Integration of a multifunctional and multispectral optical sensor for automotive applications using surface mountable planar optical interconnect

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Abstract

In this paper we present the design and fabrication of a low cost surface mountable planar optical interconnect and the integration in a low-cost multifunctional and multispectral CMOS vision sensor (MFOS) to detect critical environmental parameters (fog, rain, twilight) providing, at the same time, information on the driving scenario (oncoming vehicles, VRUs in night conditions). The project ADOSE addresses research challenges in the area of accident prevention; the focus is on functional, performance and cost limits of current sensors and Advanced Driver Assistance Systems for their extensive market penetration. The 3D structure of the interconnect makes it possible to guide collimated light to dedicated detection regions on a CMOS imager, thus making a virtual partition of the sensitive imager area in sub-areas, usually not needed by the applications requiring the frontal view monitoring, possible. Therefore one imager chip can be used for several sensing and imaging functions. The optical system can be passively assembled and is surface mountable resulting in low cost fabrication.

Introduction

Nowadays a lot of sensors are used on vehicle or are being developed to detect environmental parameters (luminance, rain, dimming) and the driving scenario (oncoming vehicles, approaching tunnels, lane detection, VRUs in night condition). These sensors provide the necessary input for comfort and safety assistance systems: illumination adapting to the visibility conditions, fog lamp lighting, turning on (off) lamps before tunnel entrance (exit), illumination adapting when crossing other vehicles, automatic activation of windscreen wipers, automatic demisting, automatic speed control, lane warning, etc. Car makers have to manage this increasing number of sensors which means complexity in terms of sensor housing, cabling, electronic interfaces and actuation strategies. For this reason, component suppliers are working toward the integration of more functions. At the moment the integration level is limited to a maximum of three different sensors in a single package and the functions involved are non-imaging. The monitoring of the area in front of the vehicle with one or more cameras allows to collect useful information on the scenario (kind, dimensions and shape of objects and obstacles) to implement comfort and safety functions. For instance, lane warning and lane keeping systems, are based on the use of a camera (CMOS array) placed close to the internal rear-view mirror. The format of the camera is often redundant for the function (e.g. VGA area is not completely used in lane warning function). The former needs (combination of imaging and non-imaging functions and reduction of number of sensors) can be successfully addressed by a multifunctional integration on a multispectral CMOS array. The advantages stemming from this solution are: increased reliability, easy-to-use functions control, reduction in number of sensors and components, lower size, easier mounting on vehicle and reduced total costs. The ADOSE project aims at developing a multifunction automotive sensor with the integration on a single CMOS array of part or all the above mentioned functions, presently performed by different sensors. The approach is to utilise the array as the photo-sensitive element and to divide it into sub-areas, each one being dedicated to one or more functions. The solution proposed by CRF will allow going far beyond in terms of both number and type of integrated functions, thus reducing system costs significantly. The acquisition and processing of each area can be optimised by the use of *windowing* (i.e. reading of sub-areas of the pixel array) and the use of the suitable frame rate and sensor parameters (e.g. gain).

To reduce the amount of detectors for such sensing applications and collect light from special directions an optical interconnect and collecting optics were developed by Fraunhofer IZM to gather and guide light to special region of interest (ROI) on one CMOS imager chip. The optical interconnect is a hollow lightpipe fabricated by hot embossing in Polymethylmethacrylate (PMMA) and coated with a thin layer of aluminum for enhanced reflection. The collection optics consists of Fresnel lenses to collect light from FOVs up to 60° and a condenser lens system to reduce the beam sizes for coupling into the lightpipe. The Fresnel lenses have been specially designed for environmental sensing applications and fabricated by hot embossing in polymer substrates. The optical system is schematically presented in Fig. 1. As it can be seen, the optical system also contains integrated deflection elements enabling sampling of the required field of view from arbitrary directions. The optical interconnect has been characterized by measuring the transmission of each channel in the visible and near-infrared spectral ranges. A transmission of up to 48% was measured, depending on the wavelength and the number of deflection elements in the channel. The optical system has been simulated using ray tracing software and a tolerance analysis was carried out which assured the passive assembly approach to meet the low cost requirement.

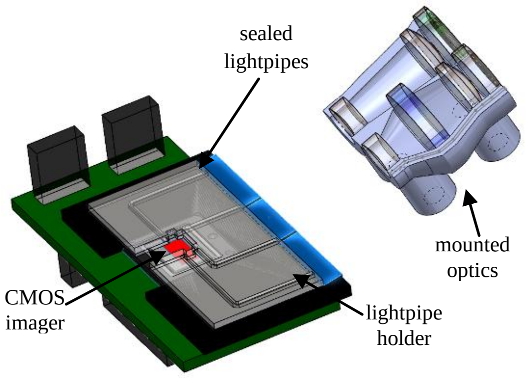

Fig.1. Schematic of the optical system

Principles of the sensor functions

First of all, the concept design was performed, in order to choose the most advantageous sensing 'principle' for each function. The main characteristics of the single functions are reported in the following table.

Table 1: Sensor Specifications

Function	Active/ passive*	Detection principle	Optical Filtering	Orientation
Area monitoring	Passive	Image analysis	None	Horizontal
Rain	Active	Image analysis	Band-pass	Orthogonal
Fog	Active	Intensity levels	Band-pass	Upward
Twilight	Passive	Intensity levels	None	Upward
(*) *Active= with emitter; passive= without emitter*				

From the functional specifications and concept design, the spectral range, the angular resolution and field of view (FOV) were evaluated. These parameters yielded the focal length and the f-number. The following figure shows the selected CMOS array partition.

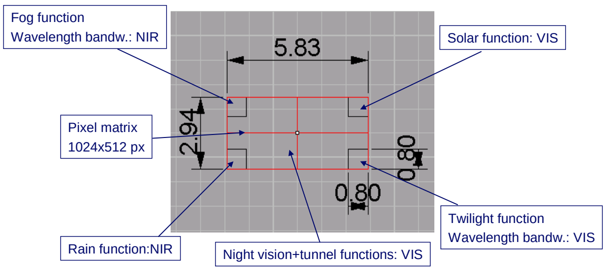

Fig. 2: Selected CMOS array partition

The working principle of the visibility function is based on the backscattering technique [3, 4] (emission of NIR beam and collection of the radiation scattered by fog particles).

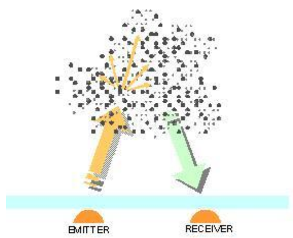

Fig. 3: Working principle of the fog function

The main advantage of this technique is that the emitter can be placed close to the detection system, thus maintaining the overall size small. An emitter (NIR-LED) and the receiver collecting lens have respectively the beam divergence and the field of view with partial overlapping. In presence of fog the concentration of small water particles in the overlapping zone produces a backscattering towards the receiver, with an intensity which is proportional to the fog density.

A first MFOS prototype [2], integrating the fog function and using a CMOS vision sensor characterised by logarithmic response, has been developed and validation measurements were carried out at the "Laboratoire Regional des Ponts et Chaussees" in Clermont-Ferrand (F), which has a tunnel for artificial and controlled fog generation. In the figure below the visibility level (metres), measured by a transmissometer, is plotted versus the analogue output (Volt).

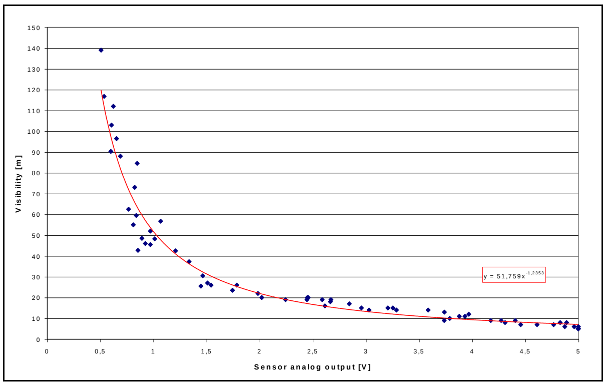

Fig. 4: Visibility vs Sensor analog output.

In the figure below the visibility level within a range of 5 to 500 metres is plotted versus the average grey scale level (ROI of 55x55 pixels). As can be seen, the intensity of backscattering radiation scales approximately as the inverse of visibility, therefore the output signal is nearly linear, due to the logarithmic response of the CMOS pixels.

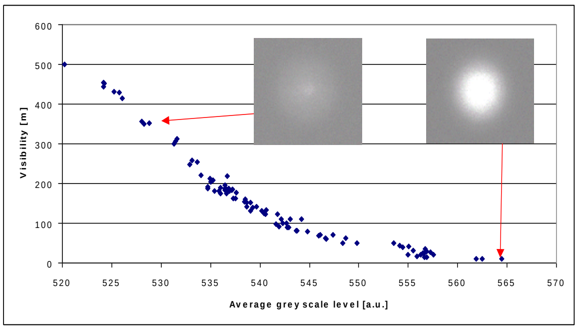

Fig. 5: Visibility vs average grey scale level.

The twilight function is devoted to the measurement of the environmental illuminance outside the vehicle to provide the automatic switching of the headlights. Moreover, this measurement is used, in combination with the information coming from the frontal view monitoring, to assess the discrimination between the tunnels and the bridges thus allowing the realisation of the tunnel function. The function has to avoid false alarms due to the presence of trees, shadows, artificial infrastructure lighting as well as automotive lighting (headbeams) with a working range between 0 to 5klux as can be derived from the table below.

Table. 2: Sensor working range

Environmental conditions	Lux
Bright sunlight	100.000-130.000
Shade illuminated by entire clear blue sky, midday	10.000-20.000
Typical overcast day	1.000-5000
Extreme of darkest storm clouds	100-300
Sunrise or sunset	<100
Moonlight	<1

Validation tests have been carried out in the first sensor prototype (CMOS logarithmic response). The figure below shows the transfer function between the external illuminance, measured by a luxmeter, and the average grey scale level (ROI of 55x55 pixels). In order to discriminate different environmental scenarios, specific ranges must be chosen: twilight (0 - 10 lux), overcast sky (10 - 1000 lux) and indirect solar light (>1000 lux).

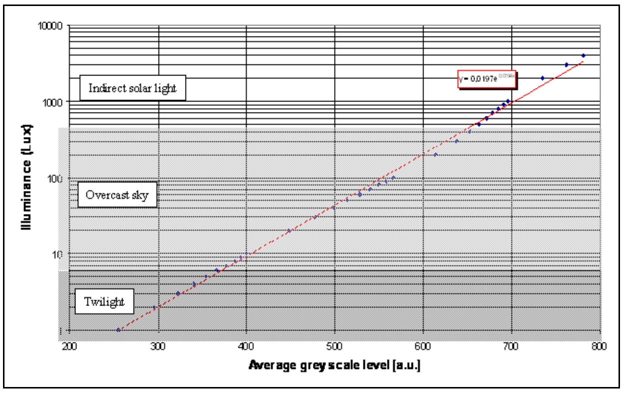

Fig. 6: Validation of the twilight function

Optical Design

The schematic of the optical system for the twilight function is shown in Fig. 7. A Fresnel lens with a diameter of 7mm and different facet angles samples the FOV of 60°. Each facet samples two degrees of the FOV and collimates the so collected light. The collimated light beam is focused through a standard plan convex lens (Ø=9mm), which is directly placed behind the Fresnel lens to reduce the beam diameter and the light is then nearly collimated by a standard bi concave lens (Ø=6mm) after 12mm. The reduced beam is reflected by an aluminum coated surface and coupled into the also aluminum coated lightpipe with edge length of 600µm and an overall length of 15mm. The lightpipe guides the light to the ROI with an edge size of 800µm placed at the corners of the CMOS imager (Fig. 2). Thus it is possible to use one imager chip for different sensing applications.

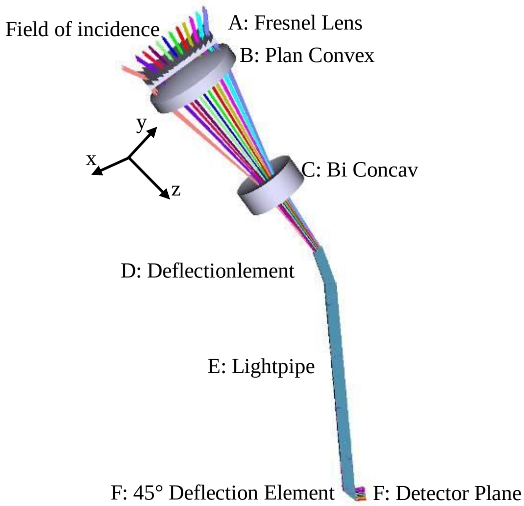

Fig. 7: Schematic diagram of the optical setup showing the optical components. The lightpipe is coated with a thin film of aluminum for enhanced reflection

To ensure the functionality of the optical design a non sequential simulation has been conducted using optical design software Zemax® to calculate the spot size on the imager and the transmission of the optical system for VIS and NIR. Fig. 8 shows the spot diagram hitting the lightpipe for field of incidence of 0° and 20°. It can be seen that the spot size diameter is smaller than the plane of the lightpipe. Fig. 9 displays the light on the ROI on the imager plane also for 0° and 20° field of incidence. The simulated transmission of the system was up to 60% depending on the field of incidence. Light of higher fields of incidence are not completely collimated and hence more often reflected in the lightpipe. Therefore the transmitted intensity is lower, due to the Fresnel losses. The calculated overall transmission efficiency is up to 46%. The losses of 54% are due to the Fresnel losses in the lightpipe as well as reflection losses at the lens surfaces, which are not anti reflecting coated.

To ensure the possibility of passive assembly a tolerance analysis was carried out vary the distances between the plan convex lens and the bi concave lens and the gap between the bi concave lens and the lightpipe in all three spatial directions. Fig. 10 shows a 2D tolerance analyses for the field of incidence of 30°, which causes the smallest tolerances for the system, vary both distances in z-direction and displaying the transmission efficiency. The tolerable tolerances in x, y-directions are ±50µm for each element and ±300µm for the z-direction allowing passive assembly of the optical parts using mechanical stops in the lens mounts which could be fabricated by e.g. injection molding meeting the requirements for the tolerances and the low cost approach.

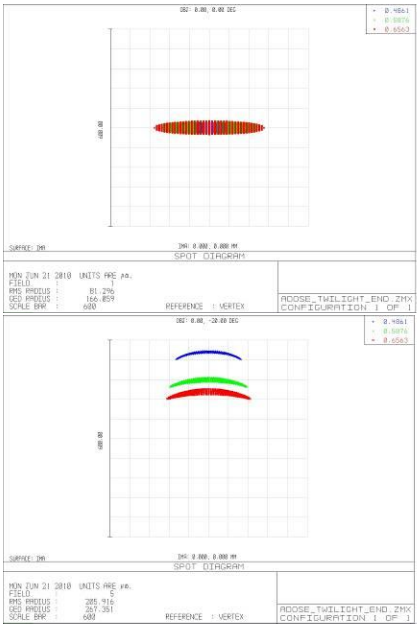

Fig.8: Spot diagram at the lightpipe entrance 4mm behind the bi concave lens. The diagram is scaled to an edge size of 600µm. The upper figure is calculated for an angle of incidence on the Fresnel lens of 0°. The lower figure shows the calculation for 20°.

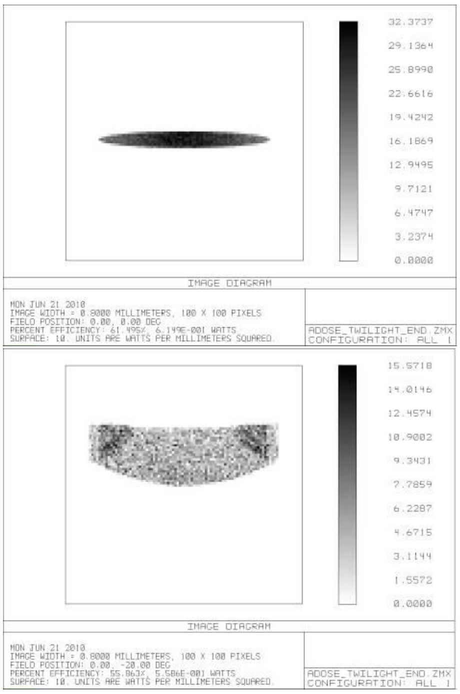

Fig. 9: Light intensity at ROI of imager plane with a 800µm edge size. The upper figure is calculated for an angle of incidence on the Fresnel lens of 0° with transmission efficiency (TE) of 61%. The lower figure shows the calculation for 20° with TE of 55%.

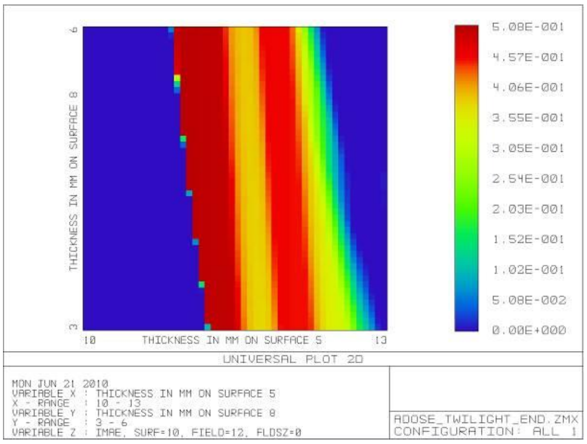

Fig.10: 2D Tolerance analysis vary the distance between the plan convex lens and the bi concave lens (x-axis) and the distance between the bi concave lens and the first the deflection element (y-axis) for a angle of incidence of 30° which causes the smallest tolerances in z-direction of the system of ±300µm.

Fabrication and Packaging

The lightpipes which couple the collected FOV to the ROI on the sensor chip are hollow lightguides embossed into a polymer substrate which is subsequently metalized to ensure reflection at all incident angles. Furthermore, the Fresnel lenses are also hot embossed in polymer substrates. To ensure the required optical quality of the surfaces of these structures, special high precision milling methods have been employed to produce the master stamps with a surface roughness of R_a=15nm. The lightpipes are square in cross section with an edge length of 600µm. In addition to the lightguide structures, grooves on either side of each lightguide are embossed into which the glue (for fixing of the lid) should flow to avoid contaminating the lightpipes. The structures were hot-embossed using a Jenoptic HEX03 hot embossing machine. The lightpipes and the Fresnel lens were embossed in 1mm thick PMMA which is perfectly suitable for CO_2 laser cutting. The laser cutting was a necessary process step to cut an opening structure into the PMMA substrate for the frontal view function which uses the major part of the CMOS imager (Fig. 12). Images of the structures embossed in polymer substrates are shown in Fig. 11. After embossing, the lightpipes were metalized with Aluminum Al using a PVD process with careful attention paid to the angle of incidence of the evaporation beam to ensure that all the fine structures and deflection surfaces are properly coated. Fig. 12 displays a laser cutted and Al coated PMMA substrate with lightpipes. The lightpipe structure was sealed by an Al coated 300µm thick PMMA foil using adhesive bonding.

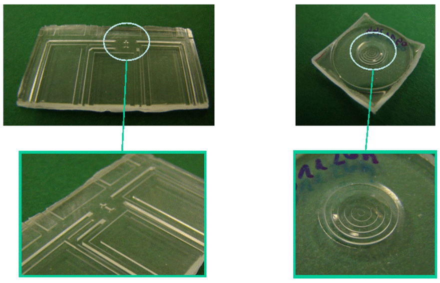

Fig. 11: Microscope picture of the hot embossed light pipes and Fresnel lens in 1mm thick PMMA

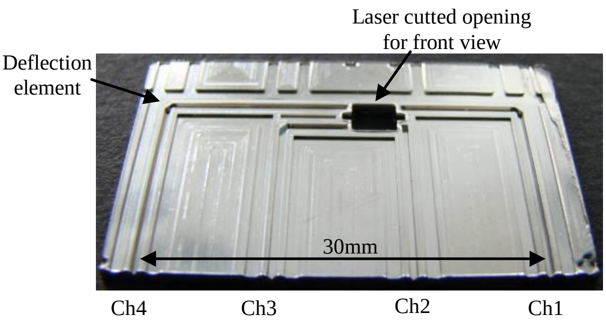

Fig . 12: Aluminum coated PMMA lightpipes with an opening for frontal vision function fabricated by laser cutting

To meet the requirements of low cost fabrication the lightpipes and the packaging concept were developed with regards to a possibility of surface mounting. The planar structure of the lightpipes, sealing foil and the lightpipe holder offer the possibility to assemble the parts by surface mounting onto the CMOS Imager PCB using adhesive bonding and clip features (Fig. 13).

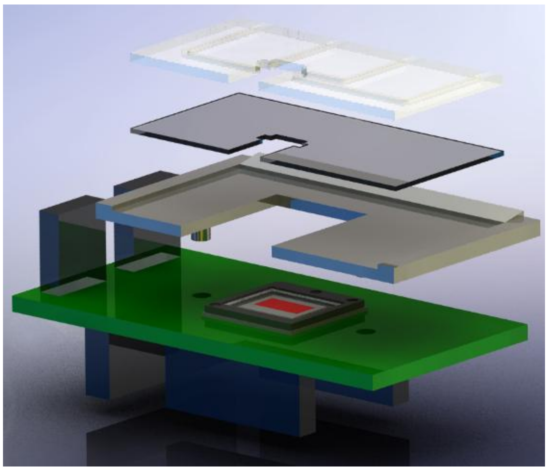

Fig 13: Schematic of surface assembly of the lightpipes. From top to bottom: PMMA lightpipes, sealing foil, lightpipe holder with deflection element, CMOS imager mounted on PCB

Characterization

The optical systems of the fog and twilight function were characterized. The Fresnel lenses were illuminated by a white light source or a NIR LED focusing the light through a plan convex lens generating the special FOV for each function. After reducing the beam diameter through the condenser optics the light were coupled via the first deflection element on the lightpipe holder into the lightpipe. The light intensity was measured using a calibrated photodiode prior the lens system and at the output of each of the four lightpipe channels (Table 3). The highest transmission of 48% ± 4% was measured for the lightpipe channel with one deflection element. The simulation with one deflection element showed a calculated transmission of 46% which is an excellent match to the measured transmission showing the accuracy of the ray tracing simulation. The transmission decreases for channels with two deflection elements due to losses caused by reflection at aluminum surfaces. Channel 4 showed the lowest transmission. This is also due to the Fresnel losses caused by multiple reflections due to longer traveling path of the light in this channel (Fig.12).

Table 3: Measured Transmission

Channel	Transmission (VIS) ± 4%
1	37%
2	48%
3	41%
4	29%

Conclusions

In this paper we presented the development of a low cost surface mountable optical interconnect for a multifunctional and multispectral CMOS vision sensor for automotive applications. The need to integrate more and more sensors providing data about the driving environment led to a combination of imaging and non-imaging functions on one CMOS chip. The working principle of a fog and a twilight (diming) sensor were presented giving information about the visibility and the illuminance around the vehicle. The collection optics was designed to cover a special field of view using Fresnel lenses and a condenser optic to collimate the light and couple into the optical interconnect using aluminium coated lightpipe channels to guide the light to the partitioned CMOS chip matrix. To meet the low cost requirements for this application the optical system was designed for passive assembly and the possibility to assemble the optical interconnect by surface mounting. A Ray tracing simulations as well as tolerance analyses were carried out to ensure a configuration with high transmission in the VIS and NIR region and the passive assembly approach. A transmission of up to 48% was achieved which could be further enhanced in the future by using anti reflective coating for each sensor part.

Acknowledgments

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http://www.adose-eu.org/

References

1 J. Bechtel, J. Stam, Control circuit for image array sensors and automatic headlamp control, Gentex Corporation, international patent WO 99/14943, 1999

2 SIRPA (Sviluppo di Sensori Integrati per il Rilievo di Parametri Ambientali), project funded by the Autonomous Province of Trento (Italy), partners: Centro Ricerche Fiat (Italy), ITC-IRST (Italy), University of Trento (Italy), Neuricam (Italy).

3 H. C. Van de Hulst, Light scattering by small particles, Dover Publications, N.Y., 1957

4 J.D. Crosby, Visibility Sensor Accuracy: what's realistic?, presented at the 12th Symposium on Meteorological Observations and Instrumentation 2003 American Meteorological Society Annual Meeting, Long Beach, CA, 9-13 February 2003

5 R. Leutz, A. Suzuki, Nonimaging Fresnel Lenses, Springer Verlag, 2001.