Ultra-Thin Camera Based on Artificial Apposition Compound Eyes

J. W. Duparré (1), P. Dannberg (1), P. Schreiber (1), A. Bräuer (1), P. Nussbaum (2), F. Heitger (2), A. Tünnermann (1)
1 : Department Microoptical Systems - Fraunhofer Institut Angewandte Optik und Feinmechanik (IOF), Albert-Einstein-Str. 7, 07745 Jena, Germany; Tel.: +49 (0) 3641 807380, Fax.: +49 (0) 3641 807603, e-mail: jacques.duparre@iof.fraunhofer.de
2 : Centre Swiss d'Electronique et de Microtechnique SA (CSEM) Neuchâtel, Jaquet-Droz 1, CH-2007 Neuchâtel, Switzerland

Abstract: *An artificial compound eye imaging system fabricated by microoptics technology is adapted and attached to an opto-electronic sensor array. The thin objective consists of a microlens array on a silica-substrate with a pinhole array of different pitch in its focal plane on the backside. First captured images are presented, resolution and sensitivity are examined.*

1. Introduction

Natural apposition compound eyes combine small eye volumes with a large field of view, by the price of low spatial resolution. For small invertebrates the compound eyes are the perfectly adapted solution to get sufficient visual information about their environment. The motivation to realize the technical compound eye presented here is to develop an imaging system with a minimum thickness.

2. Design, Fabrication and Assembly

An artificial apposition compound eye imaging system fabricated by micro-optics technology [1] is adopted and attached to an opto-electronic sensor array with 128x128 pixels and 69 µm pixel-pitch capable of on-chip analog computation of contrast magnitude and direction of image features [2]. The 206 µm thin monolithic objective consists of a microlens array on a silica-substrate with a pinhole array in its focal plane on the backside of the substrate. The pitch of the sensor- and the pinhole array differs from the lens array pitch to enable an individual viewing angle for each optical channel. The master structure for the microlens array is manufactured by lithographic patterning of photo-resist and a subsequent reflow process. It is replicated by moulding into UV-curing polymer (Fig.1).

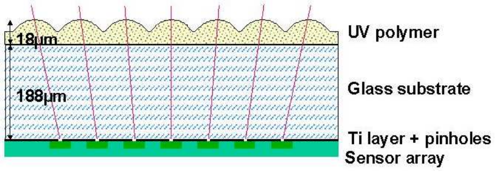

Fig.1. Schematic side view of the fabricated camera.

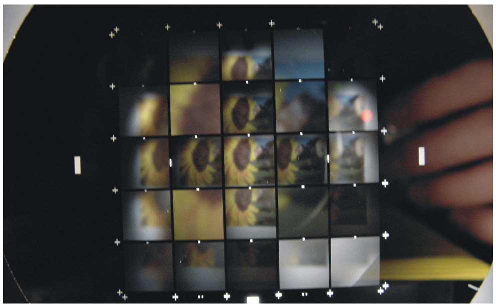

Fig.2. Wafer with 5x5 ultra-thin objectives before singularization imaging a picture of sunflower.

The fabricated imaging system has a F-number (F/#) of 2.2, a field of view (FOV) of 20°x20° and a magnification of an equivalent focal length of 24 mm. Cameras with different pinhole sizes covering the photo-sensitive area of the sensor pixels (size 20x20 μm^2) ranging from 2 to 8 µm were realized in order to examine the influence on resolution and sensitivity (Fig.2). The wafer-scale fabricated objectives are subsequently diced and aligned in front of the detector array (Fig.3).

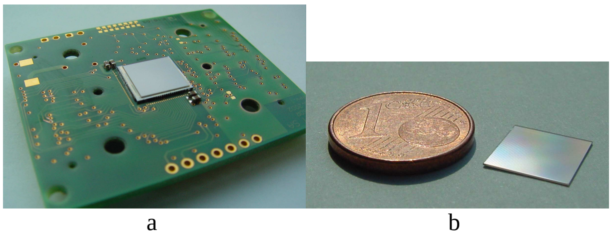

Fig.3. Diced artificial compound eye-objective attached to sensor (a) and in comparison to 1 Euro cent (b).

3. Characterization

We presented different test patterns to the vision system and investigated the captured images with respect to resolution and sensitivity. Due to the lack of opaque walls between the channels in this first technological approach, the size of the object presented to the vision system must be matched to it´s FOV to avoid cross-talk of neighbouring channels.

3.1 Captured images

A radial star pattern is well suited to determine the optical cut-off frequency of an imaging system. Here the object frequency is a function of the radial coordinate. Fig. 4a,b show the taking of the same star pattern using the artificial apposition compound eye (Fig. 4a) and using a bulk 1/3" image format objective with F/# 2.0 and a focal length of 12 mm (Fig. 4b). Fig. 4b shows the limitation of resolution by the sensor Nyquist frequency. The image resolution in Fig. 4a using the artificial compound eye objective is approximately half. The limiting factor of resolution of the compound eye objective is the overlapping of acceptance angles of the individual channels. Fig. 4c shows the caption of a portrait-photograph of Carl Zeiss demonstrating the capability of face recognition.

Fig.4. Captured test images with the artificial compound eye camera (a,c,d) and bulk objective in comparison (b).

The capabilities of the opto-electronic sensor array not only for acquisition of intensity images but especially for on-chip analogous computation of contrast and contrast direction without a need of postprocessing in a subsequent computer are presented in Fig. 5.

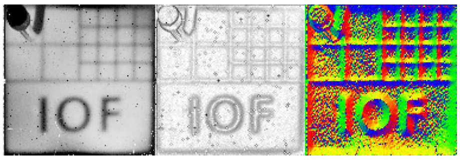

Fig.5. Capabilities of sensor array for close-to-the pixel analogous computation of contrast (b) and edge orientation (c); (a) is the intensity image.

3.2 Resolution

For a quantitative MTF-determination bar targets of different frequencies such as in Fig. 4d were imaged. Each signal frequency response (SFR) was calculated using a FFT-formalism where the first harmonics of the original and the imaged pattern are compared resulting in the MTFs presented in Fig. 6.

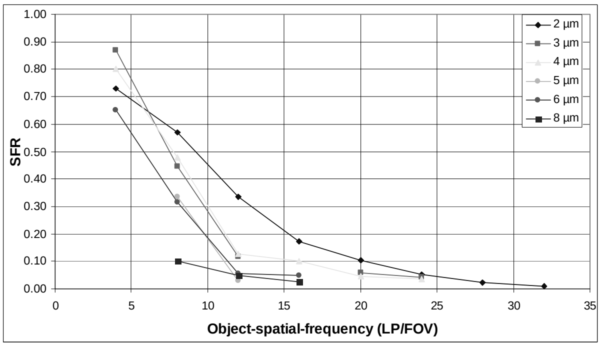

Fig.6. MTF of compound eye camera with pinhole diameter as parameter.

As expected the smallest pinhole size leads to the best MTF-characteristics.

3.3 Sensitivity

Using small pinholes for improvement of resolution of the compound eye camera results in a small sensitivity. In Fig. 7 the captured optical powers using compound eye cameras with different pinhole sizes are normalized to the power using the bulk objective with a sensor array with bare pixels for the taking of the same plain image.

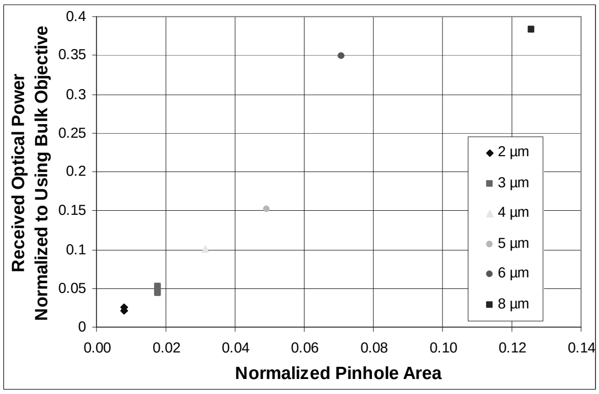

Fig.7. Sensitivity of compound eye camera. The pinhole size is the parameter. The pinhole area is normalized to the area of the bare pixel.

4. Introduction of opaque walls between channels

In case of large angles of incidence light focussed by one lenslet is received by an adjacent channel´s receptor. Ghost images (upper part in Fig. 8a). and a reduction of contrast result. In a different technological approach opaque walls are introduced between the optical channels of the objective (Fig. 8b). No ghost image appears anymore (Fig. 8c).

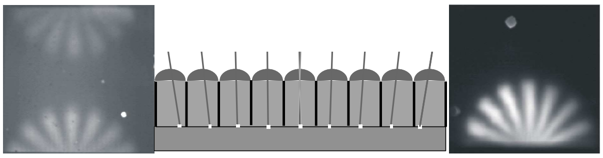

Fig.8. Ghost image due crosstalk between channels for large angles of incidence (a). Schematic side view of system with opaque walls between channels for avoiding crosstalk (b). Experimental result using opaque walls (c).

5. Conclusions

We demonstrated a novel optical sensor system based on artificial compound eye vision with an optics-thickness of approximately 0.2 mm and a resolution of 60x60 pixels. The experimental results show the perfect suitability of the artificial apposition compound eye concept for vision sensors such as sensor arrays which allow on-chip signal processing but have low optical fill factor. Opaque walls must be introduced between the optical channels to prevent from cross talk.

6. References

[1] J. W. Duparré, P. Dannberg, P. Schreiber, A. Bräuer, A. Tünnermann, “Artificial apposition compound eye - fabricated by micro-optics technology,” *Appl. Opt.* **43**(22), (2004).

[2] P.-F. Rüedi, P. Heim, F. Kaess, E. Grenet, F. Heitger, P.-Y. Burgi, S. Gyger, P. Nussbaum, ”A 128 x 128 Pixel 120-dB Dynamic-Range Vision-Sensor Chip for Image Contrast and Orientation Extraction,” *IEEE Journal of Solid-State Circuits* **38**(12), (2003).