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Wavefront folding interferometer for single-shot lensless imaging

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Abstract. We have developed a fast, high-resolution, and single-shot lensless imaging technique based on the wavefront folding interferometer (WFI). Considering a stationary, quasimonochromatic, and quasihomogeneous source of light we studied the effect of spatial coherence on the retrieved image quality. Moreover, a thorough investigation of the resolution and the semi-infinity depth of focus of the imaging system was performed and demonstrated experimentally.

1 Introduction

Lensless imaging techniques have attracted optical research communities for decades since these types of imaging methods do not rely on complex objectives. Therefore, such techniques can skip the design and fabrication part of high-quality lenses and most importantly do not suffer from aberrations. Several interesting approaches towards lensless imaging have been proposed and demonstrated experimentally [1], where most of those techniques require an image retrieval algorithm, generally based on iterative processes [1, 2].

In the present work, we propose a lensless imaging technique based on incoherent illumination measured with a WFI (see Refs. [3, 4] for more details on WFI). The method features direct image retrieval, and allows for single-shot imaging. Retrieval without noise suppression is fast and makes also real-time imaging (i.e., video recording) possible. Moreover, we demonstrate efficient noise suppression based on principle component analysis (PCA), which leads to high-quality image retrieval. Lastly, we experimentally demonstrate the resolution of the system, the effects of coherence of illumination on the retrieved image quality, as well as the semi-infinite depth of focus.

2 Central concept

Consider a quasi-homogeneous and quasi-monochromatic beam of light with intensity distribution of $S_0(\bar{\rho}')$, which transmits through an arbitrary object with transmittance $O(\bar{\rho}')$ at the plane $z = 0$. Now the cross-spectral density (CSD) of the light at some plane z in the far-field ($z >> z_R$, where z_R is the Rayleigh range) is connected with the intensity distribution at the object plane by the inverted van Cittert–Zernike theorem

$$S_0(\bar{\rho}')O(\bar{\rho}') = \left(\frac{k}{2\pi z}\right)^{-2} \int_{-\infty}^{\infty} W(\Delta\rho, z) \times \exp\left(ik\frac{\bar{\rho}'\Delta\rho}{z}\right) \mathrm{d}^2\Delta\rho. \tag{1}$$

Here, $k = 2\pi/\lambda$ is the wavenumber at wavelength λ and $\bar{\rho}' = (\rho_1' + \rho_2')/2$ denotes the average and $\Delta\rho = \rho_2 - \rho_1$ difference coordinates, with prime signifying the object plane. The central concept, therefore, is to measure the far-field CSD and recover the object transmittance information from that.

3 Experiment and illustration

A schematic of the experimental setup is illustrated in Fig. 1. In our scheme, a rotating diffuser converts a spatially coherent laser beam (with $\lambda_0 = 632.8$ nm) into a partially coherent (quasi-homogeneous) beam. Next, we use a positive lens to collimate the beam. Note that the spatial coherence area of the collimated beam can be controlled by changing the spot size at the diffuser plane. An object interacts with the collimated beam and the transmitted

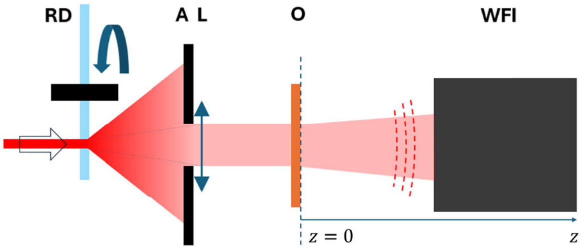

Figure 1. Schematic of the experimental setup. A quasi-monochromatic spatially fully coherent light from a HeNe laser source incident on a rotating diffuser RD, aperture A blocks a part of the light, a positive lens L collimates the scattered field and produces a quasi-homogeneous beam of light. The collimated light next illuminates the object O and the wavefront folding interferometer (WFI) records the interference pattern.

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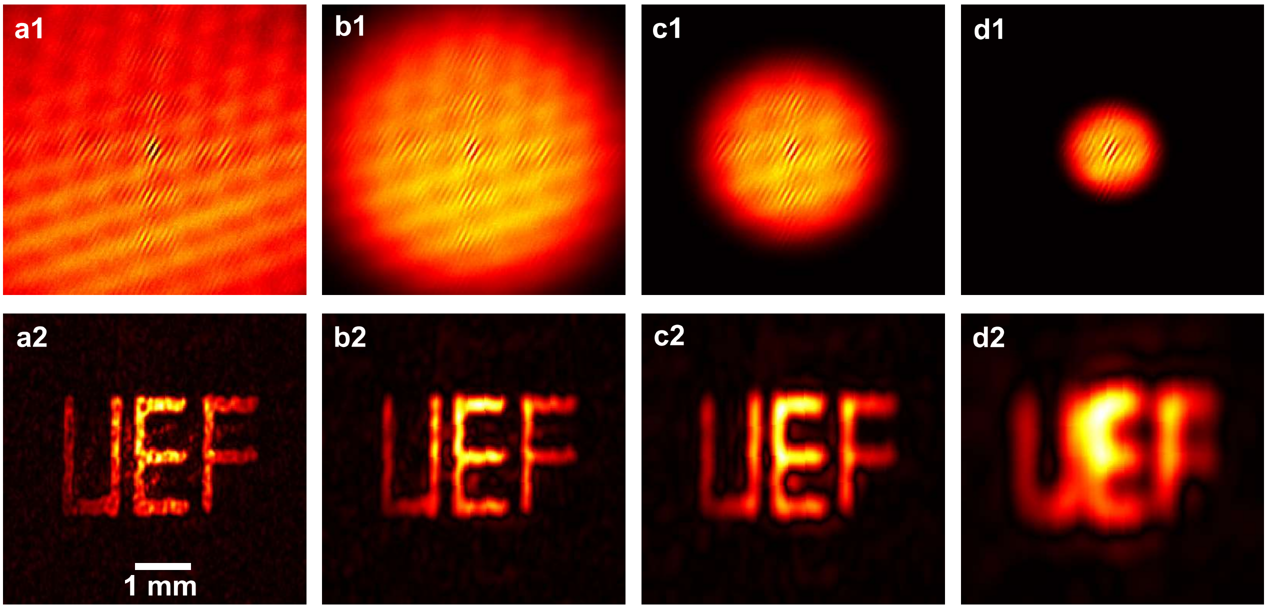

Figure 2. Illustration of the effect of recorded interference pattern on resolution of the proposed imaging technique. The upper row shows the recorded interference pattern and the lower row depict the retrieved images of ‘UEF’ sign. From left to right the sensor area diameter is reduces [a: 1040, b: 520, c: 312, and d:156 μm] → the resolution of the retrieved image decreases. Adapted from Ref. [5]

beam enters the WFI. A CCD camera records the resulting interference.

The WFI measures the CSD along the difference coordinate, $W(\Delta\rho, z)$, at some propagation distance z in a single-shot manner, which is the main advantage of using WFI for the measurement scheme. In Ref. [6], Abouraddy et al. reported similar concept, however, their measurement scheme was slower and restricted along one dimension only. The way WFI flips the incoming wavefront through its arms plays a crucial role here. We retrieve the image information directly from the interference, i.e., the CSD with a carrier, by taking a two-dimensional FFT. This allows us to make real-time lensless imaging and record video with a frame rate of 5 frames/sec with a low-grade processor (Intel i5-6500T @ 2.5 GHz).

In Fig. 2 a1, an example of the recorded interference pattern is shown, whereas in a2 the retrieved image (of an object; UEF sign) is depicted. Here, in Fig. 2, we illustrate the effect of the aperture on the retrieved image resolution. In Fig. 2 a to d, the recording area in the camera sensor decreases, as a result, the resolution of the lensless imaging system becomes poor. In our study, we also moved the object along the z-axis, starting from 440 mm up to 610 mm, from the camera detector and succeeded in recovering the image. Moreover, we also investigate the effect of spatial coherence area of the incident beam of image retrieval. As the beam becomes spatially less coherent, the retrieved image improves. The resolution of the setup follows the usual $\lambda/2$NA rule, where NA is the numerical aperture. In our setup, NA $\approx \theta = 0.015$ and thus, the resolution is $\sim$21 μm. Finally, we demonstrate an efficient noise suppression based on PCA. This allows us to recover high-quality images, close to the theoretical upper limit of resolution for the system, with the expense of further computation.

4 Summary

To summarize, we have introduced a lensless imaging technique based on spatially incoherent illumination, a WFI, and a single FFT operation. The presented technique requires only a single interferometric measurement in the far-field and the image of an object can be directly retrieved from that. This allows fast image recording, and even make videos. Moreover, additional signal processing based on PCA improves the quality and resolution of the retrieved image. The resolution of the image depends on the size of the array detector and the quality depends on the coherence property of illumination. Furthermore, the imaging system has a semi-infinite depth of focus that allows us to retrieve the image while placing the object within a large distance range from the setup.

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