Multi-spectral interference imaging using laser-induced plasma light source

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Abstract. Interference imaging techniques are widely used for studying surface and internal structure of various objects. By varying the operating wavelength of the interference system, one can also obtain the information about the spectral properties of the inspected specimen. For multi-spectral interference imaging applications, wide-band high power light sources are necessary. Most of the existing sources suffer from speckle noise, low brightness or high price. In this paper, we demonstrate the applicability of a laser-induced plasma light source for interference imaging and quantitative phase measurements. Narrow-band spectral filtration of its illumination within a wavelength range 240-2600 nm allows to design cost-effective schemes for a variety of metrological applications including digital holography and spectral-domain optical coherence tomography.

1. Introduction

Interference methods are widely used for non-invasive diagnostics of biological objects in cytological and morphological applications, non-destructive testing, deformation analysis, etc. [1-3]. They provide non-contact and fast extraction of information about both amplitude and phase of the wave reflected from or transmitted through the inspected specimen. Being complemented by tunable selection of the operating wavelength from a wide-spectrum illumination, interference schemes allow to estimate spectral properties of the specimen as well as to implement spectral-domain optical coherence tomography techniques [4-6].

The key component of any multispectral interference imaging scheme is a light source. To provide high-contrast and informative interference patterns and to be applied to practical tasks, the light source must have a rather wide spectral range, high brightness, temporal stability, long lifetime, small dimensions and low price. Simultaneous satisfaction of all these requirements is barely possible using...
conventional serially produced devices. Traditional gas discharge lamps are either not bright enough for some applications or have very low spatial coherence. Light emitting and superluminescent diodes have relatively narrow spectral band. Commercially available supercontinuum laser light sources suffer from spatial noise, relatively high price and need complicated additional processing for the reduction of parasitic interferences [7].

In this research, we propose to use laser induced plasma light source for the interferometer. It emits wide-band (240-2600 nm) and stable light nearly free of spatial noise. Together with a narrow-band filter, it provides low-coherent and powerful illumination within a wide spectral range. We demonstrate effectiveness of such light source by using it in a Mach-Zehnder interferometer for quantitative phase imaging of Fresnel lens structure and human red blood cells.

2. Light source based on laser-induced plasma

In our experiments we used laser-induced plasma light source XWS-65 (ISTEQ B.V.) The operating principle of this light source is based on a well-known phenomenon of optical discharge [8]. When focused, a powerful CW laser beam creates a self-sustained discharge in a gas media under high pressure. Plasma is localized in a small volume and provides emission with wide spectrum and high brightness. In XWS-65 light source the CW diode laser with a power of 70 W is utilized coupled with optical fiber (Figure 1). Cooling and temperature stabilization is achieved by using thermoelectric Peltier modules and appropriate control electronics. After the fiber, optical system focuses the light onto the bulb filled with Xenon under pressure of >10 atm. For initial ionization, 25 kV spark discharge is used. The dimensions of emitting area are approximately $250 \times 600 \mu m^2$. Plasma emits a wide-band light in the wavelength range 240-2600 nm with spectral brightness up to 60 mW/(mm$^2$·sr·nm).

![Figure 1. Scheme of a wide-band light source based on laser-induced plasma](image-url)

3. Experimental setup

To verify the applicability of laser-induced plasma illumination for interference imaging applications, we have assembled a setup shown in Figure 2. It consists of a fiber-coupled light source described above, collimating system CS, narrow-band filter NBF, Mach-Zehnder interferometer, two-lens magnifying system L3-L4 and a monochrome camera CAM [9]. The wide-band light is collected by the collimating system CS, filtered by the glass filter NBF and directed to the interferometer. At the entrance of the interferometer, the beamsplitter BS1 splits the light beam into two arms. In one arm, the lens L3 with numerical aperture $NA = 0.05$ directs the light onto the sample S. The light passed through the sample S is collected by the microscope objective lens MO ($40x$, $0.75$ $NA$). The intermediate image plane is in the back focal plane of the lens L2. In the second arm, two mirrors M2 and M3 are placed on a translation stage in order to adjust precisely the optical path difference between the two arms. Object and reference beams are brought together at a small angle by beamsplitter BS2. The position of the lens L3 is adjusted so that its front focal plane coincides with the intermediate image plane. The confocal system L3–L4 gives the additional magnification $3^x$. Two beams interfere in the back focal plane of the lens L4, where the image sensor of a digital camera CAM (TheImagingSource DMK27BUJ003) is placed. In this setup, the tilt angle of the beamsplitter BS2 is $2.6^\circ$, which corresponds to the Nyquist criterion.

Thus, this scheme allows to obtain holographic interference images of optically transparent specimens in narrow spectral bands in a broad range of wavelengths.
4. Experimental results
The setup was used to capture interference fringe patterns and calculate the distribution of the phase delay induced by various specimens. Image processing algorithm includes spatial filtration and centering the 1st order of the cosine term of the interferogram in Fourier domain, obtaining wrapped phase from the filtered image, applying Goldstein phase unwrapping algorithm, subtraction of the background phase and linear trend removal.
Figure 3 shows holographic images and calculated phase maps of a human red blood cell (RBC) and a structure of a Fresnel lens etched in SU-8 photoresist on a glass substrate. These are well-examined specimens and can be used as the test objects for the proposed scheme. The interference fringe patterns have high contrast and are suitable for accurate phase extraction. Phase images demonstrate good repeatability of structural elements and are in good agreement with real shape of the objects.

5. Conclusion
In this paper, we demonstrate the applicability of a laser-induced plasma light source for interference imaging and quantitative phase measurements. Narrow-band spectral filtration of its illumination within a wavelength range 240-2600 nm allows to design compact and cost-effective schemes for a variety of metrological applications including digital holography and spectral-domain optical coherence tomography. Due to high image quality, the potential applications of the proposed approach may include many fields where accurate phase and spectral measurements are needed: cell imaging, industrial inspection of thin films and coatings, etc.

The described light source provides a broad spectral range, high brightness, high temporal and spatial stability and long lifetime. It may replace traditional gas discharge lamps (Deuterium-, Tungsten-, Xenon- etc.) and diodes.

Though the proposed approach was illustrated by a specific optical scheme, there are a lot of modifications which have the potential for many biomedical and industrial applications of phase imaging. Laser-induced plasma light source can be applied not only to digital holography but also to other multi-spectral interference techniques, for example, spectral-domain optical coherence tomography.

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References
[1] Kim M K 2011 Digital Holographic Microscopy: Principles, Techniques, and Applications (Springer)
[2] Paturzo M, Pagliarulo V, Bianco V, Memmolo P, Miccio L, Merola F and Ferraro P 2018 Digital holography, a metrological tool for quantitative analysis: trends and future applications Opt. Lasers Eng. 104 32–47

[3] Bhaduri B, Edwards C, Pham H, Zhou R, Nguyen T, Goddard L and Popescu G 2014 Diffraction phase microscopy: principles and applications in materials and life sciences Adv. Opt. Photonics 6 57–119

[4] Bouma G T 2002 Handbook of Optical Coherence Tomography (NY: Marcel Dekker, Inc.)

[5] Kemper B, Kastl L, Schnekenburger J and Ketelhut S 2018 Multi-spectral digital holographic microscopy for enhanced quantitative phase imaging of living cells Proc. of SPIE 10503 1050313

[6] Dontu S, Miclos S, Savastru D and Tautan M 2017 Combined spectral-domain optical coherence tomography and hyperspectral imaging applied for tissue analysis: preliminary results Appl. Surf. Sci. 417 119–23

[7] Kosmeier S, Langehanenberg P, von Bally G and Kemper B 2012 Reduction of parasitic interferences in digital holographic microscopy by numerically decreased coherence length Appl. Phys. B 106 107–15

[8] Lieberman M and Lichtenberg A 2005 Principles of Plasma Discharges and Materials Processing (NJ: John Wiley & Sons)

[9] Machikhin A, Polschikova O, Ramazanova A and Pozhar V 2017 Multi-spectral quantitative phase imaging based on filtration of light via ultrasonic wave J. Opt. 19 075301