Toward extremely efficient, lensless, holographic laser projectors

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A new projection method using laser diodes, optical fibers, and liquid crystal phase modulators can produce color, high-quality, high-contrast images with a handheld device and without photon loss.

Image projectors have many advantages over flat-screen displays, including the ability to produce significantly larger images from a relatively small and portable device. However, mainstream projectors use hot light bulbs and bulky, complicated objective lenses to project images onto a distant screen. They are far from being quiet or energy efficient, and efforts to miniaturize them are inevitably constrained by the size and focal length of the lens. Additionally, for small-diameter lenses image, sharpness is compromised by unwanted diffraction. Another drawback of standard projectors is that 3D stereoscopic viewing is problematic, mainly because of the lack of polarization control and a limited LCD response time (which prevents the optimal use of electronic shutter-glasses).

There have been many attempts to overcome these disadvantages. Luckily, thermal light sources are increasingly being replaced by LEDs and eventually by laser diodes. LEDs and lasers are very compact and efficient, but the presence of a lens and liquid crystal light modulators limits the overall efficiency and disables any further miniaturization. We are developing an alternative, lensless, and ultra-efficient technology for miniaturizable, portable projectors that turns the diffraction to its advantage.\(^1,2\)

We have proposed eliminating the lens and using spatial light modulators (SLMs) to efficiently redirect light rays in any given direction without moving parts. In this way, we are able to accurately direct photons emitted by laser diodes to form pixels of the projected image on a screen. Moreover, we create dark points simply by not directing any light there. Thanks to this principle, no photon is lost in the process, which makes the proposed technique extremely efficient. The optical function of the missing lens is included in the especially calculated (in real time) holographic patterns sent to the SLM, and therefore the adjustment of projection distance is done electronically without a traditional focus ring. Additionally, the image contrast is theoretically infinite, since no light reaches the black pixels on the screen. Although the projection takes advantage of holographic means, the images are 2D.

We obtained high-quality color images experimentally from a very simple optical setup consisting of three fiber-coupled lasers

Figure 1. The projection head.

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and an SLM (a Holoeye PLUTO). Light emerges from the fine-cut ends of the fibers and illuminates the SLM. Each fiber carries light in a primary color (red light at 671nm, green at 532nm, and blue at 445nm) and illuminates its designated area of a third of the active window of the SLM panel (see Figure 1).

Light is reflected from the surface of the SLM with the appropriate phase shift for the intended pixel. The SLM works like a miniaturized PC monitor, where every pixel can be addressed with a brightness value between 0 and 255, yielding a given phase shift due to specific reorientation of liquid crystal molecules. In this way, any given distribution of phase retardation can be applied to an impinging wavefront by simply displaying prepared bitmap files on the SLM.

The image quality depends solely on those distributions, and the critical part of the process is their optimal calculation. In our approach, the input frame is split into its color components, forming three separate bitmap files. Each of these files is then treated separately with a Gerchberg–Saxton iterative phase optimization algorithm. The outcome after 5–10 iterations is an optimized phase distribution of a Fourier hologram of the input frame. Such a hologram can be reconstructed by illuminating with a light beam converging in the plane of the projection screen. Our light fibers give divergent beams, and so the phase distribution of a highly focusing lens must be added to the holographic distributions by a complex multiplication operation. The focal length of the virtual lens is established to the holographic distributions by a complex multiplication of the phase distribution of a highly focusing lens must be added to the inclusion of properly oriented phase factors of saw-tooth gratings in the holographic design. For example, multiplying a hologram with the phase factor of a grating with a period of \( \pi \) shifts the image on the projection screen by \( \pm 2 \text{cm} \) in a direction dependent on the orientation of the saw-tooth grating. Figure 2 shows examples captured at a projection distance of 1m.

The color rendering and contrast reach levels acceptable by consumer electronics industry standards. The amount of speckle noise can be further reduced with mechanical vibrations of the projection head, or with a new generation of phase modulators for visual light that have a higher pixel count and smaller pixel pitch. The image size was \( \approx 10 \text{cm} \), which gives the projection throw angle of \( \approx 2.4^\circ \). This is too low for fast commercialization, but will increase as future SLMs improve. Each image point is formed collectively by all of the SLM pixels, and so even large defects in the SLM plane—such as dirt or scratches—have no visible effect.

In summary, we have proposed a novel, energy-efficient method for color image projection. Low energy needs and high resistance to dirt and scratches mean that the extremely simple optical head can be made almost planar and installed in portable devices without compromising image quality. Our future work will focus on improving SLM panels and incorporating higher-power lasers.

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References