Lux junior 2019

14. Internationales Forum für den lichttechnischen Nachwuchs
Dörnfeld/Ilm, 06. – 08. September 2019
DOI (proceedings): 10.22032/dbt.38440

DOI: 10.22032/dbt.39620

High-Resolution Laser Scanning Systems with Acousto-Optic Deflectors and Optimised Optics Design

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Abstract

In recent years, automotive headlight systems have been improved in a considerable extent for a safer drive. In this paper, an optical design is presented for scanning headlight systems with an alternative deflection unit and an RGB laser source to optimise the light distribution and create desired illumination patterns adapting to the driving situation. Recently developed scanning lighting systems incorporate mechanical deflection systems. Here, since the redistribution of the light is mostly depending on the fixed deflection pattern, several drawbacks are emerging. As an alternative method, acousto-optic deflection technology can deflect the light without any mechanical displacement. They offer high-flexibility to redistribute the light in the desired intensity. Thus, the main role can be undertaken by acousto-optic deflectors as laser scanners and illumination units. However, although they have a mechanic-free deflection mechanism, their narrow deflection range causes difficulties in realising the desired illumination and scanning applications. An optics design to enlarge the deflection range for Acousto-Optic Deflectors (AODs) is required. In this project, an optical system is purposed for high resolution and contrast illumination in automotive lighting using acousto-optic deflectors.

Index Terms: Acousto-optic deflector, Laser, Scanner, Automotive, Lighting

1 Introduction

Over the last years the rapid development in automotive headlights, has led to technology capable of adaptive lighting. Lasers were brought to the stage to make major progress due to their small size and power for high range lighting. Moreover, as an advanced step, these light sources were combined with scanning systems in headlights. Laser scanning systems controls the deflection of the laser beam to create the desired illumination area depending on the use-case. The advantage is their potential to redistribute the light. Light can be deflected in the desired intensity to the desired angle and thus the illumination can be actively formed according to the use-case. Nevertheless, laser scanning headlamps have not been introduced yet, while research and development are still ongoing.

The aim of this project is to show an innovative setup for scanning headlight systems and its promising features. A deflector of a mechanical free configuration based on the acousto-optic effect carries out the deflection of light. The goal is hereby to realise high-dynamic and high-resolution light distributions with two acousto-optic devices deflecting in the horizontal and vertical direction. The challenge is the trade-off between high resolution and wide field of view (FOV). To optimise the relation between resolution and FOV, an optical system has been designed amplifying the FOV as well as maintaining the high resolution.

2 Possible applications for acousto-optic deflectors

Depending on the use-case, acousto-optic deflectors can be used in automotive lighting systems. The working principle and the functionality of the acousto-optic deflection mechanism will be introduced in this chapter for varied applications.

2.1 Introduction into the acousto-optic principle

An acousto-optic device includes a crystal and a piezoelectric transducer attached to the crystal. By driving the piezo device with an RF amplifier, sound waves are applied to the AOD's crystal. A sound wave travelling through a medium, creates a mechanical (tensile or compressive) stress in the medium. Due to this stress, the refractive index of the medium changes. A change in the refractive index of an environment with an acoustic wave is called the "acousto-optic effect". Because of the periodic change in the refractive index of the medium, an AOD acts like an optical grating device, moving at the speed of the sound, diffracting the incident laser beam. The deflection of the light via this diffraction phenomena is called "Bragg's diffraction". According to Bragg's diffraction every wavelength $\boldsymbol{\lambda}$ is diffracted in a different angle. Therefore, if the angle of the incident laser beam is fixed to the Bragg angle, the deflection angle $\boldsymbol{\theta_d}$ can be expressed by the frequency of the acoustic wave $\boldsymbol{f_a}$ the acoustic velocity $\boldsymbol{v_a}$ and the refractive index $\boldsymbol{n}$ of the material [1].

$$\theta_d = \frac{\lambda f_a}{2 \boldsymbol{n} v_a} \tag{1}$$

We can express the acoustic wavelength as $\boldsymbol{\Lambda}$ [2].

$$\Lambda = \frac{v_a}{f_a} \tag{2}$$

According to the relation (1) and (2), the dependency of the deflection angle to the acoustic and optical wavelengths can be clearly observed.

$$\theta_d \propto \frac{\boldsymbol{\lambda}}{\boldsymbol{\Lambda}} \tag{3}$$

This dependency plays a crucial role for AODs to have a small deflection angle range. Because the sound wavelength is usually greater than the optical wavelength. If the oscillation frequency of the piezo electric transducer, or in other words the frequency of the acoustic wave, is varied the deflection of the diffracted beams varies. This sweep from the initial frequency of the sound wave to the final frequency is expressed by the frequency bandwidth $\Delta \boldsymbol{f}$, of the transducer, which is an important property and has a strong effect on the efficiency of the deflection. Besides, depending on the wavelength every colour will have a different deflection angle offset. This chromatic dependency leads to a limited deflection range for white light which is produced by additive colour mixing of different wavelengths [6].

2.2 Deflector Specifications

The specifications of the deflectors used in the experimental setup, which will be presented afterwards, are shown in the table below. These are typical values for deflectors optimised for the visible wavelength range.

Material	$\mathrm{TeO_2}$
Acoustic velocity	650 m/s
Wavelength range	350 – 1600 nm
Optical transmission	> 90 %
Aperture	7.5 x 7.5 mm^2
Scan angle	41 mrad ~ 2.3° @532 nm
RF frequency, power	50 – 110 MHz, 1 W

Table1. Technical specifications of AO deflectors, AA Opto-Electronic [8].

The mechanism offered by acousto-optic deflectors differs from other deflection devices due to their mechanical-free principle. This can be a great advantage in many applications, since only altering the frequency of the device will provide desired deflection patterns. However, there are also certain challenges regarding to the AOD’s nature and mechanism such as its narrow scan range.

2.3 Projection Applications

Adaptive and automated lighting systems in car headlights have led to a safer and more comfortable drive. High-resolution headlight systems are believed to improve that further. There are still ongoing developments for high-resolution scanning systems to realise, for example, projections for communication between the car and the driver.

In order to generate intense and possibly coloured projections, a combination of an RGB laser and Acousto-optic Deflectors can offer promising performance. It is possible to direct only one colour to the AODs from the laser and deflect it in the desired angle. For symbol projections desirable deflection range is approximately $\pm 4°$ in the vertical direction and $\pm 6°$ in the horizontal direction. Besides the deflection range, another important parameter to realise high resolution symbol projections is the laser beam divergence. The scanning resolution can be explained as the ratio of the scan angle to the beam divergence. That is the number of different directions that can be addressed by the projection system. Therefore, laser beam divergence must be maintained at its minimum for the system to address as many directions as it can [6].

2.4 Illumination

Usage of an RGB laser with AODs provides white light generation by additive colour mixing [3]. However, this requires a more sophisticated configuration, especially for the optics design to illuminate the road in wider angles compared to projections and with a good contrast. The desirable area for illumination applications is ±5° in vertical plane and ±20° in horizontal plane.

An optical system combined with the AODs, can give attractive features for road illumination. The mechanism free deflection of the AODs leads to high degrees of freedom for the deflection patterns. The deflection pattern can be adjusted to the desired light distribution. Redistribution of the light can be used, for instance, to generate low beam, glare-free high beam and bending light.

3 Optics Design

The implementation of Acousto-optic deflectors in automotive headlights, as indicated before, offers a great potential in terms of adaptive lighting systems. The basic principle of this project is sketched below.

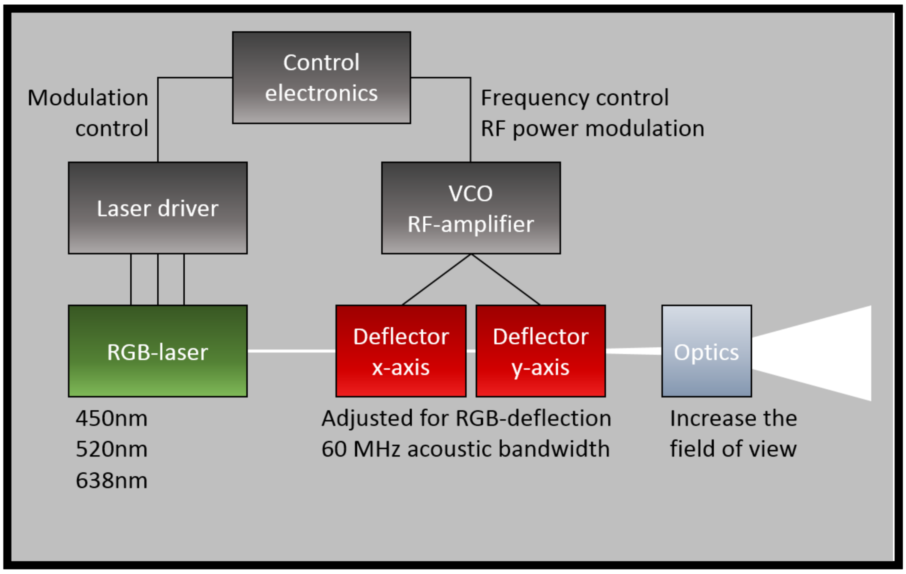

Fig.1. The working principle of the headlight system.

The laser beam from an RGB laser source is sent to two acousto-optic deflectors deflecting the light beam in horizontal and vertical directions. From equation (3), the wavelength dependency of the deflection angle can be seen. Since all three wavelengths will end up in different deflection areas, the longer the wavelength the higher the deflection angle, only the intersection of these three deflection ranges can be used for white light illumination. Thus, the deflection of the generated white light results in a relatively small deflection range. This range of chromatic overlap of three wavelengths was measured to 19,6 mrad, hence the total scan range is determined to approximately $1° x\, 1°$. Deflected light must pass an optical system which is increasing the field of view of the illumination in the desired area. The trade-off is clear: the larger the field of view the larger the beam divergence. The resolution of the whole system is directly depending on the single beam divergence. Minimisation of the divergence of the beam is the requirement to realise adaptive high-resolution scanning applications.

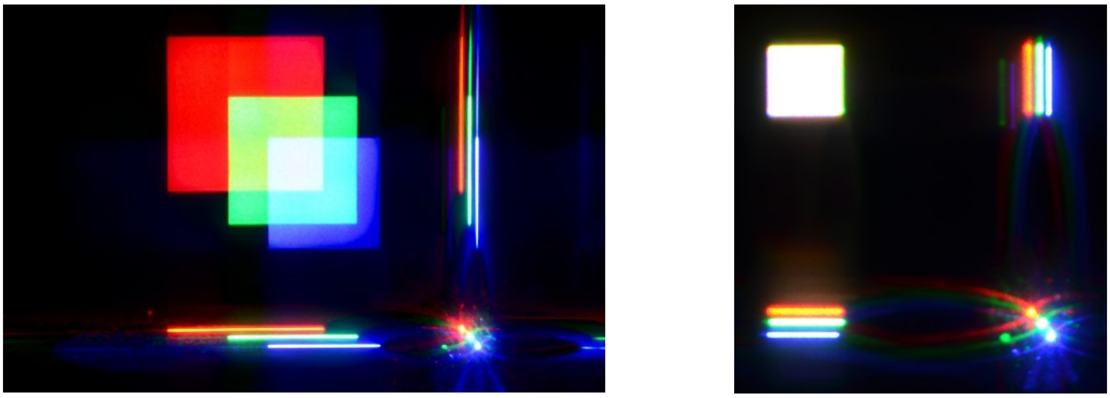

Fig.2.a

Fig.2.b

Fig.2. a. Simultaneous deflection and the chromatic overlap of the wavelengths and b. white light generated by the colours and cut-off by serial deflection via electronic control [10].

3.1 Amplification of the angular range versus resolution

Obviously, increasing the field of view is possible by using additional optics, however, as they increase the single beam divergence at the same time, more sophisticated lens configurations are required. The narrow angular range of the AODs must be increased up to ±5° in the vertical plane and ±20° in the horizontal plane for illumination applications.

Initial FOV	**H, V: 1°**
Targeted FOV	**H: ±20° , V: ±5°**
Aspect Ratio	**4:1**

Table.2. Illumination window for automotive illumination.

Resolution is the number of resolvable spots and it is given by the total scan angle of the AODs divided by the single beam divergence. A minimum beam divergence is achieved by maximising the beam radius of the collimated input beam. Therefore, a low divergence and highly collimated input beam is ideal for the optical system.

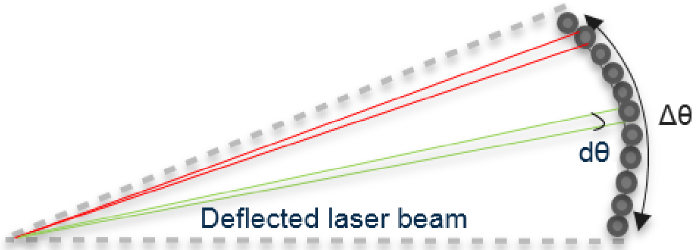

Fig.3. Illustration of different points addressed by the deflectors.

Where $\Delta\boldsymbol{\theta}$ is the total scan angle, $\boldsymbol{d\theta}$ is the single beam divergence and the resolution is ***N*** [7].

$$\boldsymbol{N} = \frac{\Delta\boldsymbol{\theta}}{\boldsymbol{d\theta}} \tag{4}$$

Initially the RGB laser source used, has a full angle beam divergence of 1 mrad (0.06°), which is highly collimated and will further increase after passing through the optical system.

The optical assembly was set up right after the deflectors, based on imaging optics. Two crucial properties were considered: minimum beam divergence and target field of view (FOV). Two different approaches were realised. Principally, both approaches are telescopic systems, however, to reach the target aspect ratio, the second system was improved by implementing special curved surfaces when designing the lenses. With the first basic telescopic system a squared pattern was achieved, which can be used for symbol projection, however for illumination usage the pattern must have an aspect ratio of 4:1.

3.2 Basic Telescope

One of the advantages using a laser light source in automotive lighting is that their high range to illuminate the road with highly collimated light. To maintain this property of the laser beam, imaging optics such as telescopes, can be helpful. A system without focus or an infinite focal length is called afocal system. Such a system produces an image at infinity just as what an optical telescope can produce. An image at infinity means the output of the system is collimated, and that is the target to be achieved as an output in the proposed headlight system [4] [5].

Galilean telescopes and Kepler telescopes are examples for afocal systems including two lenses. Their distance equals to the sum of their focal lengths. The first lens is called objective lens having lower refractive power and the second lens is called eyepiece or ocular lens with greater refractive power. Below, both telescopic systems have illustrated and compared.

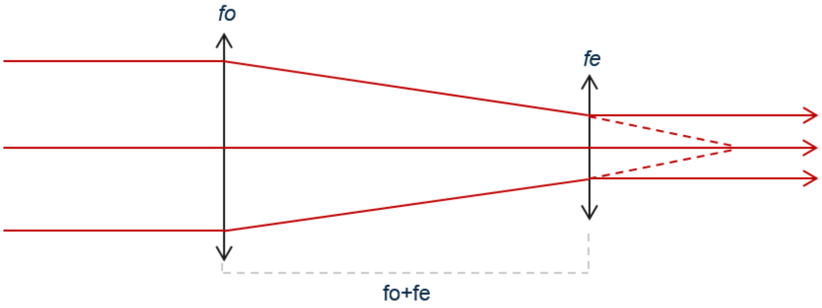

Fig.4. Galilean Telescope

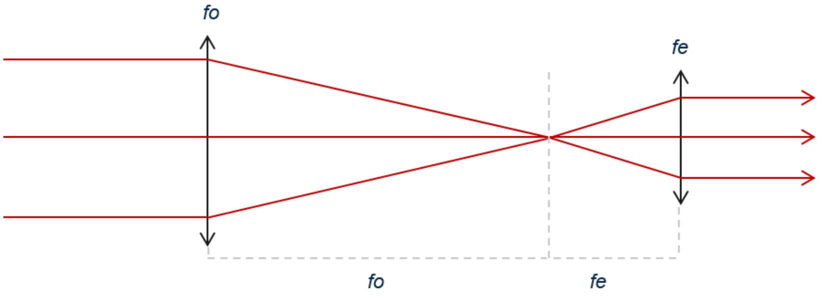

Fig.5. Keplerian Telescope

In both telescopic systems the angular magnification is calculated by the ratio of the power of the eyepiece lens and the power of the objective lens.

$$M = \frac{fo}{fe} \tag{5}$$

In Galilean telescopes the eyepiece lens has a negative focal length which is generating an upright image, while in Kepler telescopes the eyepiece is a focusing lens, resulting in a reversed image [5].

To simulate telescopic systems, LightTools optical design, simulation and optimisation software was used. In order to evaluate the illumination and scanning applications at the same time, the illumination window (FOV) and the divergence of a single beam must be observed. Therefore, several rays were simulated, especially the ones reaching to the edges, sides and the centre. The configuration of the deflection has been simulated in a 1° total scan range just as the output deflection range of the deflectors. So, the centre beams were deflected $\pm 0.5°$ horizontally and vertically. Since the RGB laser source has a 0.06° divergence angle, the same property was assigned to every simulated beam. The profiles of the scan beams are shown in fig.7.

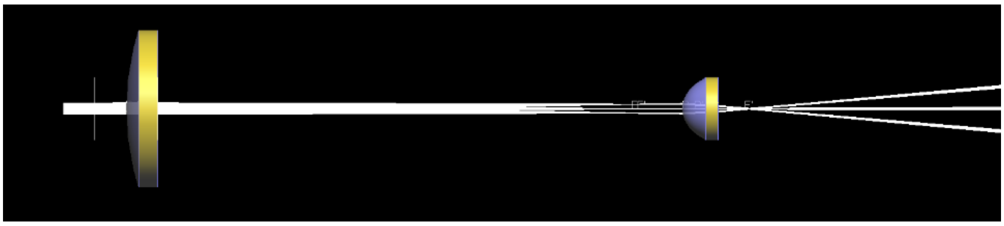

Fig.6. Simulation of Keplerian Telescope

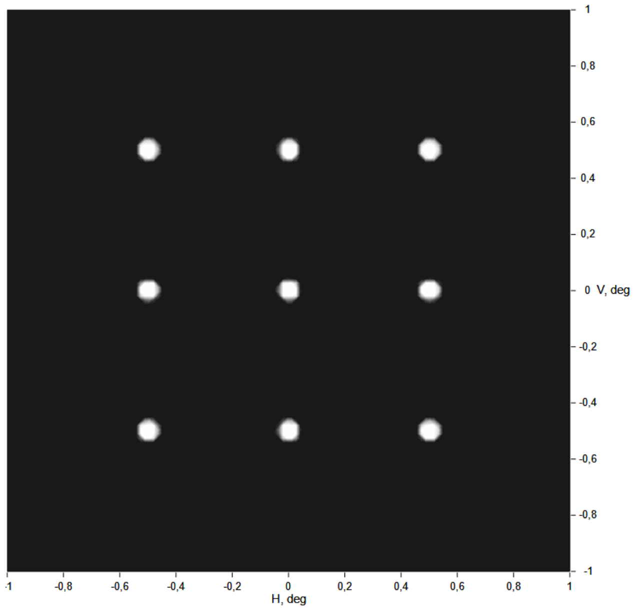

Fig.7. Simulation of deflectors' output indicating the initial FOV in both horizontal and vertical directions in degrees.

As a next step by using two convex lenses a Keplerian telescope was simulated. The lenses were selected to obtain a magnification factor of 10, so that the initial 1° full angle FOV can be expected to reach up to 10°. The eyepiece lens was selected to have an aspherical surface to reduce spherical aberrations. The telescope and simulation results are shown in fig.6. and fig.8. Figures are shown in grayscale indicating the intensity information. The contrast ranges from black at the lowest intensity to white at the highest [9]. Approximately, ±5° FOV are obtained in horizontal and vertical direction, which is applicable for on-road symbol projections.

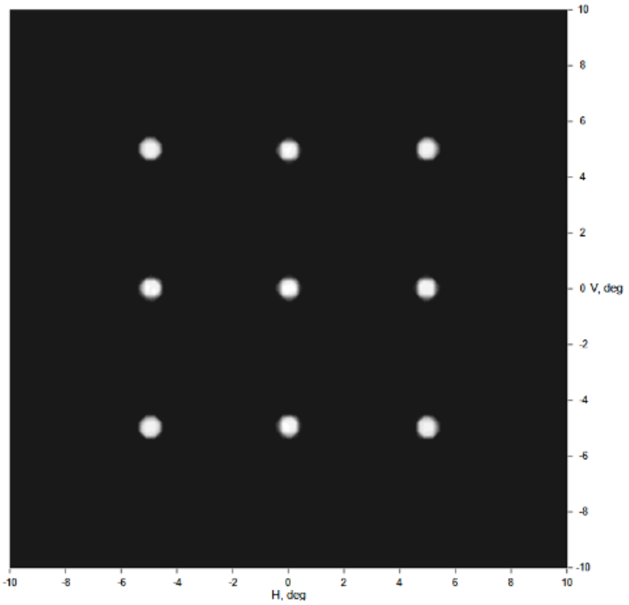

Fig.8. Simulated output of the Keplerian Telescope. The angular intensity distribution is shown in a grayscale plot.

3.3 Toroidal Telescope

There are certain requirements for automotive lighting. Several optical requirements have been already mentioned in the previous chapters including the FOV range for illumination applications. However, there are other aspects regarding to automotive lighting including mechanical requirements, complexity and costs. As a mechanical requirement, the system's overall length, is limited to approximately 120 – 200mm. Respectively, in vertical and horizontal directions, the angular range of $\pm 4°$, $\pm 6°$ for projection and the angular range of $\pm 5°$, $\pm 20°$ for illumination applications are the optical requirements for automotive lighting.

Although the Keplerian telescope system can be quite suitable for projection applications, the illumination window must be squeezed in the vertical direction and stretched in the horizontal direction for illumination applications. At this point cylindrical lenses can help, however as the system requires more compactness, useful lenses were designed to combine the properties spherical and cylindrical lenses in one element.

To achieve such a compact system the number of the optical elements can be reduced just by designing their optical properties. A toroid lens, for instance, shows different refracting powers in perpendicular planes. In this step, the lenses used in the first setup were replaced by two toroid lenses to achieve the targeted aspect ratio.

For the objective lens a focal length of around 100mm is considered to make the length of the system shorter. For both lenses aspherical surfaces are selected to minimize the spherical aberrations. The refractive powers of the toroid lenses have been chosen in order to achieve the target field of view. Curvatures of the torus were calculated in both planes, to reach a magnification factor of 40 in the horizontal plane and 10 in the vertical plane.

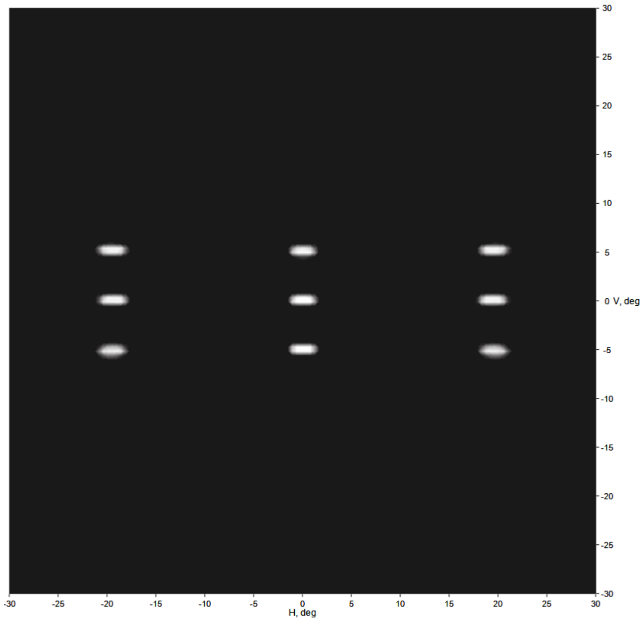

Fig.9. Output of the toroidal telescope.

3.4 Experimental Evaluation

An experimental setup was built to demonstrate the headlight system including an RGB laser source, two AODs and optics. In fig.10. the illustration of the setup can be seen. In the experimental part, the realisation of optics for projection applications showed results that are well matching the simulation.

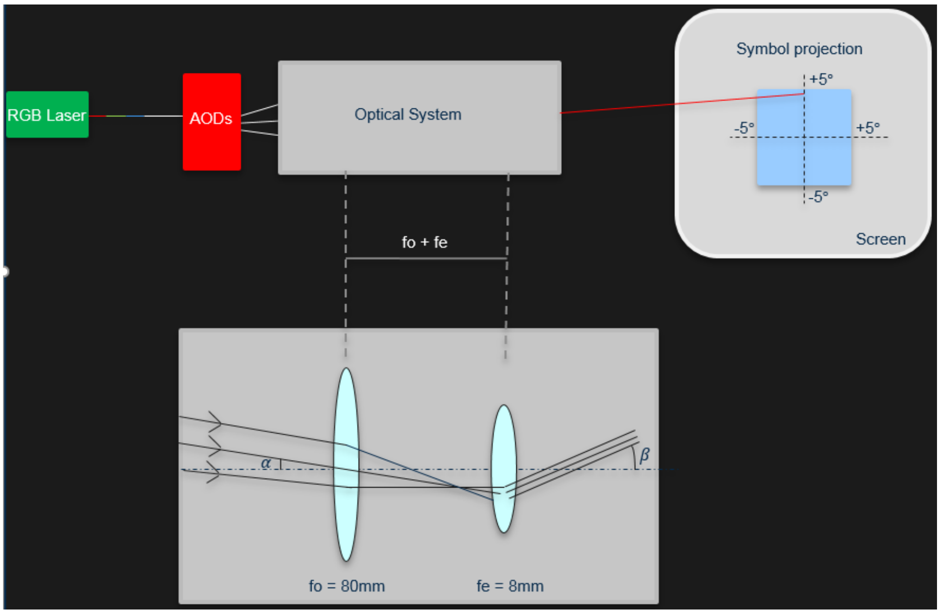

Fig.10. Principle of the experimental setup. Keplerian telescope has been sketched to show the principle rays, hence the relation between input angle α, and the output angle β.

As in simulations, two convex lenses were used to build the Keplerian telescope. The results proved that the optical system is suitable for realising coloured symbol projections. In fig.12. the experimental deflection patterns are shown. The first pattern is the output of the deflectors deflecting green light in 1° full scan angle. The second is the final deflection pattern of the light passing the telescope. The magnification factor is 10, hence the total deflection is $\pm 5°$ in both directions.

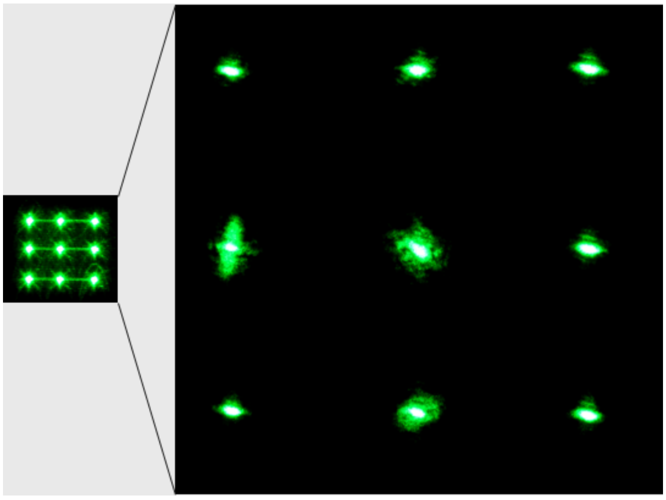

Fig.11. Experimental results.

However, there is still ongoing research to achieve the desired FOV for illumination applications. At this point the manufacturability and expense of toroidal lenses are the debate topics. Yet, as they showed satisfying results for the desired FOV and the system's compactness, it is wort to proceed further to evaluate the potential of toroidal lenses in real applications.

4 Conclusion

The potential of an alternative deflection unit included in a headlight system has been presented in this paper. Acousto-optic deflectors offer promising features to the automotive lighting technology, since they have certain advantages compared to other deflection mechanisms. Any deflection pattern with the desired intensity distribution can be created by acousto-optic deflectors for scanning and illumination applications. It was shown that their scan range can be enhanced and optimised for a variety of automotive lighting applications. In the simulations, the targeted FOV for both projection and illumination applications was achieved by implementing toroidal lenses in a telescopic setup, while in the laboratory a Keplerian telescope was built showing results which are matching prior simulations. In both configurations, the restriction of the imaging system showed the same effect for the beam divergence, which still needs to be reduced for high-resolution applications. Another approach to increase the resolution or to decrease the divergence of the beam, the efficient use of the deflector's active aperture. Herein, beam expanders can play a crucial role. Nevertheless, these approaches are included in further steps to be evaluated.

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