Uniformity of Concentration Factor and BFL in Microlens Array for Image Dectectors Applications

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Abstract: We use an array of polymer microlenses spatially matched to an array of SPADs (Single Photon Avalanche Detector) to mitigate the loss of sensitivity due to the area fill-factor. The lens array is fabricated by polymer casting in a photoresist replica mold. We report results about reproducibility of concentration factor and back focal length within an individual 32x32 array. At a C factor of 35 and a focal length F=40 μm, the spread of concentration is < 6%, and the spread of BFL is <0.5 μm.

OCIS codes: (040.00040) Detectors; (040.1240) Arrays, (220.1770) Concentrators

1. Fill-factor Recovery

In image detectors, on-board processing of signal from each pixel is not practicable, because using sensitive area to allocate circuits introduces a fill-factor loss of sensitivity, usually too serious to be tolerated. In previous works [1,2] we propose to use an array of micro concentrators to recover the area fill-factor at the expense of a tolerable decrease of numerical aperture [2,4].

Our intended application is about an array of avalanche photodiodes or SPAD (Single Photon Avalanche Detector) [3], which requires a quenching circuit to recover fast from triggering after detection of a single photon initiating the avalanche. Further, important circuit functions that are required be integrated along with the pixel photosensitive area for specific applications of SPADs are: single-photon counters, time-of-flight sorters for rangefinders and spectrum analyzers, in applications to time-resolved spectroscopy, gene sorting and 3-D imaging [3].

Typical sizes involved in our FET European Union Project, based on a 120-nm technology, are: pixel size 50 μm by side, detector size 6.0 μm, number of individual SPADs 32x32 in a first demonstrator, then 128x128 in the final device. Thus, we need an array of microlenses of 50 μm pitch (≈ diameter), and the achievable fill-factor recovery (area ratio) is 69.5 (55 after the π/4 square-to-circle fill ratio).

2. The Concentrator Array

As the optical elements of the array, we first considered non-imaging prisms of different shape (cone, parabolic and tilted parabolic) which have been studied thoroughly with reference to photovoltaic cells [4] and that theoretically can attain high values of concentration C (up to 100 and more) [1]. [Here, C is defined as the ratio of irradiances on the detector with and without the concentrator element]. However, individual elements 50 μm in diameters are difficult to figure in the required exact shape and pose a formidable fabrication problem.

Thus, we moved to a much easier plano-convex lens array. This can readily provide C factors in the range of 20 to 40, adequate for a substantial recovery of fill-factor. Several approaches to fabricate the array have been demonstrated in literature. We have chosen the replica casting of a co-polymer into a photoresist mold, as described in Refs.[5,6]. The mold is obtained first by patterning an array of cylindrical rods in a photoresist film defined by photolithography, and followed by a baking that generates a spherical dome by thermal reflow.

Before fabrication, we checked the C-factor of the plano-convex lens array, using a computer ray-tracing routine to follow ray trajectories across the lens down to detector and calculated the C factor for NA from 0 to 0.4. As a typical result of simulations [2], the plano-convex lens attains a good C=55 at NA=0 and C=45 at NA=0.15 (corresponding to an objective lens F#=4), and also has an adequate depth of focus (about ±5 μm at focus distance=65 μm).

3. Experiment

A microphotograph of the lens array fabricated by the replica casting is shown in Fig.1. By a separate assembly operation, the array will then be aligned and glued onto the silicon chip carrying the SPAD array [3]. Size of the lens array is 1.6x1.6 mm, to match a 32x32 SPAD array with pixel size 50μm.

The lens array was first tested by an optical bench, comprising a variable input-beam NA objective and a scanning CCD array, interfaced to a personal computer. Results of concentration factor, measured on typical sample of the fabricated lens array, along the Z-axis parallel to the optical axis of the lenses is shown in Fig.2. Compared to theoretical value of 55 (at small NA), the measured maximum concentration 35 (at small NA) is smaller, by a factor about 35%. Possible reasons, presently under investigation, are: defects at the spherical-to-plane edge of lens base; deviation from the spherical shape; residual scatter of the lens surface.

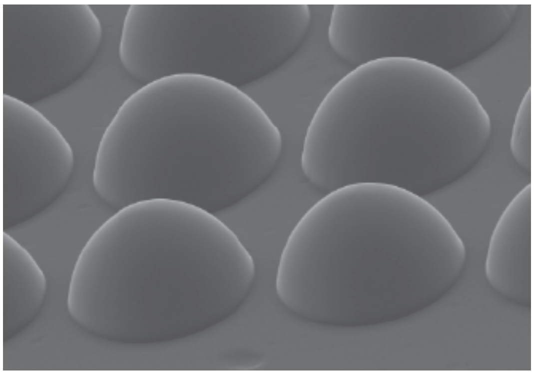

Fig.1 Microphotograph of plano-convex lens in the 32x32a rray, 50-μm pitch, 46-μm diameter
fabricated by polymer molding (by courtesy of J.-H. Lee).

More important, the uniformity of C and the BFL, the back focal length, were assessed on a number of individual lenses inside a single array and along a number of arrays. Both C and BFL are important because they reflect in a spread of signal amplitude of detected signal. The statistical data about the two sub-classes (inter- and intra-array) were quite similar giving evidence to their belonging to the same population. In Fig.2 we report typical samples of measured iso-concentration C curves, plotted in a NA-z (numerical aperture versus distance along the optical axis) graphs. From these data, we found that the rms spread in concentration was $\sigma_C<6\%$, whereas the back focal length has a rms deviation $\sigma_{BFL}<0.5$ μm.

Compared to other lens array fabrication techniques, namely the ink-jet printing [8], for which spreads as large as 12% in diameter (24% in concentration) have been reported, the replica mold technique looks performing better.

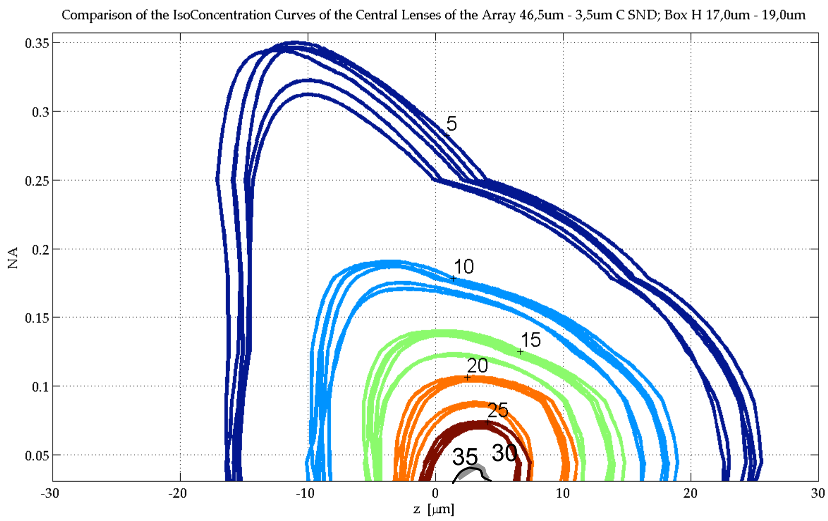

Fig.2 A sample of iso-concentration curves plotted on a NA-z diagram for the plano-convex lens array. The parameter is the value of concentration factor C.

This work has been supported by the European Community within the Sixth Framework Programme IST FET Open MEGAFRAME project (contract No. 029217-2). Disclaimer: *The publication reflects only the author's (authors') views. The European Community is not liable for any use that may be made of the information contained herein.*

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