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Project title:

Lens-free Tomography of Transparent Materials with Super-high Resolution

The project is focused on the basic research of optical methods for three-dimensional imaging of microscopic structures in transparent materials. Examples of such structures are domains in ferroelectric materials, strain fields around topological defects in photoelastic materials, phase interfaces in solid-solid phase change materials, etc. The main goal of the project is to develop methods for optical spatial imaging of microscopic structures in transparent materials using on-chip microscopy and super-resolution tomography.

Human vision and all the commonly-used means of imaging are based on detecting changes in light intensity. Despite being applicable in a majority of situations, this principle brings limitations in observing a broad range of samples, where the structure of interest does not have any effect on the intensity of the transmitted light at all. In chemically complex structures, such as biological tissues, this problem can be resolved by sample treatment using staining techniques, which use preferential bonding of antibody labels to particular structural elements in the tissue. Unfortunately, there exists a large group of transparent inorganic materials with pronounced microscopic structures, where such staining techniques cannot be used. This varied group includes domain structures in ferroelectric materials, strain fields around topological defects in photoelastic materials, or phase boundaries in solid-solid phase change materials. The internal structure of these specimens is encoded in their refractive index changes.

The need for imaging such specimens has led to an extensive effort devoted to devising imaging techniques featuring contrast in the refractive index. A possibility for imaging refractive index variations is enabled using methods based on holographic interferometry. The spatially non-uniform refractive index produces the deformation of the wavefront of the transmitted optical wave, which can be measured using digital holographic interferometry (DHI).

Another issue of optical measurements is their resolution, which is limited by the so called Abbe diffraction limit $\lambda/(2\,\mathrm{NA})$, where λ is the wavelength of the optical wave and NA is the numerical aperture. The maximum resolution given by the diffraction limit is about 250 nm for green light. In order to overcome this fundamental limit, super-resolution methods based on so called on-chip imaging have been developed. On-chip imaging has proven to be a straightforward and cheap alternative to conventional microscopy, which makes super-resolution imaging possible using incomparably simpler optical arrangements than those employed in conventional microscopy. Unfortunately, super-resolution on-chip microscopy can only be applied to measurements where the image information is encoded in the intensity of the light wave. No method has been developed for super-resolution measurements of phase deformations so far.

The core of the project will be the development of methods for on-chip microscopy and tomography, which allow measurements of the spatial distribution of the refractive index in transparent materials.

The conventional arrangements of on-chip tomography and super-resolution on-chip microscopy are shown in Fig. 1. In both of these arrangements, the specimen is placed on top of the transparent layer, while the CMOS sensor array is placed just beneath the transparent layer. The laser point source located above the specimen illuminates the objects above the CMOS sensor. The specimen produces diffraction of the incident laser light. The diffracted wave is superposed with the incident wave resulting in the creation of a hologram, which is captured by the CMOS sensor.

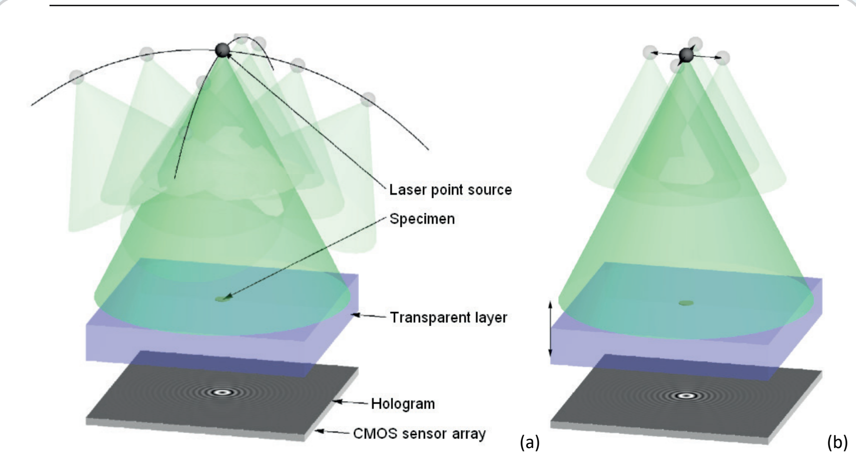

Fig. 1: The conventional arrangement of on-chip tomography (a) and super-resolution on-chip microscopy (b).

The main objectives of the presented project are the following:

- (O1) Design of optical systems for imaging transparent materials based on on-chip microscopy.
- (O2) Development of numerical algorithms for on-chip microscopy of transparent materials.
- (O3) Development of numerical algorithms for tomographic reconstruction.
- (O4) Performing experiments with the constructed on-chip tomograph and performing a characterization of the refractive index distribution in selected transparent materials.

In order to achieve the main objectives of the project specified above, two different experimental arrangements will be considered. The first arrangement employs a single laser beam and a system of diffractive elements. The second arrangement utilizes two coherent laser beams.

The scheme of the setup for on-chip tomography with a single laser beam and a system of diffractive elements is shown in *Figs. 2 (a)* and *(b)*. The system consists of a ferroelectric single crystal with transparent top and bottom electrodes. The system of diffractive elements is deposited on the top electrode. The CMOS sensor array captures the micro-interference pattern (hologram). In the case of uniform refractive index, i.e. in the zero applied field in the ferro-electric domains, the captured hologram has a form of circular fringes, see *Fig. 2 (a)*. When the external electric field E is applied to the ferroelectric single crystal, the fringes move and the hologram captured by the CMOS sensor is changed due to the inhomogeneous distribution of the refractive index in the ferroelectric domain pattern in the external electric field E, see *Fig. 2 (b)*. *Figure 2 (c)* shows the on-chip tomography setup with two coherent laser point sources. In this case, the captured hologram has a form of linear fringes, whose width depends on the value of the refractive index in the transparent layer above the CMOS sensor array.

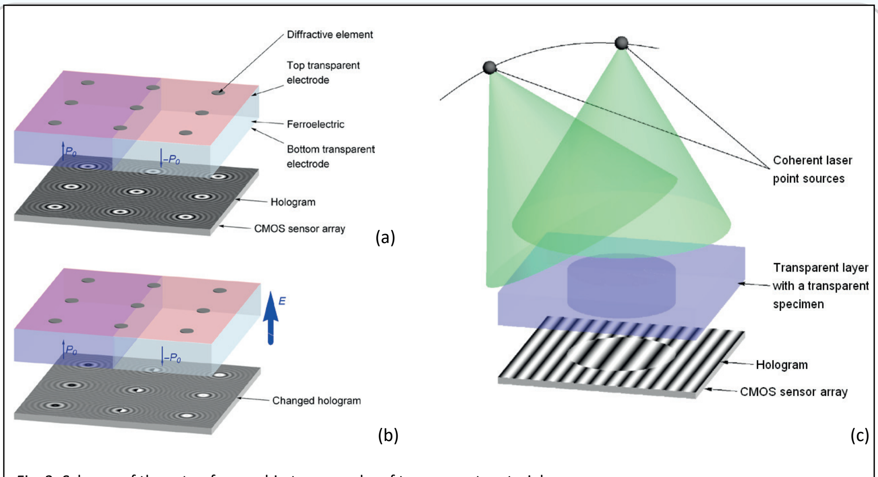

Fig. 2: Scheme of the setup for on-chip tomography of transparent materials