UV photonic integrated circuits for robust quantitative phase imaging

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Abstract: Photonic integrated circuits have been demonstrated to benefit super-resolved fluorescence microscopy. Here, we propose a UV PIC-based quantitative phase imaging based on Kramers-Kronig relationships, achieving robust and high-resolution phase image retrieval in a low-cost and compact way.

1. Introduction

Photonic integrated circuits (PIC) benefiting from its complementary metal-oxide semiconductor (CMOS) compatibility and large scale fabrication have accelerated the development of many optical fields. Recently, PICs have been demonstrated for the applications in advanced microscopies, including fluorescence based supper-resolution microscopy using techniques of direct stochastic optical reconstruction microscopy (dSTORM) [1], points accumulation in nanoscale topography (PAINT) [2] and structured illumination microscopy in the evanescent field [3]. In particular, we have recently demonstrated super-resolved structured illumination microscopy in the far-field by using a PIC operating in the ultraviolet wavelength (UV) range [4]. These optical fluorescence microscopy techniques break through the diffraction limit of traditional microscopy, but the photobleaching of fluorophores hinders their applications for image acquisitions over long-exposure times.

Quantitative phase imaging (QPI) has emerged as a powerful technique for inspecting the morphology and chemical compound of transparent objects such as biological cells without the need of labeling [5]. An interferometry setup is generally required in this technique, in order to record the hologram generated by the sample beam and reference beam. The phase information is then recovered from the recorded hologram. However, the interferometry approaches require high standards of mechanism stability to minimize phase fluctuations and enable a precise phase recovery. Alternatively, an intensity-based QPI technique was proposed and demonstrated to offer a more robust phase recovery, based on space domain Kramers-Kronig relationships (KK-relationships). The concept was first developed for electron microscopy in 1974 [6] and more recently elaborated in optical microscopy [7].

In this paper, we propose a UV PIC-based QPI technique based on space-domain KK-relationships, which is compact and cost-effective. Implementing this technique in the UV range allows us to push both the phase and the transverse resolution limit.

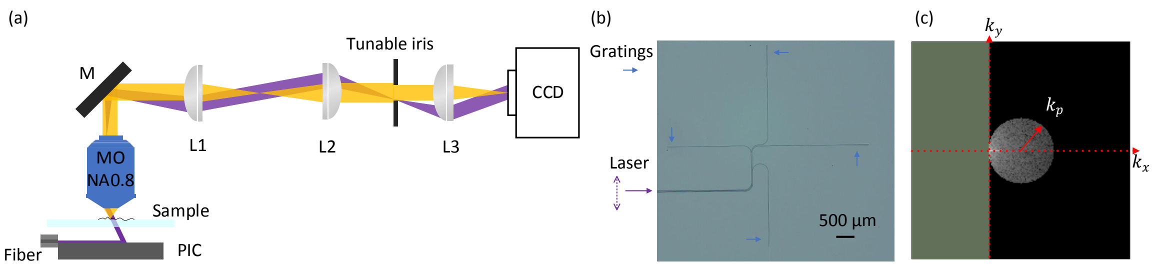

Fig. 1. (a) Schematic of the configuration of UV PIC based QPI. (b) Optical image of a PIC fabricated on a AlO_x/SiO_2 platform. (c) Amplitude image of optical field at Fourier plane where the iris is placed in (c) such as $NA_{ex}= NA_{co}$.

2. Implementation and results

The schematic of the configuration is shown in Fig. 1(a). A UV laser operating at 360 nm is coupled into on-chip circuits via a single mode fiber. The light confined in waveguides is routed to a grating out-couplers, scattered into free space and illuminates the sample above the chip. Both the illumination (purple) and light scattered by the sample (yellow) are collected by the microscopy objective (MO) with a numerical aperture (NA) of 0.8. Lenses L1 and L2 are used to image the Fourier plane of the microscope objective. A tunable iris is placed at the focal plane of L2 to reshape the aperture of the imaging system. The signal filtered by the iris is then collected by a lens L3, which forms an intensity image in a camera. The photonic integrated circuits are designed to generate azimuthal rotation illuminations with four orientations rotated by an angle of 90^o. A low-loss UV compatible AlO_x photonic integration platform is used to construct the circuits and validate the concept, see Fig. 1(b). The grating is shallowly etched with a depth of 20 nm and a grating pitch of 185 nm, which provides scattered beams with a numerical aperture NA_{ex} of 0.45. The orientation of the illumination is switched by lateral shifting the input fiber. In order to apply the KK-relationships to retrieve the phase from an intensity image, the collection numerical aperture NA_{co} is adjusted to match that of the excitation NA_{ex}. In this way, signals at one of the half planes in Fourier space are canceled and the illumination beam is simultaneously collected to fulfill the condition of analyticity [7]. Figure 1(c) shows an amplitude of a complex field at the Fourier plane in the case of NA_{ex}=NA_{co}. The light green area indicates the signals at $k_x<0$, which is not collected due to the limited bandwidth of the apertures.

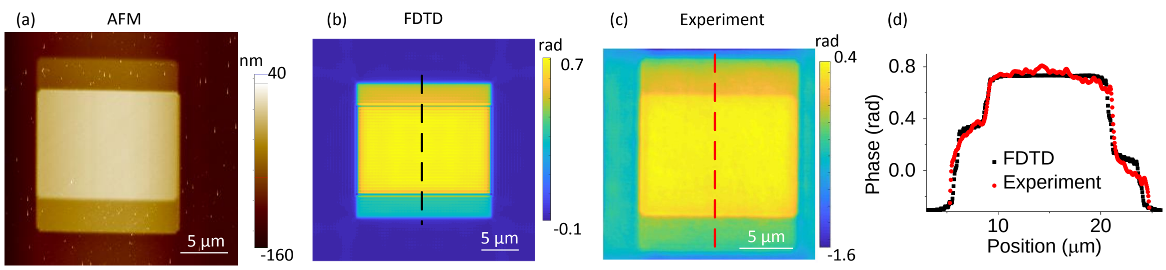

Fig. 2. (a) AFM topographic profile of the studied phase object. (b) phase map from FDTD simulation and (c) from experimental QIP. (d) phase profiles along the dashed line in (b) and (c).

A pure phase object made of borosilicate glass is fabricated after two steps of RIE etching using a gas mixture of CF_4/O_2. The profile of the object is measured by atomic force microscopy (AFM), see Fig.2(a). Three blocks with different heights are measured, with values of 43 nm, 72 nm, and 115 nm respectively. The topographic profile measured with AFM is used as the ground truth of the object in the experiment and simulation. The light field propagating through the object is simulated with a finite-difference time-domain (FDTD) method, in the same illumination condition as mentioned above. The intensity images of the simulated light field are used as raw data to retrieve the phase by applying the KK-relationship. After stitching the images in the Fourier domain, the 2D optical complex field is obtained in the space domain, the phase of which is shown in Fig. 2(b). The experimental phase map is shown in Fig. 2(c). In Fig. 2d, the cross-section along the dashed line in Fig.2(b) and (c) highlights the good match between the simulated and experimental results. With the current configuration, the optical resolution and spatial phase sensitivity are determined to be 400 nm and 1.4 mrad, respectively.

To conclude, we have proposed and validated a UV PIC-based quantitative phase imaging technique that offers a low-cost and compact solution with improved transverse optical resolution.

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