Investigation of high radiance laser-pumped phosphor converted light sources in sensor applications

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We investigate the relation between radiance and spectral filter effect of a miniaturized illumination system based on volume holographic optical elements (HOE). Optical simulations, verified in experiments, show that high radiance light sources as phosphor-converted lasers and HOE cascades are beneficial.

1 Introduction

Actively illuminating sensor applications, as fluorescence analysis in life sciences, require spectrally condensed and well-defined radiance in different spectral bands [1]. To serve this purpose, an illumination head based on volume holographic optical elements (HOEs) is presented. Fig. 1 shows a sketch of such an illumination head realizing two different spectral bands which are selected by addressing the corresponding light source. The first HOE directs collimated light to a second HOE, which is realized as a multiplexed HOE. The latter one directs light from different angles and with different wavelengths out of the illumination head, aligned on a single optical axis. Due to the spectral selectivity of HOEs, this setup acts as spectral filter.

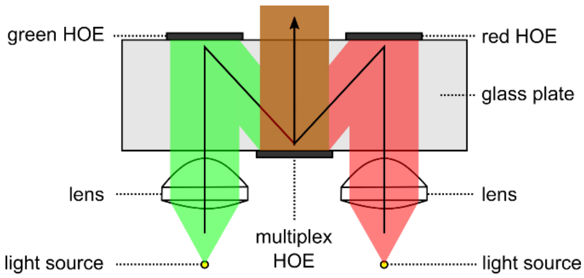

Fig. 1 *Illumination head based on HOEs for actively illuminating sensor applications.*

The illumination head is of particular interest, when realized as a miniaturized device to allow for cost-efficient production and to reduce installation space. At the same time a high quality of spectral output is critical. As known from the theory of HOEs and etendue considerations, see section 2, the radiance of the light source is a limiting factor for miniaturization. To design the optical system of the illumination head, the presented contribution sets up a simulation to model the relation between radiance of a light source and filter effect of a HOE and validates the simulation in an experiment for two setup sizes in section 3. The simulation is used in section 4 to evaluate the filter effect of a miniaturized HOE cascade comparing a phosphor-converted LED (pc-LED) and a phosphor-converted laser (pc-laser).

2 Theoretical background

The function of a volume HOE is described by a diffraction on Bragg-layers if the Bragg-equation is satisfied [2]. In the Bragg-equation

$$n\,\lambda = 2\,d\,\sin(\theta) \tag{1}$$

the thickness of the Bragg-layer d is depending on the HOE whereas the wavelength λ and the incident angle to the Bragg-layer θ are properties of the ray. n is the diffraction order. From equation (1) it becomes evident that a HOE will not only diffract rays of the design wavelength and the design incident angle but also rays which are originating from another incident angle having a suitable wavelength.

A light source with higher radiance and same radiant flux can be collimated with lower rest-divergence. Hence, the angle distribution impinging the HOE is narrower for higher radiance sources which leads, according to equation (1), to fewer spectral parts in the diffracted rays. Therefore, the filter effect is better for high radiance light sources.

3 Experimental proof and simulation

In the experimental setup, see Fig. 2, a blue laser is focussed on a phosphor sample (SYB35) [3] with broad emission spectrum operated in transmission. The fluorescence of the phosphor is collimated with an exchangeable lens (A: f = 30 mm, B: f= 8 mm) before it interacts with a volume HOE designed for 528 nm and 16 µm thickness which deflects plane waves from 0 to 50°. A spectrometer, attached to an Ulbricht-sphere, detects the diffracted waves. Different radiance levels are realized by altering the position of the focussing lens. A camera measures the resulting emission spot size on the phosphor.

The simulation in *Zemax OpticStudio* utilizes the phosphor as a light source and models aperture and collimator lens as in the experiment. The described HOE is implemented as volume HOE and its refractive index modulation is chosen to match the HOE efficiency in the experiment. A detector represents Ulbricht-sphere and spectrometer.

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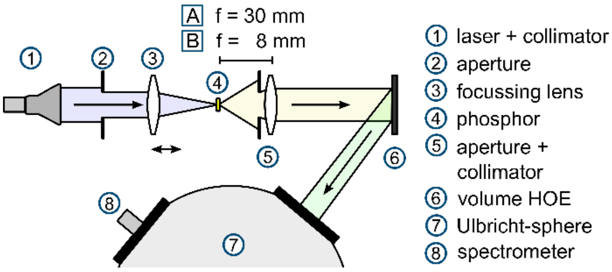

Fig. 2 *Experimental setup with exchangeable lenses A/B.*

The resulting spectra are plotted in Fig. 3. In the larger setup A, the spot size does not have a significant impact on the spectrum, whereas the central spectral intensity drops by 50 % in the smaller setup B when the spot diameter is increased by a factor of four. This effect is observed in the experiment and successfully modelled in the simulation.

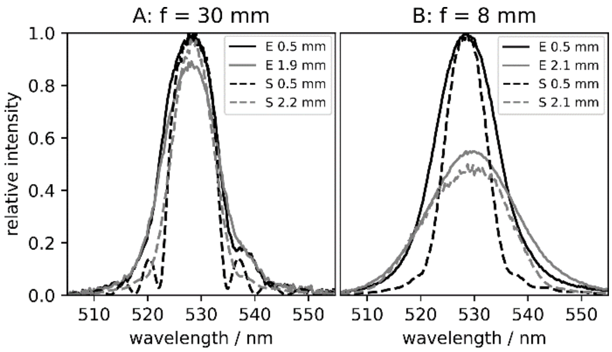

Fig. 3 *Resulting spectra of different spot sizes (see legend for spot diameter) in experiment (E, solid lines) and simulation (S, dotted lines) for the large setup A (left) and the small setup B (right). In each plot, the spectra are normalized to the maximum value of the smallest spot, for experiment and simulation respectively.*

4 HOE cascade

Since experiment and simulation give approximately equivalent results, the simulation is used to lay out the miniaturized HOE cascade. The setup represents one spectral band of the illumination head in Fig. 1. A lens with 8 mm focal length collimates light from the source onto a first volume HOE which directs the rays onto a second volume HOE (modelled as singleplex). Both HOEs are attached to a glass plate with thickness of 16 mm and have a lateral distance of 13 mm (centre to centre). Two detectors are placed in the setup, one after the first and one after the second HOE. As light source, a pc-LED is compared to a pc-laser. Consisting of a thermally conductive phosphor, e.g. a ceramic YAG:Ce^{3+} [4], on which a laser is focussed to realize a small emitting spot, pc-lasers emit higher radiance levels than pc-LEDs. As pc-laser, a surface mount device (SMD) is used with an elliptical emitting area of 250 x 450 μm and a luminous flux of 500 lm [5]. Comparable LEDs with similar flux have an emitting area of about 1 x 1 mm [6]. The emitting area of both light sources is simulated in the setup using the same spectrum and luminous flux.

Fig. 4 presents the resulting spectra. Stray light decreases significantly using a HOE cascade since scattered light and Fresnel reflections are mitigated by the second HOE. Comparing the pc-laser to the pc-LED, the pc-laser ends up in a higher efficiency (intensity is increased), and in a better filter effect (spectrum is less spread) than the pc-LED for both, a single HOE, and a HOE cascade. Hence, a high radiance light source is not only beneficial for a single holographic filter, but also for a HOE cascade.

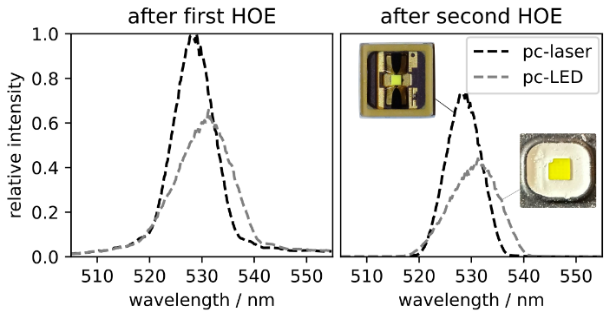

Fig. 4 *Resulting spectra after first (left) and second HOE (right) for a pc-laser and a pc-LED. All spectra are normalized to the same value and can be compared to each other.*

Conclusion

In the context of an illumination head for sensors based on holographic filters, the dependency of filter effect and radiance of the used light source is investigated with special remark on miniaturization. A dependency is observed in experiments and successfully modelled with simulations. We found that the radiance of a light source is even more important for smaller setups. The usage of a filter cascade improves the overall filter effect but cannot compensate for a lack of radiance. Especially in miniaturized setups, pc-lasers are beneficial.

Acknowledgement

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