

Adaptive illumination systems with programmable freeform optics ?

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Abstract. Adaptive illumination systems are capable of changing their emission pattern in a dynamic and flexible manner. Such systems can be realized with tunable optical components. We analyse the possibilities and limitations of phase-only spatial light modulators, implemented as a kind of programmable freeform optics, to realize adaptive illumination systems. First, the calculation of the required phase shift patterns to generate specific target irradiance distributions from arbitrary incident wavefronts, is elaborated. Second, the practical limitations of generating prescribed target patterns are experimentally tested and critically discussed.

1 Introduction

By combining freeform optics with compact light sources it is possible to create accurate, prescribed light patterns [1]. But once the freeform reflector or lens is fabricated, the resulting illumination pattern is more or less fixed. In recent years however, there has been a growing interest in adaptive illumination systems for lighting. Such systems can change their radiation pattern depending on the specific external situation. Examples are adaptive car headlights [2], but also for other lighting application there is interest [3].

In order to create a variable radiation pattern, tuneable optical components can be used. Besides refractive and reflective optics, also diffractive optical elements can be considered. Phase-only spatial light modulators (SLMs) are programmable diffractive optics that can manipulate the incident wavefront. State-of-the-art phase-only SLMs are capable of modulating the optical path length by multiple wavelengths. The similarity with shaping the outgoing wavefront via freeform optics, motivated Bawart et al. [4] to introduce the term programmable freeform optics.

2 Phase shift calculation for illumination control

To calculate the smooth phase shift pattern that needs to be applied to the SLM, to transform the incident wavefront into the desired target pattern, a ray mapping algorithm is used. A smooth and continuous source wavefront S , with arbitrary shape and intensity, as well as a desired far-field target irradiance T are given (see Figure 1).

The procedure starts with the calculation of an initial optimal mass transport ray mapping from an intermediate starting grid S' at the position of the SLM to the target distribution T [5]. The normal vector field N orthogonal to the outgoing wavefront W that results in the target distribution T , is then sampled by the ray direction vectors

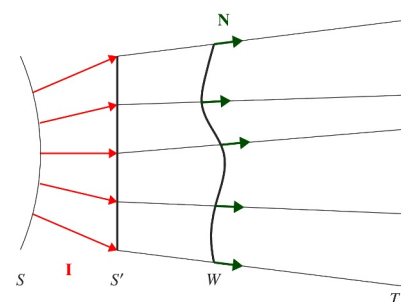


Figure 1. The incoming source wavefront S , sampled by orthogonal ray vectors I , is given. A smooth, continuous target wavefront W that results in the prescribed irradiance pattern T can be constructed from an integrable surface normal vector field N .

from the starting grid S' to the target grid T . In principle, this surface normal vector field N can be used to calculate the orthogonal wavefront W via a suitable fitting procedure. A vital condition for obtaining a smooth, continuous wavefront however, is that the surface normal vector field N satisfies the integrability condition, or equivalent that N is curl-free. In order to adapt the initial ray mapping in such a way that the resulting normal vector field N is indeed curl-free, we rely on an algorithm that has been detailed in [6]. The resulting smooth, continuous wavefront W can now be used to calculate the required SLM phase shift, such that the incident wavefront S will be converted into the outgoing wavefront W . Following Fermat's principle, the optical path length from the source grid points on S (which are directly connected to the grid points on S') to the corresponding grid points at W , should be equal. The additional optical path length that should be induced by the SLM, to transform S in W , can thus be calculated from the optical path lengths from S to S' , and from S' to W [7]. The resulting optical path length difference, can then simply be wrapped to a phase shift pattern with a maximal retardation of 2π , 4π or 6π (see Figure 2).

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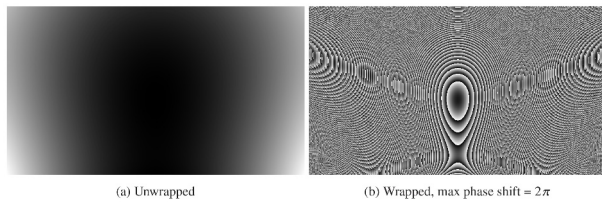


Figure 2. (a) Example of calculated optical path length difference that should be induced by the SLM. (b) Corresponding wrapped phase shift pattern with a maximal retardation of 2π .

3 Experimental analysis

3.1 Coherent, zero-étendue illumination

Calculated phase shift patterns to generate a uniform triangle with an angular extent of 2.6° were implemented on the reflective (PLUTO 2.1) phase-only SLM of HOLO-EYE, and illuminated with a collimated green laser beam (532 nm). The obtained experimental patterns are clearly much less uniform, compared to the geometrical/physical optics simulation results (see Figure 3). These large deviations are due to the zero-order and higher-order diffraction modes, which are a direct consequence of the unavoidable spatial phase discretization and phase depth discretization in a practical SLM. One notices that the angular separation between the higher-order modes can be reduced by considering a larger maximum phase delay (e.g. 4π or 6π). Also the fact that the diffraction efficiency of the applied phase pattern is significantly smaller for larger deflection angles, reduces the uniformity of the target pattern, and is also a severe limitation to the angular extent of the light patterns that can be realized with current SLM technology.

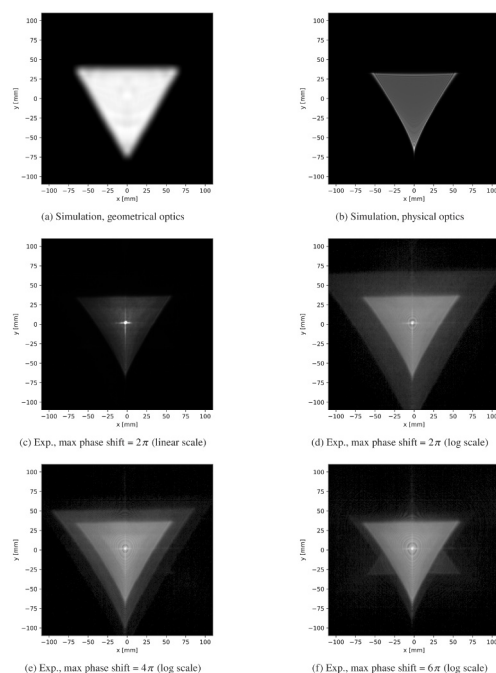


Figure 3. Obtained target irradiance patterns via simulations and in practice (using a collimated laser beam).

3.2 Broadband, non-zero-étendue illumination

The laser illumination is replaced by an extended high-brightness white LED with variable diaphragm to control the illumination étendue. Hyperspectral images of the obtained target patterns are captured with a specimIQ. For sufficiently small illumination étendue, accurate target patterns can be obtained when considering the wavelength for which the phase shifts are calculated (see Figure 4(a)). This pattern even has improved uniformity compared to fully-coherent laser illumination, at least with a 2π maximum phase delay. For broadband (white) illumination, color separation due to the intrinsic wavelength dependency of the various diffraction orders, prevents the realisation of accurate target patterns. A reduction in phase wrappings by increasing the maximum phase depth, reduces the angular separation between the higher/lower orders, which clearly reduces chromatic effects.

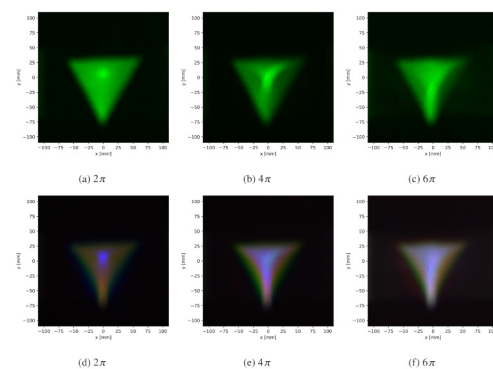


Figure 4. Obtained target irradiance patterns for green light, white light, and maximal phase delay of 2π , 4π and 6π .

3.3 Conclusion

Current SLM technology seems not yet ready for using them as programmable freeform optics in the non-paraxial regime, for broadband (extended) light sources. A significant increase of the diffraction efficiency for larger deflection angles, and further increase of the maximal phase depth would be required to make this happen.

References

- [1] Wu, R., Feng, Z., Zheng, Z., Liang, R., Benítez, P., Miñano, J. C., Duerr, F., Optics. Laser & Photonics Reviews, **12**(7), 1700310 (2018).
- [2] Wang, L., Ma, J., Su, P., Huang, J., Applied Sciences, **11**, 3368 (2021).
- [3] Rondelez, N., Ryckaert, W. R., Meuret, Y., Lighting Research & Technology, **53**(4), 345-358 (2021).
- [4] Bawart M., Bernet S., Ritsch-Marte M., Optics Express **25**(5), 4898-4906 (2017).
- [5] Wu R., Zhang Y., Sulman M. M., Zheng Z., Benitez P., Minano J. C., Optics Express **22**(13), 16161–16177 (2014).
- [6] Desnijder K., Hanselaer P., Meuret Y., Optics Letters **44**(4), 771–774 (2019).
- [7] Rondelez N., Desnijder K., Ryckaert W., Meuret Y., Optics Express **31**(2), 1303-1317 (2023).