanical profilometer.

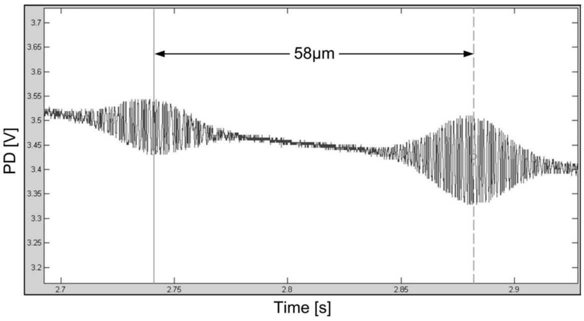


Fig. 4 Interferometric pattern of single layer foil

Fig. 5 shows raw signal that we obtained in case of three layer foil. Here, we have four distinctive intererometric patterns that correspond to the four interfaces occurring along the path of the optical beam. The first pattern occurs at the air/PAR interface, the second at the PAR/glue interface, the third at the glue/PAR interface and the fourth at the PAR/air interface. It appears that the intensity of the last pattern is smaller than previous due to attenuation of the optical power.

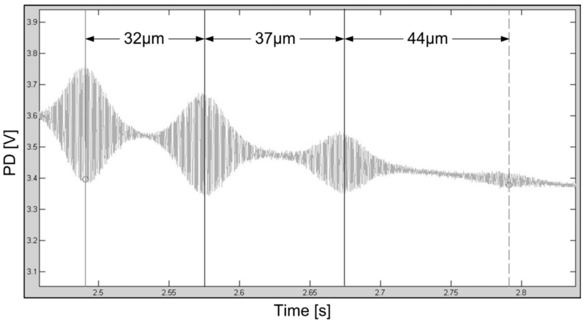


Fig. 5 Interferometric pattern of three layer foil

After fitting procedure and finding of position of the central interference fringe for every pattern we determined the separation between the patterns. These values correspond with optical thicknesses of the layers. Using the above procedure we calculated the physical thicknesses of every layer. In case of PAR layers the first layer is 19.87 µm thick and the second layer is 27.32 µm thick. The interfacial glue thickness is 31.81 µm. The calculated index of refraction of the glue is now 1.16.

Fig. 6 depicts the results of investigation of the five-layer foil. There are six interferometric patterns that are in accordance with number of the interfaces along the optical trip of the travelling beam. We applied the same procedure for determination of separation between the central interferometric fringes. Again, using data of index of refraction of PAR we calculated the physical thicknesses of the PAR layers (the first, third and fifth). Respectively, they are 15.52 µm, 20.49 and 18.63 µm. We could not calculate the physical thicknesses of the glue because we have had no data about the index of refraction of the glue. The type of the glue in this case was not the same as in previous case. One interesting thing can be noticed from the Fig. 6. Between second glue layer and the rare PAR layer there is strong reflection of the light that is probably induced by delamination between these two layers, which significantly increases the reflectance of the light. Practicaly, it means that air comes in the interface changing the reflection conditions. Instead of single reflection from the glue-PAR surface we have now two close reflections from the glue-air and air-PAR surfaces, which are due to the higher index of refraction discrepancies much more pronounced. Normally, we should see additional new one interferogram. However, the generated interferograms are probably overlaped so we can see just one with rather high intensity.

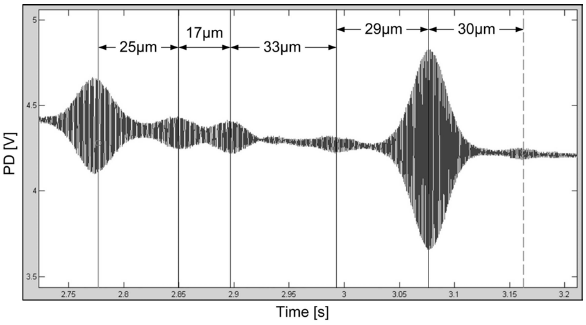


Fig. 6 Interferometric pattern of five layer foil

We investigated multilayer foils by scanning of the sensing fiber in matrix of 1×1 mm. We found some discrepancy in thicknesses of the glue layers between singular measuring points. It is probably caused by non-uniform distribution of the glue during industrial production of the foils. This fact is very important because it can explain some differences in sound characteristics of loudspeakers.

5. Conclusion

In this paper we presented a non-destructive technique based on low-coherence interferometry capable for measuring of physical thicknesses and index of refractions of the multilayer structures. We tested polymer based single, three and five layers foils in order to measure thicknesses of every singular layer. We performed our technique as an “all-fiber” Michelson interferometer suitable for mapping of the foil scanning the subjected area in x-y direction with steps of 1 mm. The accuracy of the technique in thickness measurement was about 40 nm and was limited by the accuracy of the applied mechanical scanner.

This technique seems to be very effective not only for this purpose but in every field where the layers are optically transparent for the used light wavelength.

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