Acousto-optic filtration of interfering light beams for visualization of amplitude and phase structure of small-size objects

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Abstract

A technique for acousto-optic image filtration in full-field interferometry is proposed. It is based on the spectral selection of light in the registration channel of the Michelson interferometer by an imaging acousto-optical tunable filter. The technique is applicable for various full-field spectral-domain systems in profilometry and optical coherence tomography. It is experimentally shown that registered spectral signals may be used for 3-dimensional visualization of structure of optically inhomogeneous objects.

Keywords: acousto-optical tunable filter; imaging spectrometer; optical coherence tomography; Michelson interferometer.

1. Introduction

Techniques most commonly used for visualization of inner structure of optically transparent microscopic objects in biology, medicine and non-destructive testing are optical coherence microscopy (OCM) and digital holography. These two techniques are based on spectral interferometry and digital image processing [1-3].

In practice, for these applications acousto-optical tunable filters (AOTFs) are already being used for wideband light source wavelength sweeping in spectral domain (SD) OCM [4]. However, another approach, namely, acousto-optic (AO) filtration of light interacted with an inspected object, appears to be more promising. This approach allows to inspect an object by means of wideband microscopy, spectral imaging and OCM at once with no need to move it.
Such a feature is called multimodality, i.e. the integration of various inspection modalities based on different physical principles in one device, and now it is one of the major trends in biomedicine.

A principal possibility of AO filtration of two interfering beams, which transfer images, has been proved previously [5-8] for surface and inner structure visualization though it is not so obvious that phase structure is kept.

In this paper we experimentally demonstrate the applicability of AOTFs for interfering beams filtration in two widely spread and practically important applications: OCM and thickness measuring of optically transparent objects.

2. Spectral-domain OCM

Fig. 1(a) shows the optical scheme for SD OCM measurements. Light emitted by a wideband light source 1 is collimated by lenses 2 and is split by a beamsplitter 3 in two beams: one is reflected into the sample arm, the other is directed into the reference arm. Two identical microscope objectives 4 focus beams on an inspected object 6 and on a reference mirror 5. The same objectives collect the light reflected from the mirror 5 and backscattered from the object 6. The beamsplitter 3 combines the returning sample beam and reference beam into one and directs it to an AOTF 7. An objective 8 focuses the narrowband light diffracted by an acoustic wave on sensor of monochrome camera 9 to produce a spectral interference image at selected wavelength $\lambda$ which is driven by frequency of the radio-frequency oscillator. Interference images can be acquired by spectral scanning. Digital processing of acquired images gives signal dependence $S_{x,y}(z)$ on depth $z$ in each pixel $(x,y)$.

Our experimental setup comprises a wide-angle TeO$_2$ AO cell for image filtration in spectral range $\Delta \lambda = 700 - 1000$ nm. The AO cell provides angular resolution of approximately 500x500 resolved elements and spectral resolution $\delta \lambda \approx 1.2$ nm; its entrance angular aperture is 3.5° and entrance pupil diameter is 6 mm. We used a stack

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Fig. 1. Scheme and results. (a) scheme: 1 – wideband light source; 2 – collimating optical system, 3 – beamsplitter, 4 – microscope objectives, 5 – reference mirror, 6 – object under inspection, 7 – AOTF, 8 – objective, 9 – monochrome camera; (b) interference image ($\lambda=740$ nm); (c) B-scan along p-line.
of two polyethylene films (refractive index was $n \approx 1.5$, estimated thickness was about $d \approx 12 \, \mu m$) placed on black light-absorbing paper as the sample to demonstrate the inspection capabilities for SD OCM. A series of 160 interference images within the spectral range 740 – 900 nm with scanning step of 1 nm was registered. Fig.1(b) shows one of the captured spectral interference images at wavelength $\lambda = 740$ nm. B-scan along $p$-line is shown in Fig.1(c). Four reflective surfaces (two for each film) are clearly distinguishable. Visualized thickness of each film $\Delta = 35 \, \mu m$ depends on polyethylene refractive index $n$ and approximately corresponds to the estimated value: $\Delta/(2n) \approx d$.

3. Thickness measurement

Fig.2(a) shows the optical scheme for thickness measurements, in which the object in the sample arm is replaced with a mirror 5. Optical components are equal to those of the previous scheme. The inspected optically transparent object 6 is placed in the reference arm so as to obstruct about a little less than half of the light beam. All the light rays returning from the reference arm either has passed through an object once or hasn’t passed at all. In that way, at the output of the reference arm the phase shift $\Delta$ induced by the object is symmetrical with respect to the horizontal plane containing the axial ray. It depends on the object’s thickness $d$ and the refractive index $n$ of the object as $\Delta = dn$.

Once again, we used one polyethylene film ($n \approx 1.5$, $d \approx 12 \, \mu m$) as the sample in our experiment, but this time without black paper in order to demonstrate the inspection capabilities for thickness measurements. Fig.2(b) shows one of spectral interference images at wavelength $\lambda = 740$ nm. Phase shift induced by film is seen on $B$-scan along $p$-line in Fig.2(c). Visualized thickness of film $\Delta \approx 19 \, \mu m$ approximately corresponds to the estimated value: $\Delta/n \approx d$.

Fig. 2. Scheme and results. (a) scheme: 1 – wideband light source; 2 – collimating optical system, 3 – beamsplitter, 4 – microscope objectives, 5 – reference mirror, 6 – object under inspection, 7 – AOTF, 8 – objective, 9 – monochrome camera; (b) interference image ($\lambda=740$ nm); (c) $B$-scan along $p$-line.
4. Conclusion

In this paper, we have described the interferometer-based scheme for inspection of microscopic objects. It is based on AO filtration of interfering beams, which transfer images. We experimentally demonstrated two operating modes of the scheme: SD OCM and phase visualization. Experiments have shown that the proposed imaging-AOTF-based approach can become an effective solution to these two fields. The achieved depth resolution ≈ 1 μm is sufficient for many applications and may be increased by using the AOTF with broader spectral range.

It should also be noted that the same scheme with a little modification allows object inspection by means of wideband optical microscopy and spectral microscopy.

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