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Holograms in Automotive Headlamps – Chances and Challenges

Daniela Karthaus*, Oliver Sandfuchs**, Stefan Sinzinger***

**L-LAB – Research institute for automotive lighting and mechatronics, Lippstadt*
***Hamm-Lippstadt University of Applied Science, *** Ilmenau University of Technology*

mailto:daniela.karthaus@l-lab.de

Holograms provide the possibility to modulate incident light waves in an almost arbitrary way. This leads to the idea to use holograms as supplementing or replacing element in the optical system of automotive headlamps. In this paper one important aspect, the efficiency of a volume hologram, is discussed regarding conditions of automotive headlamps.

1 Introduction

Holograms provide the possibility to modulate and diffract light waves in almost arbitrary directions. Therefore, holographic optical elements could be used in illumination systems to realize specific light distributions. In particular, the application of transmission holograms in headlamps gives the chance of a reduction of installation space and weight. Hence, it would offer new possibilities for design concepts. However, there are several challenges such as the realization of white light distributions and the resistance to internal and external influences, e.g. large temperature ranges, of the headlamp system. Another aspect is the energy efficiency of modern headlamp systems. As large ranges of the road have to be illuminated using as less energy as possible, we focus in this paper on the physical background concerning the performance of a hologram with imperfect illumination and the consequences for the design of holograms for automotive headlamps.

2 Theoretical Background

A volume hologram is an interference pattern that is generated by two overlapping light waves, recorded in a photosensitive material, which thickness is larger than the grating period *g* [1]. One of the waves, the object wave, is modulated by an object before it impinges on the holographic plate, while the second wave, the reference wave, is unmodulated [1]. The simplest hologram is a volume grating that is generated by to plane waves. The relative angle θ between the object and the reference wave determines the period *g* or the spatial frequency f_s (in lines per mm) of the grating. When a hologram is illuminated with a reconstruction light source, a conjugate image (-1st order) appears in addition to the recorded image of the object (+1st order) and a part of the incident light remains undiffracted (0th order). The intensity of the mentioned orders differs from each other and depends on the holographic material and the recording set-up (cf. [1], [2]). The response of a volume grating on an incident light wave could be described by the Bragg condition (cf. [3]):

$$\cos(\theta_{in}) = m\frac{\lambda}{2g} \qquad (1)$$

where λ is the wavelength and θ_{in} the incident angle of the impinging light and *m* is an integer. From equation 1 follows that the reconstruction of a hologram reaches maximum efficiency, if the frequency ν of the reconstruction light wave is a multiple of the Bragg frequency ν_B ($\nu = m \cdot \nu_B$) and if the light impinges at Bragg angle ($\theta_B = \sin^{-1}(\lambda/2g)$) (cf. [3]). To calculate the performance of a volume hologram fulfilling or violating the Bragg condition, Kogelnik's coupled wave theory can be used. This approximated approach, that only takes the 1st or 0th diffraction order into account, is also used for the considerations in this paper, assuming a lossless transmission grating. For details about Kogelnik's theory we refer you to [2].

3 Performance of Holograms in Headlamps

Two important aspects regarding the application of holograms in headlamps are the realization of a homogeneous white light distribution and positioning tolerances appearing during the fabrication process. To prove the expectation that the efficiency of holograms is affected by these issues, it is numerically calculated for different conditions. As different holographic materials are currently available (e.g. cf. [4], [5]), a photopolymer of the thickness 8.8µm is assumed with a refractive index of 1.5* and a maximum index modulation of 0.032 (cf. [4]).

3.1 Angular Deviations

As mentioned in section 2, a deviation from the Bragg angle results in a reduction of the diffraction efficiency. For the calculations a deviation of $\Delta\theta=0.57°$ (resulting from a positioning tolerance of 0.4mm and a distance between hologram and reconstruction light source of 20mm) is assumed.

* a refraction index of 1.5 is assumed, as there is no specification in [4]

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The diffraction efficiency is calculated for a recording wavelength of 532nm, for different frequencies and angles θ_B as listed in table 1.

f_s [lines/mm]	θ_B	η ($\Delta\theta$=0°)	η ($\Delta\theta$=0.57°)	$\Delta\eta$ [%]
653	20°	0.986	0.972	1.4
1286	40°	0.961	0.907	5.6
1880	60°	0.883	0.774	12.3
2417	80°	0.681	0.533	21.7

Table 1 *Decrease of diffraction efficiency $\Delta\eta$ for different grating periods and an angular deviation of $\Delta\theta$=0.57°.*

Comparing the values for the different spatial frequencies, two main effects become noticeable: the maximum efficiency for $\Delta\theta$=0° is greater for lower frequencies (up to 30%) and the loss of efficiency is greater for higher frequencies (up to 20%).

3.2 Deviations of Wavelength

As mentioned before, another requirement on the application of holograms in headlamps is the realization of a white light distribution. For the following considerations it is assumed that such a distribution is realized by color multiplexing (cf. [6]), using LEDs with wavelengths 447,5nm, 530nm and 655nm for reconstruction and lasers with wavelengths 457nm, 532nm and 660nm for recording. The diffraction efficiency is calculated using the same material parameter as in section 3.1 and assuming a grating with a frequency of 1286 lines/mm. The results are presented in table 2.

λ_{LED} [nm]	λ_{Laser} [nm]	$\Delta\lambda$ [nm]	η ($\Delta\lambda$=0)	η ($\Delta\lambda$)	$\Delta\eta$ [%]
447.5	457	10.5	0.779	0.679	12.9
530	532	2	0.961	0.959	0.2
655	660	5	0.979	0.974	0.5

Table 2 *Decrease of diffraction efficiency $\Delta\eta$ for different wavelength deviations $\Delta\lambda$.*

For deviations up to 5nm, the decrease of the efficiency is negligible (<1%). But, for the LED with 447.5nm and a deviation of 10.5nm, the loss of efficiency is greater than for the angular deviation (12.9% vs. 5.6%). Further calculations indicate that this effect shows a strong increase for larger frequencies, e.g., for 1880 lines/mm and a deviation of $\Delta\lambda$=10.5nm $\Delta\eta$ becomes 60.6%.

4 Conclusions

The numerical calculations show that the diffraction efficiency is a complex parameter that depends on different variables. As some of them are fixed, e.g., the thickness and the refractive index of the holographic layer, or limited, e.g., the index modulation, it is important to choose the best recording and reconstruction geometry. For example, if the holographic material from section 3 is used, the recording of low spatial frequencies would lead to a greater maximum efficiency and less efficiency decrease in the case of Bragg violation. However, smaller angles, that are necessary to record low frequencies, can lead to an overlap of 1st and 0th order. For example, if a low beam distribution with an angular range of ±35° is realized by using an off-axis setup, a minimum frequency about 1280 lines/mm will be expected. A concept that integrates the 0th order in the light distribution might be an alternative solution. However, this might also lead to an inhomogeneous light distribution. In prospective tests several concepts have to be proved to find the best solution.

The results concerning wavelength deviation, generated by the use of standard colour LED, show that the loss of efficiency depends also on the spatial frequency of the grating. The wavelengths of the recording and the reconstruction light sources have to be adapted to avoid efficiency losses. However, there is a limitation of available wavelengths for lasers and LEDs. A compromise between the fulfilment of legitimate colour requirements for headlamps and the efficiency of the holograms is inevitable.

Finally, it has to be taken into account, that Kogelnik's theory is valid only for weak index modulation, plane wave reconstruction and others [2]. These assumptions are markedly different from the conditions in the automotive sector, e.g., the divergence angles of LEDs, which are about 120°. In addition, comparisons between Kogelnik's theory and rigorous approaches showed that the neglect of other diffraction orders is not recommendable in any case [7]. So the use of an adaptable approach might lead to more accurate results, which can then be used as guidelines for the design of holograms for automotive headlamps.

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