Multi-spectral phase imaging based on acousto-optic selection of light in common-path interferometer

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Multi-spectral phase imaging based on acousto-optic selection of light in common-path interferometer

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Abstract. Multispectral interference techniques are widely used in biomedicine and science for quantitative characterization of morphological, chemical and other properties. These techniques, for example, multispectral digital holography and spectral-domain optical coherence tomography, require wavelength tuning in the interferometer. In this paper, we discuss the effectiveness and potential applications of acousto-optic light filtration for this purpose. We show experimentally that acousto-optical tunable filters are effective for simultaneous spectral and phase data collection not only in conventional dual-path interferometers but also in a common-path interferometer. Scheme of a compact spectral interferometric module based on such interferometer is presented.

1. Introduction

Interference techniques for objects inspection are widely used in biomedicine, industry and science. They provide contactless operation, high precision and data acquisition speed. Along with the interference systems utilizing coherent monochromatic (laser) radiation, systems based on low-coherence radiation are in use, as they allow avoiding speckle noise and parasitic interference patterns. In the majority of such systems, spectral selection of light is necessary for implementing the interference measurements (for example, by optical coherence tomography or digital holography techniques) [1, 2]. For wavelength tuning in the interferometer, various spectral elements, such as diffraction gratings, liquid crystals and acousto-optic (AO) filters may be used. AO filters allow to acquire full two-dimensional (2D) image, do not require an additional scanning in one or two spatial coordinates [1] and provide narrow spectral bandwidth and high tuning speed [3]. The use of AO filters for filtration of interfering light beams in the output arm of the interferometer allows to create multimodal systems for spectral and interference analysis [4]. Spectral data can be used for contrast visualization of the object elements with particular physical and chemical properties as well as for spectral measurements, i.e. for calculating spectral dependences of object characteristics. On the one hand, special features of AO filters (absence of moving elements, fast electronic control, random spectral access, compactness, etc.) offer new opportunities for combination of spectral and low-coherence interference techniques. On the other hand, the feasibility of this approach is not evident since AO filtration may destroy the interference pattern as well as the angular spectrum of each of beams may be distorted and decrease the image quality. The possibility of applying AO filtration of
interfering image-carrying light beams was demonstrated experimentally for low-coherence interferometry in classical versions of interferometers [4-6].

2. Conventional two-beam interferometers and common-path interferometers

Conventional low-coherence interferometry schemes are based on two-beam interferometers, such as Michelson, Mach-Zehnder and others (figure 1). The inspected object is located at one of the interferometer’s arm, which is called “object arm”. In this case, the object is located like “inside” the interferometer and the image of the object is formed by optics of the interferometer. These systems have relatively large dimensions, require time-consuming adjustment but they provide “flexibility”, i.e. a possibility of beam convergence condition control for each specific task. AO filtration of interfering image-carrying light beams, in particular, in Michelson interferometer allows implementing measurements by spectral-domain optical coherence tomography technique and acquiring wideband and spectral image as well as phase profile without the inspected object displacement [4]. AO filtration in Mach-Zehnder interferometer allows implementing the multispectral holography mode and acquiring the phase maps and spectral images [5].

Lately, an alternative approach to the design of interference schemes, in which the inspected object is located "outside" the interferometer, is being actively developed. It is called "common-path interferometry". In this case, optical system (such as, for example, microscope, endoscope or telescope) forms the beam that carries image of the inspected object. This beam enters the common-path interferometer in which two interfering beams are formed from it in different ways. For example, it can be simple division into two for the autointerference (self-referencing) beams [7-11]. Alternatively, the reference beam can be formed by spatial filtration of the object beam [12-16]. The common-path interferometers are robust to the environmental vibrations (since the interfering beams propagate along approximately the same path), compact, relatively simple in terms of adjustment while they give less "freedom" for it. Based on common-path interferometers, compact modules for phase measurements using conventional imaging devices may be created. Applying of AO filtration in such modules could provide the device with a larger number of functions by adding a possibility of a spectral analysis for receiving more information about inspected object.

Figure 1. Approaches to interference schemes design: conventional two-beam interferometers (left) and common-path interferometers (right).
3. Compact common-path interferometer based on acousto-optic filtration

To demonstrate the potentials of AO image filtration in common-path interferometers, we introduce spectral interferometric module based on off-axis τ-interferometer [16] with nearly common-path beams propagation (figure 2). The module consists of confocal lenses L1 and L2, beamsplitter BS, roof mirror M1, mirror M2 with pinhole P (point reflector), AO tunable imaging filter AOTF and digital camera. The wideband light beam enters the module from outer imaging system and then is divided into two. In figure 2, outer imaging system is a transmitted light microscope. One of these beams preserves the image of the inspected object while being reflected from roof mirror M1. The second beam is spatially filtered by point reflector (mirror M2 with pinhole P) to become a reference beam. Then both interfering beams are simultaneously spectrally filtered by AOTF. They form spectral holographic image on camera sensor. To calculate the phase map, acquired image is processed by digital holographic techniques, including double Fourier transform and phase unwrapping. With electronically controlled AO spectral tuning, several spectral interference images can be acquired. Multispectral holographic acquisition can be used to increase phase measurement precision [6] as well as to increase phase unwrapping algorithm accuracy [17]. Unlike the interferometers [12-14], it is possible to adjust the interference fringe appearance by tilting and moving roof mirror M1. The disadvantages of this arrangement include the difficulty of the pinhole alignment (to get a beam into the pinhole in the reflection mode is much harder than in transmission mode; this, however, can be solved as proposed in [15]) and significant energy losses (because of the pinhole, beam splitter and anisotropic diffraction mode implemented in AOTF).

![Figure 2](image_url)

Figure 2. Proposed scheme of multi-spectral phase imaging.

For experimental research, we used the following components. Superluminescent diode Superlum S-785-B-I-15 (Δλ = 770-810 nm) coupled into single-mode fiber was used as a light source. Single mode fiber is necessary to increase the spatial coherence. Microscope with infinity-corrected microscope objective MO 20x (NA 0.4) formed an image of the inspected object in the focal plane of the lens L1. Lenses L1 and L2 had focal lengths f_1 = f_2 = 90 mm. Pinhole diameter was 25 μm. AO filter was made of TeO2 cell placed between two crossed polarizers. In the filter, wide-angle non-collinear configuration of AO interaction was implemented for extraordinary polarized light. Its tuning range was Δλ = 740-1000 nm with spectral bandwidth of approximately Δλ = 4 nm (at λ = 800 nm),
entrance pupil 5 mm, angular aperture 2.5°× 2.5°. For image acquisition, we used monochrome CCD camera Prosilica GC1380.

Figure 3 shows the images of a Fresnel lens made of SU-8 photoresist. Upper row contains spectral holograms acquired with AO spectral tuning in range from 770 nm to 810 nm with 10 nm step. Bottom row contains numerically reconstructed phase maps. Phase maps are inverted due to "-1st" diffraction order selection during filtration in the spatial frequency domain, i.e. physically lens is thicker in regions with negative phase delay. Measured profile height is \( h = \Delta \phi \cdot \lambda / [2\pi(n-1)] \); \( \Delta \phi \) is measured phase delay, \( \lambda \) is a wavelength selected by AO filter, \( n \) is refractive index of the lens material at \( \lambda \). An average measured height \( h = 460 \) nm. It coincides with the results acquired by atomic-force microscope.

\[
h = \Delta \phi \cdot \lambda / [2\pi(n-1)]
\]

\( \Delta \phi \), rad

\( \lambda = 810 \) nm

\( 770 \) nm

\( 780 \) nm

\( 790 \) nm

\( 800 \) nm

\( 810 \) nm

Figure 3. Experimental results: spectral holographic images acquired with AO tuning (\( \lambda = 770:10:810 \) nm) (upper row) and reconstructed phase maps (bottom row) of a Fresnel lens.

4. Conclusion
In this paper, we have shown that AO filtration of interfering light beams in common-path interferometer may be effectively used for multispectral low-coherence interferometry. It enables
formation of two interfering narrow-band beams from one wideband beam and allows collecting both phase and spectral information about the inspected object. Based on this approach, the spectral interferometric modules for microscopes, endoscopes and other imaging systems may be produced.

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