Complex light modulation for lensless image projection

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We present a lensless projection of color images based on computer-generated Fourier holograms. Amplitude and phase modulation of three primary-colored laser beams is performed by a matched pair of spatial light modulators. The main advantage of the complex light modulation is the lack of iterative phase retrieval techniques. The advantage is the lack of speckles in the projected images. Experimental results are given and compared with the outcome of classical phase-only modulation.

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In most fields of consumer electronics a strong trend towards miniaturization and portability is observed. Recently this tendency has reached image projectors, which are currently associated with bulky, noisy, and heavy appliances. Thermal light sources are being constantly replaced by more efficient and long-life light emitting diodes (LEDs) and lasers, hence eliminating the noisy ventilation and reducing the chassis size. On the other hand the strong obstacle in the miniaturization of projectors is the necessity of installing the imaging lens. Its presence involves size requirements along the light path due to the non-zero focal length and in transverse directions to minimize image blur due to low lens aperture. Using smaller lens strongly decreases the image sharpness to an unacceptable level. In order to overcome this limitation numerous concepts of lensless projection were reported. Most of them have serious disadvantages. For example, commercially available beam scanning systems have low resolution, high speckle contrast, inevitable image distortions[1], and problematic health aspects due to naked laser beam exposure and highly flickering images. In order to encode color information, the time-division switching of images of primary colors is commonly used[2,3]. It provides rich colors and requires relatively simple optical setups for the price of unstable images, which is especially visible when fast-moving objects are projected. Therefore alternative techniques of color projection based on the diffraction of light have been reported to be superior[4].

Our approach is based on real-time reconstructions of two-dimensional images from a set of Fourier holograms. The power of the missing imaging lens is integrated in the phase transmittance of holograms, which are displayed on spatial light modulators (SLMs). The approach is similar to the one by Buckley *et al.*, where lasers were used with SLMs and only one lens[5]. In principle, when a Fourier hologram is reconstructed with a single phase modulating device, one removes the amplitude information from the process. Therefore a strong speckle pattern is observed in the output plane, which is due to a random initial phase usually used in iterative phase retrieval methods. In previous works we successfully used iterative fourier transform algorithm (IFTA) and time-integration of holograms with different random initial phase patterns to significantly reduce the speckle contrast[6,7]. There was also introduced an additional phase factor to separate images from the zero-order light peak, which can be then blocked with amplitude filtering[8,9]. However, according to obtained results further suppression of speckle pattern and spurious diffractive orders lead to an inevitable degradation of output image resolution. Another solution of the speckle problem is to preserve the amplitude information in the holographic process. In this contribution we have added a second SLM to act as an amplitude modulating device[10−12]. The design of two distributions: amplitude and phase became trivial as it included a single propagation of the wavefront at the projection distance. Note that as the propagation distance we understand the distance between the last SLM used (SLM2 in Fig. 1) and the projection screen, is equal to 200 mm in our experiments. Eventually, as a consequence of amplitude modulation we have observed a suppression of speckles and a decrease of non-diffracted light, that substantially contributed to better quality of output images.

The ideal scheme of the optical setup for the proposed color projection is presented in Fig. 1. Two liquid crystal on silicon (LCoS) full-HD Holoeye Pluto SLMs are used with three lasers operating at 671 nm (He-Ne), 532 nm (diode pumped solide state Nd-YAG), and 445 nm (laser

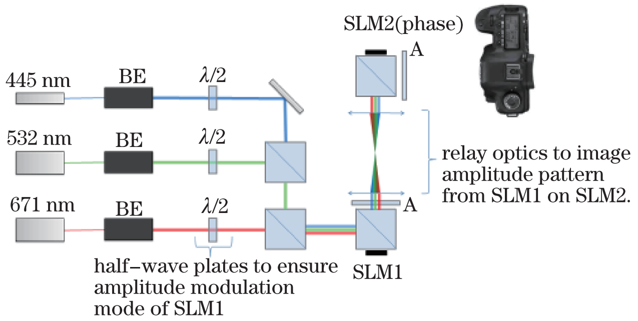

Fig. 1. Scheme of the optical setup for image projection with complex light modulation. BE: beam expanders.

diode). A structured intensity pattern tailored by the SLM (SLM1) illuminates the other phase modulating SLM (SLM2 in Fig. 1). Both SLMs are addressed by the same PC. The particular laser works within a proper one-third part of each SLM similarly to solutions described in our previous works[7,9].

The illumination of SLM1 with a 45° polarization angle and the use of the analyzer (A) ensure the work in an amplitude modulation mode. The intensity pattern and the phase state are projected in 1:1 scale on the surface of SLM2 with help of the achromatic relay optics. The phase modulation is then added by SLM2, which is fine aligned against SLM1 pixel-in-pixel, which means a 8-μm accuracy. The mutual alignment includes the following adjustments: transversal and lateral shifts, rotation, and tilt in both directions. The use of a fine relay optics and a careful alignment makes possible to avoid any phase correction at the plane of SLM2. The beam splitters allow to adjust a zero angle of incidence onto the planes of the SLMs. The images were captured directly on a surface of the CMOS sensor in the Canon 5D digital camera. Note that the pixel pitch of the camera was 6.4 μm, being smaller than the pixel size of the SLMs equal to 8 μm, hence the quality of output images was assessed with all details.

In this letter, we intend to illustrate advantages of the complex light modulation. Therefore, although the optical setup shown in Fig. 1 is designed generally for the color projection, we have limited experimental results to a monochromatic illumination. The obtained images are presented in Fig. 2. By disabling or enabling the SLM1 device, we were able to observe the difference in image quality when phase-only modulation and a complex modulation were used.

The image in Fig. 2(a) shows the results for phase-only modulation with iterated phase retrieval. Strong speckles due to IFTA optimization are clearly seen. On the other hand, simply eliminating the phase retrieval technique leads to strong defects in the output image (Fig. 2(b)). As defects we understand the non-uniform brightness of the parts of the "IF" symbol. Figure 2(c) illustrates the optimal case, where no iterative techniques are used and a complex light modulation is implemented. The speckles are not visible and the reconstruction defects are almost eliminated, i.e., the brightness of symbols is much more uniform. The same effect is observed for different wavelengths, e.g., for red laser illumination (see Fig. 3).

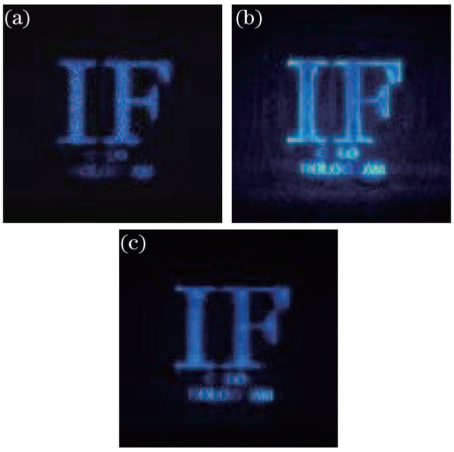

Fig. 2. Experimentally obtained images with (a) phase-only modulation and iterative phase optimization, (b) phase-only modulation with direct phase calculation, and (c) complex modulation with direct phase calculation.

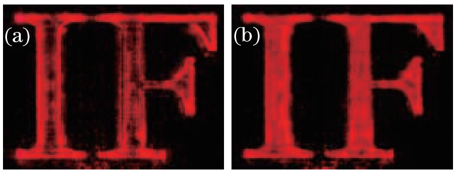

Fig. 3. Experimentally obtained projected images for red illumination. (a) Phase-only modulation with direct phase calculation; (b) complex modulation with direct phase calculation.

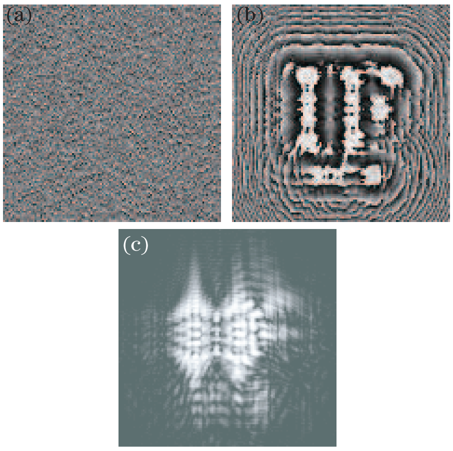

Fig. 4. Exemplary distributions for (a) phase-retrieval method (phase), (b) proposed method with complex light modulation (phase), and (c) proposed method (amplitude).

The lack of speckle patterns can be explained by the non-stochastic nature of non-iterated distributions addressed on the SLMs in the proposed method. Exemplary phase and amplitude distributions used in classic methods and in our approach are shown in Fig. 4. Note the highly random-like phase pattern in the case of iterated phase retrieval and smooth phase and amplitude patterns in direct calculation method.

The residual defects in reconstructed images are mainly due to the limited contrast ratio of the amplitude modulation with SLM1. The Holoeye Pluto modulators are originally designed for phase modulation, hence we plan to replace one of them with a dedicated high contrast liquid crystal display modulator. Additionally the Pluto used as SLM1 introduced minor spurious phase shifts, which were not cancelled by SLM2. The third origin of the defects in output images is the complex shape of the intrinsic backplane curvature of the SLMs. We were unable to fully compensate this defect by using a spherical lens. For this reason, the beam shaping techniques for illuminating beams should be used. In our opinion, after removing the mentioned obstacles the presented complex light modulation could be potentially applied in future consumer projection devices as an alternative to classic projectors equipped with a lens.

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