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Wavelength multiplexed field of view expansion for high-resolution near-to-eye displays

Ted Liang-Tai Lee, Peng-Yu Liu, Brandon Hellman, and Yuzuru Takashima*
Wyant College of Optics, University of Arizona, 1630 E. University Boulevard., Tucson, AZ, 85721

ABSTRACT

We demonstrate a hologram-based image projector that expands the field of view (FOV) via wavelength multiplexing while retaining the flexibility of the high-resolution image displayed by a Digital Micromirror Device (DMD). Current Near-to-Eye Displays (NED) for AR/VR/MR applications are often limited in Etendue of the display devices and of the image transfer optics. Moreover, angular resolution and FOV are typically coupled, therefore a large physical package volume is also needed for large FOV optics. Our group previously reported increasing Etendue by custom pulsed illumination sources synchronized to a single DMD. To effectively utilize the increased Etendue along with the often angularly band-limited optical channels, for example, a TIR image guide, additional means to effectively increase Etendue of image transfer medium is needed. To address this challenge, wavelength multiplexed image transfer with extraction volume holograms proved to effectively increase the FOV at least by factor of 2. Along with the volume hologram, the prototype projector system employed 100ns pulsed dual lasers as sources, with a 0.7” DMD operating at 20kHz, coupled with a reflection type extraction volume hologram. In this talk, we address the optical architecture of wavelength multiplexed and FOV expanded projector, and are undergoing quantitative assessments of image quality, such as uniformity, resolution, contrast, and crosstalk.

Keywords: DMD, ALSM, Near-to-Eye Displays, Etendue, Field of view, FOV, Wavelength multiplexing

1. INTRODUCTION

Current Near-to-Eye Displays (NED) for AR/VR/MR applications typically have to tradeoff, particularly in resolution, Field of View (FOV), and display size that also defines packaging volume of projection engine. Full FOV, 2θ, is related to half of the display size h via a relation, $h = \mathrm{f} \times \tan(\theta)$ where f is a focal length of the projection lens. This simply means that wider FOV requires a larger display size. Moreover, to accommodate resolution requirements, the number of pixels of the display device linearly scales with FOV too. Since FOV is coupled to the display size, and number of pixels, therefore a large physical package volume is also required for a large FOV image projection.

Previously we have proposed and demonstrated time-multiplexed display with pulsed illumination to increase the number of effective pixels while not increasing the size of the display[1]. The display system modulates spatial and angular contents of the image simultaneously (Angular and Spatial Light Modulation). In the system, reflective Micro Electro Mechanical System (MEMS) display such as Texas Instruments Digital Micromirror Device (TI-DMD) are used along with the ns pulsed illumination with laser diode[2].

Although the Angular and Spatial Light Modulation technique solves FOV-display size tradeoff, an AR display is also limited in FOV due to the angular bandwidth of the waveguide, which couples the image from projector to the user’s eye. The usable angular bandwidth of the image guide becomes even narrower when RGB image is employed due to the dispersion of input and output coupling gratings[3]. To overcome the limited angular bandwidth of the image guide device, multi-layer image guide, dividing total FOV into left and right FOV were proposed.

Despite the solutions[4], the FOV-display size trade-off is left unsolved especially with AR optical engine employing image guides. To address the challenge, image transfer via bandlimited optical channel (i.e., image guide) with an increased bandwidth device (i.e., Angular and Spatial Light Modulation device) is discussed in this paper. We propose to solve the bandwidth limitation of waveguides by time and wavelength multiplexing, followed by demultiplexing of sub FOVs by using volume holograms. Simulation and experimental verification proved that two wavelengths (658nm and 638nm) in red accompanied with VHG stacks will have the potential to double the output FOV.

*ytakashima@optics.arizona.edu

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2. ANGULAR SPATIAL LIGHT MODULATOR IN TIME AND WAVELENGTH MULTIPLEXING MODE

Our group previously reported increasing Etendue by custom pulsed illumination sources synchronized to a single DMD. To effectively utilize the increased Etendue along with the often angularly band-limited optical channels, for example, a TIR image guide, additional means to effectively increase Etendue of image transfer medium is needed. To address this challenge, we propose a wavelength multiplexed image transfer method with extraction volume holograms to effectively increase the FOV at least by factor of 2.

2.1 ASLM based time multiplexing

The reported "Angular Spatial Light Modulator" (ASLM) light engine, which demonstrated multiple perspectives with no additional active devices[5] shows significant promise to enhance field of view (FOV), while decoupling the traditional limitation of display size verses package volume, energy consumption. The ASLM used in the proposed projector design utilized a programmable blazed grating steering technique reported previously while only selecting parts of the micromirrors to transition to achieve a predefined special resolution[1].

This is achieved by "freezing" the moving micromirrors in time via a 100ns pulsed laser, the timing when the laser pulse is fired then determines at which angle the micromirrors are located and dictates the output diffraction. By varying this delay, we can then send photons to different subsections of the FOV. The display image at this sub-FOV is then the displayed spatial pattern of micromirrors for that transition. With sufficient refresh rate, such as the 20kHz refresh rate of the DLP7000 used in this study, at the output the whole FOV is perceived as a single large image due to image retention. Thus, at the observation plane we have time multiplexed a sub-FOVs with a small angular extent to a large FOV display.

2.2 ASLM based wavelength multiplexing

By further using multiple pulsed illumination sources at different wavelengths, synchronized to the DMD, with a de-multiplexing reflection type volume holographic grating (VHG) that is sensitive to the different wavelengths[6]. We now have another degree of freedom to compress more data into the light field. This is particularly useful since we now can keep the angular extent of the display at its original value, but still display a large FOV. This simplifies the downstream waveguide and/or optics design needed to propagate the image to the viewers eyes, thus decupling the display size and relay optics needed.

This multiplexing is done as an extension of the time multiplexing discussed in the previous section. The light source is still pulsed in synchronization with the DMD, but now we alternate between the two different wavelengths on each pulse. Each wavelength now corresponds to a different sub-FOV, and since here the timing on the laser pulse is kept the same for both sources, thus the two wavelengths share the same angular extent till the VHG stack. The VHG output coupler then is designed to reflect light at different angles depending on which wavelength corresponds to which sub-FOV region.

In this paper we will demonstrate projecting across the entire 40° FOV from a single 0.7" DMD (DLP7000) subtending 20°. By using multiple pulsed wavelength sources with the ASLM's programmable blazed grating technique to steer light with a VHG output coupler, we effectively double the angular output without increasing the display size or the waveguide bandwidth needed, thus making this a great candidate for future NED systems.

3. PROJECTOR SETUP

The projector design block diagram is depicted in Fig. 1:

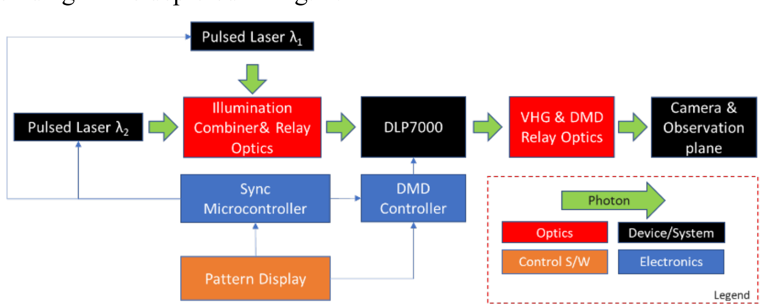

Fig. 1. Schematic block diagram of projector system

The projector system starts with two laser diode light sources for illumination with their wavelengths centered at 658nm and 638nm, respectfully. This is done to ensure significant wavelength separation to maintain good SNR for the output VHG stack, which in turn are designed to operate at these wavelengths. These VHGs are of the reflective type and are designed to reflect the different displayed perspectives of the FOV to their corresponding angles. The laser diodes are both driven individuality by our in house constant current architecture presented in the previous work[2].

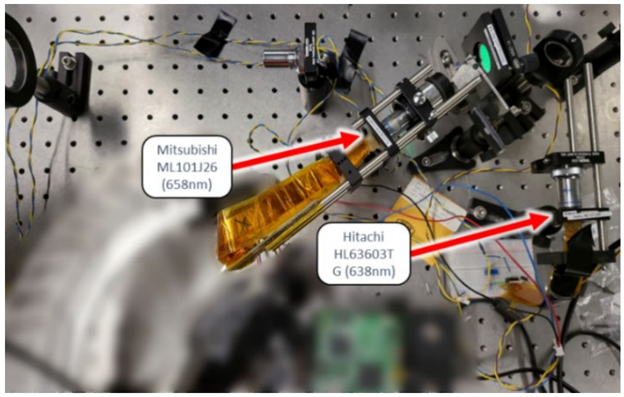

Fig. 2. Light source setup for projector, the projection optics is to the left (Fig. 3)

The sources are combined and collimated as shown in Fig. 2. After the collimated beam is expanded, it is propagated to achieve a normal incidence input and output angle to the DMD. The DMD system used is the high speed DLi4130 kit paired with an DLP7000.

Due to the large FOV camera needed to capture the whole output FOV, we mounted a DLSR with an 50mm/f1.2 lens to a rotation arm that rotates around the center point of the half-mirror, while capturing multiple images. The captured images are then stitched to complete the full FOV in post. The finalized projector system is shown in Fig. 3:

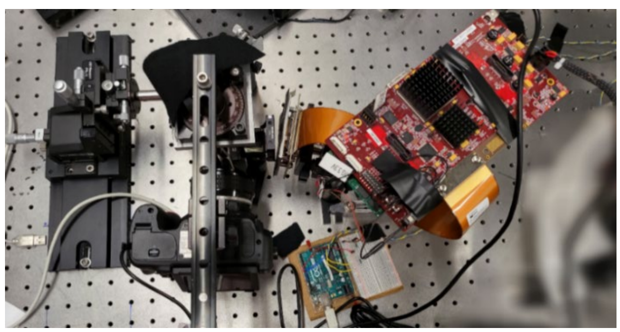

Fig. 3. Projector system for demonstration of WDM based FOV expansion, light sources to the right (Fig. 2)

Including the volume hologram stack, the prototype projector system employed 100ns pulsed dual lasers as sources, with a 0.7” DMD operating at 20kHz, coupled with a reflection type extraction volume hologram.

4. FULL FIELD-OF-VIEW DEMONSTRATION

The final demonstrated are images with markings corresponding to the different wavelengths as shown in Fig. 4. These are wavelength multiplexed, propagated and de-multiplexed, then captured while spanning the entire 40° FOV. This demonstrates the wavelength multiplexing capabilities of our setup and shows how different images for each sub-FOV can be shifted to fill the whole FOV as shown below in Fig. 5.

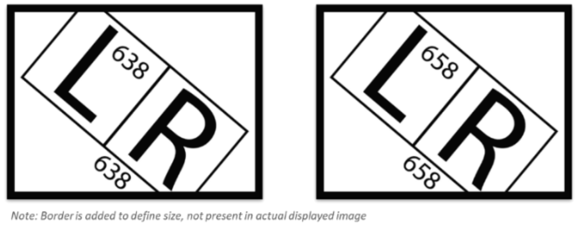

Fig. 4. Images presented on DMD, note the rotation axis on a 45° angle due to the DLP7000 used. Left – Image for 638nm. Right – Image for 658nm.

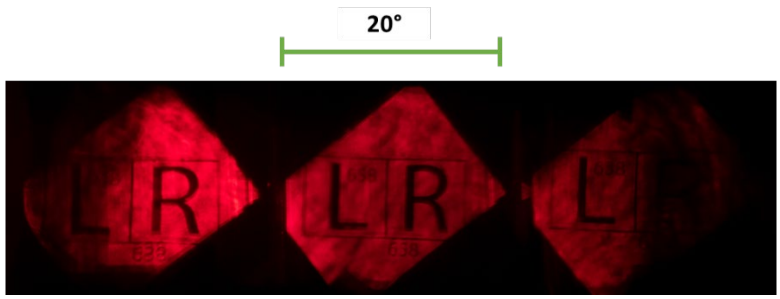

Fig. 5. Full 40° captured image at observation plane, stitched in post from multiple images.

Overall, the display image is clean, and well defined. It is evident that there is stray light and crosstalk between wavelengths, which is suspected to be from various surface reflections throughout the system, which will be addressed in later iterations. We also plan to incorporate multiple, quantifiable image metrics to evaluate and track the improvements between the VHGs and various changes in the projector development process. The current four metrics undergoing testing are: uniformity, resolution, contrast, and crosstalk.

5. CONCLUSION

We demonstrated a hologram-based image projector that expands the field of view (FOV) via wavelength multiplexing while retaining the flexibility of the high-resolution image displayed by a Digital Micromirror Device (DMD). Current Near-to-Eye Displays (NED) for AR/VR/MR applications are often limited in FOV and packaging size of the image transfer optics. Moreover, angular resolution and FOV are typically coupled, therefore a large physical package volume is also needed for large FOV optics.

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To address this challenge, wavelength multiplexed image transfer with extraction volume holograms proved to effectively increase the FOV at least by factor of 2 subjectively. With undergoing quantitative assessments of image quality, such as uniformity, resolution, contrast, and crosstalk.

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