DOI: 10.22032/dbt.49313

Chromaticity of white light volume holographic cell arrays for divergent illumination with phosphor converted LEDs in automotive headlights

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Abstract

Holographic optical elements (HOEs) offer the possibility to replace conventional optical elements like lenses, reflectors and apertures in illumination lighting systems such as vehicle headlights. In this context reflection-type volume holographic optical elements (vHOEs) represent a promising approach. Although illuminated by incoherent light emitting diodes (LEDs), they provide good beam-shaping quality due to their high wavelength and angular selectivity. However, to achieve high efficiency in operation the vHOE must utilize the full spectrum of the illumination systems light source. Therefore, when using phosphor converted LEDs, vHOEs with multiple recording wavelengths are required. In addition, the generated light distribution must comply with the chromaticity requirements of the ECE regulations for vehicle headlights. Therefore, a major goal in development of vHOEs as optical elements for vehicle lighting is to produce a white light distribution for vehicle headlights while achieving high efficiency.

Previous work based on the Lippmann color process [1] attempted to record full-color holograms to produce highly realistic three-dimensional images by using multiple wavelengths in the recording process. Bjelkhagen and Mirlis [2] for example focused on undersampling in the wavelength domain and the resulting false coloration of the recorded objects. Similar problems occur, when a noncontinuous white light LED spectrum is used to illuminate vHOEs, which must produce a white light distribution.

In this paper, simulations based on Kogelnik's coupled-wave-theory (CWT) [3] are presented for selecting appropriate laser wavelengths for hologram recording and white light LED illumination. The holographic recording medium and the recording angles of the reference and object beams are first defined. Then, several commercially available laser wavelengths are chosen to calculate the spectral diffractive efficiency of each laser wavelength. The results are then convolved with the spectral power distribution of white light LEDs and the chromaticity coordinates are calculated accordingly.

Various combinations of laser wavelengths and LED spectra are presented as the results. Suitable combinations of recording lasers and LEDs could be found to achieve the color locus required in the ECE regulations.

Index Terms: holography, automotive lighting, computer-generated hologram (CGH), holographic optical element (HOE)

1 Introduction

The electrification and efficiency enhancement of motor vehicles requires the reduction of weight, installation space and energy consumption, not only of the powertrain, but of all system components in the vehicle. One approach in the field of automotive lighting is the development of new concepts and optical elements for head- and taillamps. By reducing the number of optical components and integrating several lighting functions into one surface, a major contribution to the above-mentioned goals can be achieved. The simplification of optical systems is opposed by the increasing complexity of head- and combination rear lamps, which is driven by new safety and comfort functions, such as adaptive driving beam. Current headlamp systems generate their light distribution by means of free-form reflectors or projection lens systems [4] . Due to their optical system, these headlamp systems require a large installation space.

Since the introduction by Gabor in [5], various uses of holograms have been investigated. Holograms can store the phase and amplitude information of wave fields, thus enabling three-dimensional imaging of objects. In particular, holographic optical elements (HOEs) can be used to replace conventional optical elements, such as lenses, reflectors, and optical apertures [6–8]. Thus, volume holographic optical elements (vHOEs) provide a promising approach for automotive lighting applications [9].

At the L-LAB research institute for automotive lighting and mechatronics various aspects of the development of vHOEs for automotive applications were investigated [10–15]. Different exposure, design and simulation approaches were developed with the focus on the usage of uncollimated light emitting diodes (LEDs) for reconstruction of arbitrary light distributions stored in vHOEs. The challenge here is the strict wavelength and angular selectivity of vHOEs in contrast to the Lambertian characteristics of LEDs. However, good results were archived by adding the complex conjugate of the LEDs local phase to the computer-generated hologram (CGH) to compensate the wavefront curvature during exposure [10]. Another approach is given by dividing the vHOE into an array of sub holograms and varying the reference-beam-angle per sub hologram exposure to mimic the Lambertian radiation characteristic [11]. These works mainly focused on the spatial radiation characteristics and the manufacturing of monochromatic vHOEs. In the here presented work simulations will be performed to investigate the extension of these vHOEs for white light.

Manufacturing vHOEs for shaping of a white light distribution is closely related to the three-dimensional recording of colored objects in holograms. Such attempts date back to the early 1960's [16–18]. The manufacturing of color-holograms is realized by recording with multiple lasers of different wavelengths in a film suited for volume-holograms. The corresponding interferometric pattern of each wavelength recorded by the film are superimposed. It was shown that the crosstalk between these pattern is small due to the wavelength selectivity of the structures [17] and white light sources can be used for the reconstruction of the recorded image [18]. Later investigation for recording holograms with realistic coloring of the reconstructed image was presented by Bjelkhagen and Mirlis [2]. Colored objects of different materials have a specific reflection spectrum when illuminated. Undersampling occurs, when these objects are recorded with a finite count of laser wavelengths, which led into false coloration of the reconstructed image. A tungsten lamp was used as a white light source by Bjelkhagen and Mirlis to generate a quasi-continuous spectrum. In contrast, for automotive applications phosphor converted white LEDs should be used. Consequently, these spectra are non-continuous as they have a peak in the short wavelength domain (at about 450 nm) and yellow emission generated by the phosphor. Alternatively, red, green, and blue (RGB) LEDs could be used in a holographic headlamp [9].

When designing the spectrum of a light distribution generated by a vHOE, the following questions occur:

- How is the spectral power distribution of the light source/ LED?
- Which laser wavelengths are available that fulfill the requirements for holographic exposure?
- How is the spectral diffraction efficiency distribution of a vHOE of a specific holographic film and exposure wavelength?
- What are the regulations towards the color locus of vehicle headlamps?

2 Methods

Simulations are performed to investigate suitable combinations of light sources, laser wavelengths and holographic films. In this paper, an implementation of Kogelnik's CWT [3] was used to approximate the diffraction efficiency of the vHOE. It should be noted that the CWT is restricted to holographic records of sinusoidal fringe pattern and that only two light waves, the incoming reference and the outgoing signal wave, are considered. Higher diffraction orders are neglected, and more complex holograms are regarded as a superposition of the simple hologram gratings. For investigations in this paper, these assumptions are sufficient, because only slanted sinusoidal hologram gratings are examined exemplary. The diffraction efficiency calculated by the CWT depends on the parameters shown in Figure 1. The wavevector k_R represents the direction of a plain wave with a fixed wavelength. K is the grating vector and is orthogonal to the grating fringes. The signal is represented by k_S. Other parameters, like the volumetric absorption, are neglected since only lossless hologram gratings are of interest. These gratings are in the form of refractive index modulation and are recorded by interferometric exposure, where a higher exposure dose causes a higher modulation of the refractive index.

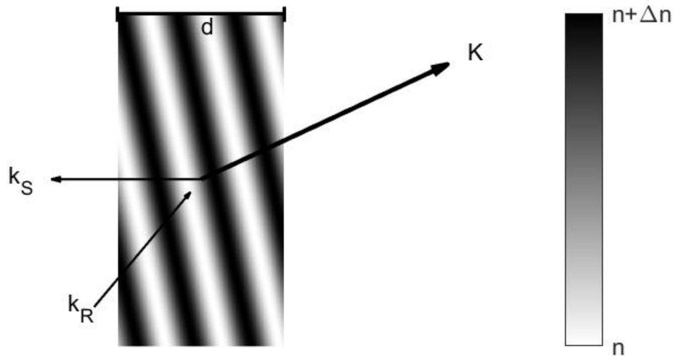

Figure 1: Simulated reflection hologram with grating vector K, reference wavevector k_R, signal wavevector k_S, thickness d, index of refraction n and modulation Δn

Here the slanted hologram grating is designed to reflect an incoming reference wave with an angle of 50° to the optical axis. The generated signal wave then propagates in the negative direction of the optical axis. The function of the grating is the same for all simulations in this paper. Following, the direction of the grating vector is fixed and only the periodicity changes with the design wavelength.

The simulation parameters of the recording media are chosen with Bayfol HX [19] and wavelength multiplexing [20] in mind. The thickness d of the photopolymer recording media is up to 50 µm and the modulation of the refractive index Δn is up to 0.05. The range of the modulation can be understood as the dynamic range of the recording medium. Because wavelength multiplexing and multiple exposure is of interest, the refractive index modulation must be divided by the count of the exposures to provide sufficient dynamic range to each exposure.

Suitable laser sources for hologram recording must operate with good wavelength accuracy and power stability. For example, such lasers with fixed wavelengths are available with 457 nm, 473 nm, 491 nm, 515 nm, 532 nm, 561 nm, 594 nm 640 nm, and 660 nm in the visible wavelength range (VIS). Alternatively, tunable lasers are available to cover nearly the complete VIS (450 nm – 650 nm, 510 nm – 750 nm) [21].

Different LED-types are examined in terms of applicability for the hologram reconstruction. In headlamps phosphor converted LEDs are state-of-the-art and automotive certified types are available in arbitrary formfactors. Also, less color fringing compared to multicolor LEDs is present in this LED-type. Due to these arguments, phosphor converted LEDs are worth considering for hologram-based headlamps although issues regarding efficiency and color locus caused by the spectral power distribution must be compensated. Typically, automotive certified phosphor converted LEDs have blue wavelength-peak at 445nm to 450nm. However, laser-wavelengths for holography are not available in this spectral domain or very expensive. The simulation results will discuss these problems in detail. Alternatively, multicolor LEDs are examined, as mentioned above problems regarding color fringing may occur with this approach and cannot be investigated in this simulation setup.

To examine the color locus of a hologram, first the spectral power distributions of the LEDs are needed. These are available by measurements with an Ulbricht-sphere and a radio spectrometer or by the manufacture's datasheet. In some cases, only the respective dominant wavelengths and the corresponding full width half maximum (FWHM) are given for multicolor LEDs. A gaussian spectral power distribution is assumed in these cases and calculated by the dominant wavelengths and the FWHM.

Secondly, the laser sources and the constants of the recording medium are defined. Each recording wavelength is investigated separately as a monochromatic hologram. By using the CWT, the spectral diffraction efficiency of each hologram is derived by calculating the diffraction efficiency in the wavelength range from 400 nm to 750 nm with a resolution of $\delta\lambda = 0.5$ nm. The direction of the reference wave is set to 50° as intended in the design of the slanted grating. Changes in the direction of the signal wave are not considered in this work. The spectral power response of the multiplexed hologram is given by summing up the respective spectra. This simplification is only valid if the recording wavelength difference is sufficiently large and crosstalk between the holograms can be neglected.

Finally, the spectral diffraction efficiency of the multiplexed vHOE is convolved with the LED spectrum. This results in the spectral power distribution of the vHOE image. The corresponding color locus and the limits of the ECE regulations for headlamps are displayed in a chromaticity diagram to verify the fulfillment of the requirements.

Beside the color locus, the efficiency of vHOEs is of interest. Numerical integrations were performed to calculate the flux of the LED and the vHOE's light distribution. The radiometric efficiency is given by $\eta = \Phi_{\mathrm{vHOE}}/\Phi_{\mathrm{LED}}$. For calculating the photometric efficiency, first the spectral power distributions need to be convolved with the $V(\lambda)$ curve and numerically integrated respectively. Then, the photometric efficiency is given by $\eta_{\mathrm{p}} = \Phi_{V_{\mathrm{vHOE}}}/\Phi_{V_{\mathrm{LED}}}$.

3 Simulation Results

Simulation results of three different LEDs are presented below. For the holographic recording medium with the thickness of $d = 30$ µm the refractive index modulation was set to $\Delta n = 0.045$.

First a phosphor converted LED designed for automotive applications is examined. In Figure 2: Chromaticity of the hologram image and relative spectral emission of a phosphor converted LED OSRAM LUW CEUP, the diffraction efficiency of the monochromatic vHOEs and the spectrum of the hologram image. $\eta = 25.58\%$, $\eta_p = 26.84\%$ the relative spectral emission is shown. The spectrum was measured with an

Ulbricht-sphere and a radio spectrometer. A good result for the color locus was found by multiplexing four wavelengths (457 nm, 532 nm, 594 nm, and 640 nm). Each wavelength used a quarter of the index modulation Δn. Respectively, the diffraction efficiency of each hologram exposure and the spectral power distribution of the hologram image is displayed. The color locus of the hologram image is in the limits of the ECE regulations. As shown in Figure 2 the LED spectrum is only partially reconstructed, which results in a radiometric efficiency of $\eta = 25.58\%$ and a slightly higher photometric efficiency of $\eta_p = 26.84\%$.

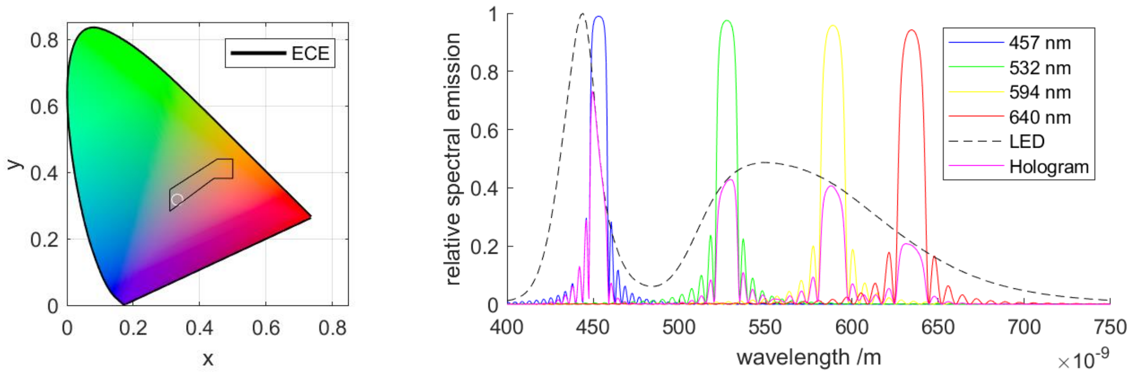

Figure 2: Chromaticity of the hologram image and relative spectral emission of a phosphor converted LED OSRAM LUW CEUP, the diffraction efficiency of the monochromatic vHOEs and the spectrum of the hologram image. $\eta = 25.58\%$, $\eta_p = 26.84\%$

Alternatively, the same recording wavelengths and the same holographic medium was combined with an RGBY LED in Figure 3. This LED is not designed for automotive applications, but for the use in stage and event lighting. It consists of four independent addressable active areas. The red, green and blue emission is generated directly by the diodes. The yellow emission is generated by phosphor converting of a fourth diode. The red and the yellow LED were dimmed to 50% of their spectral flux to provide a color locus in the ECE regulations limits. Comparing the maxima of the LED with the spectral diffraction efficiency of the hologram, slight offsets of the peaks can be observed. Although the peaks of the blue, green and red diode are narrow, the yellow emission has a large spectral width causing less usage of the flux of the light source and resulting in a radiometric efficiency of $\eta = 32.69\%$ and a photometric efficiency of $\eta_p = 33.32\%$.

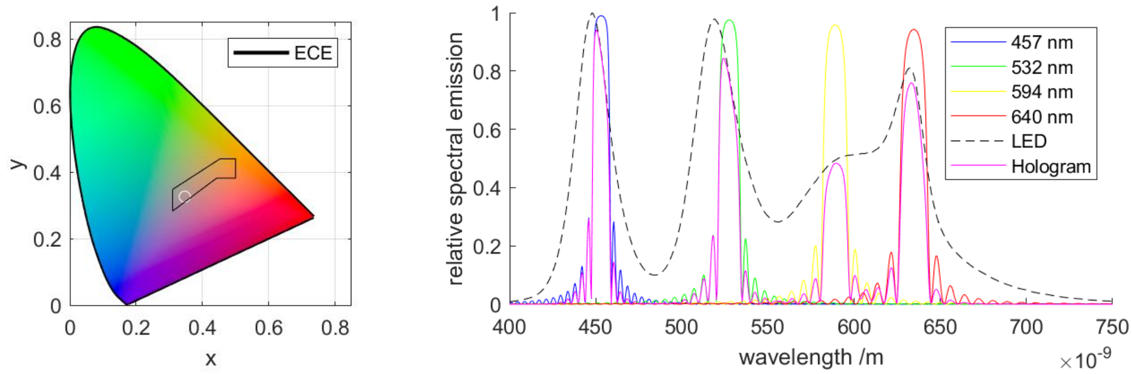

Figure 3: Chromaticity of the hologram image and relative spectral emission of a RGBY-LED OSRAM LE RTDCY S2WN, the diffraction efficiency of the monochromatic vHOEs and the spectrum of the hologram image. The yellow and the red LED were dimmed to 50% to match the color locus. $\eta = 32.69\%$, $\eta_p = 33.32\%$

Finally, an RGB LED is examined. This LED is also designed for stage and event lighting. In this case only three recording lasers (457 nm, 532nm, and 640 nm) are used, since there is no spectral emission near 594 nm by the LED. Following, the index modulation $\Delta n = 0.045$ is divided by three exposures, resulting in wider peaks of the spectral diffraction efficiency. The blue and green LED were dimmed to 60% and 70% of the flux to match the color locus. In comparison to the other approaches a higher radiometric efficiency $\eta = 54.01\%$, and higher photometric efficiency $\eta_p = 53.34\%$ was achieved.

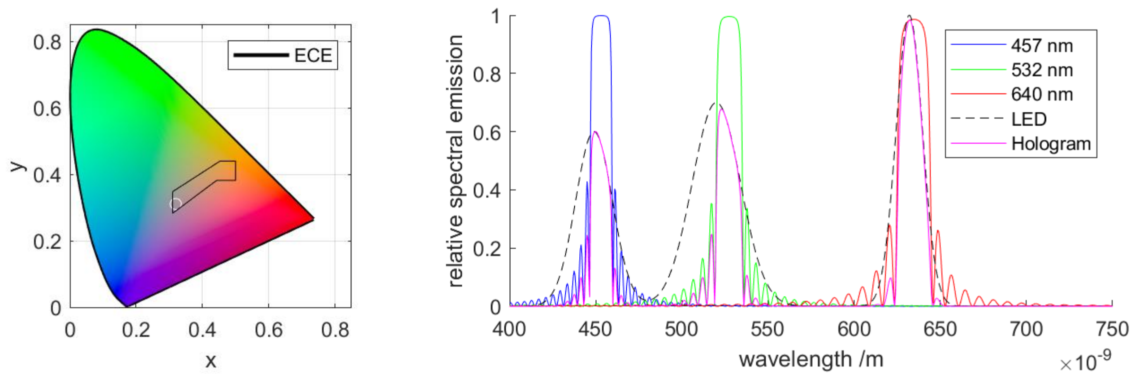

Figure 4: Chromaticity of the hologram image and relative spectral emission of a RGB-LED OSRAM LE RTDUW S2WP, the diffraction efficiency of the monochromatic vHOEs and the spectrum of the hologram image. The blue LED was dimmed to 60% and the green LED was dimmed to 70% to match the color locus. $\eta = 54.01\%$, $\eta_p = 53.34\%$

4 Discussion

The above shown approaches show good results regarding the color locus of the hologram image. However, the respective LED and vHOE pairs differ in terms of efficiency and the count of recording wavelengths.

The lowest efficiency is found with the phosphor converted LED. As shown in Figure 2 the peak wavelength of the blue LED is at around 445 nm. On the other hand, the recording wavelength is 457 nm resulting in a high flux transmission rather than usage for the hologram image. Replacing the 457 nm recoding laser with a tunable laser would slightly improve the wavelength match to 450nm. At this point in research, such tunable lasers are too expensive. Adding more recording wavelengths to the vHOE could also improve the diffraction efficiency at the cost of longer manufacturing times and higher equipment costs.

The RGBY LED provides a higher efficiency for the same vHOE. Dimming the red and yellow diode to 50% of the flux is required to match the color locus. In comparison to color matching via less diffraction efficient holograms in specific wavelength ranges, this has no negative effect on the system efficiency.

For the RGB LED the highest efficiency was investigated. Another advantage is given by the need of less recording wavelengths and therefore less manufacturing time. As a result, the RGB solution is preferred over the RGBY solution in this case.

It must be mentioned that this simulation cannot consider color fringing. For multicolor LEDs color fringing is more likely since there is spatially offset of the emission surfaces of the respective color diodes. This offset must be compensated by the vHOE. Future work must verify the simulation results experimentally and beside the color locus, effects on the light distribution and color fringing must be investigated.

5 Conclusion

In this paper various LED vHOE pairs via simulations with the CWT were investigated. Exemplary, three simulation results of phosphor converted and multicolor LEDS were presented and discussed. White light vHOEs were of interest. All shown approaches had a color locus within the ECE regulation limits and only differed in diffraction efficiency and the count of recording wavelengths. The best results were found with an RGB LED. Here the photometric efficiency was $\eta_p = 53.34\%$, while only three recording wavelengths were used. RGB LEDs are not used in vehicle headlamps yet, why further investigation regarding color fringing and changes in ECE regulations are needed. Therefore, future research needs to consider multicolor but also the conventional phosphor converted LEDs.

As a simplification, the presented simulations showed the efficiency and color locus for one specific slanted grating and illumination direction. However, for headlamps the vHOEs will be of more complex fringes in the recording medium and will also differ in the illumination direction. For further investigations experimental validation of these results are needed and the nontrivial task of generating high quality light distributions with LED vHOE pairs must be faced.

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