Uniformity of Concentration Factor and Back Focal Length in Molded Polymer Microlens Arrays

Silvano Donati, Giuseppe Martini, Enrico Randone and Mohammad Fathi
Dipartimento di Elettronica, Università di Pavia, Via Ferrata 1, I-27100 Pavia, Italy
e-mail address: silvano.donati@ieee.org
Jiun-Haw Lee
Graduate Institute of Photonics and Optoelectronics,
National Taiwan University, Taipei 10617, Taiwan
Edoardo Charbon
Delft University of Technology, The Netherland

Abstract - An array of polymer microlenses, made of 32x32 individual elements spaced by a 50-μm pitch, is used in connection to an array of 32x32 6-μm diameter SPADs (Single Photon Avalanche Detector), with the aim of mitigating the loss in sensitivity due to the area fill-factor. The lens array is fabricated by polymer casting in a photoresist replica mold. Results about repeatability of concentration factor and back focal length are reported. At C= 35 and a focal length F=40 μm, the spread of concentration is < 6%, and that of BFL is <0.5 μm.

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

1. Introduction

On-board processing of the pixel signal is never attempted in imaging detectors, because even a simple circuit generally occupies a large area and spoils the effective efficiency. If spectral sensitivity is σ (A/W), a partial filling η of pixel area reduces the apparent sensitivity to ση, where $\eta=A_d/A_p$ is the fill factor, ratio of detector (A_d) to pixel area (A_p). If η is small (e.g. 0.01), on-board processing is impractical.

This issue is particularly important for array of SPAD (Single Photon Avalanche Detector), in which a quenching circuit is needed for fast recovery after detection of a single photon initiating the avalanche. Other processing circuits that can be integrated along with the photosensitive area for specific applications of SPADs are: time sorters, time-of-flight rangefinders and spectrum analyzers, for use in time-resolved spectroscopy, gene sorting and 3-D imaging [1].

Taking advantage of acceptance AΩ conservation [2], we may indeed focus the power collected by pixel area A_p in a smaller detector area A_d – provided the decrease in area is balanced by an equal increase of solid angle Ω, from input to output. The solid angle can be written as $\Omega=\pi\ NA^2$, where NA is the numerical aperture of the field-of-view of the receiver area. Thus, to get a high concentration ratio A_p/A_d we shall trade the numerical aperture NA^2_L of the lens imaging the scene. Frequently, the objective lens NA is limited by other considerations, like layout, depth of focus, available size or weight, etc., so there is an ample range of recovery allowed for fill-factor recovery. Typical sizes involved in our FET EU Project, based on a 130-nm technology, are: pixel size 50 μm by side, detector size 6.0 μm, number of individual SPADs 32x32. Thus we need an array of micro-lenses 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. Types of Optical Concentrators

As the optical element of the array, we may use non-imaging prisms of different shape (cone, parabolic and tilted parabolic) [3,4]which theoretically reach high values of concentration (up to 100 and more) [5]. But, on individual elements 50 μm in diameters, prisms are difficult to shape to the required accuracy. Instead, thermal reflow readily generates a spherical dome, thus micro lens array fabrication is a feasible approach [7-9] and can readily provide C factors in the range of 20 to 40, adequate for a sizeable recovery of fill-factor.

Before fabrication, we started assessing concentration performance, using a computer ray-tracing sub-routine to evaluate the concentration factor of the plano-convex lens array, following ray trajectories across the lens down to detector and calculating concentrations for NA from 0 to 0.4. As a typical result of simulations [6], the plano-convex lens attains theoretically 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. Fabrication

A lens array was fabricated by the replica casting of a polymer in a photoresist mold, as described in [7-9], A microphotograph of the array is shown in Fig.1, left. By a separate assembly operation, the array is then be aligned and glued onto the silicon chip carrying the SPAD array. Total size of the lens array is 1.6x1.6 mm, to match a 32x32 SPAD array with pixel size 50μm.

Lens arrays were first tested by a specially designed optical bench, comprising a variable input-beam NA objective and a scanning CCD array, interfaced to a PC. Experimental results of concentration factor, measured on a typical sample of the fabricated lens array, along the Z-axis parallel to the optical axis of the lenses is shown in Fig.1 right, with NA as a parameter. Compared to the expected theoretical value of 55 (at small NA), the measured concentration 37 is smaller by about 32%. 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.

Anyway, the value of 37 at small NA is a good result, because it allows recovering of the same amount the quantum efficiency – no more penalized by the small area fill-factor, and this is the main conclusion of this work.

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. In Fig.3 we plot the BFL deviation as a function of NA. From these data, we find that the rms spread in concentration was σ_C<6%, whereas the back focal length has a rms deviation σ_{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 performs significantly better.

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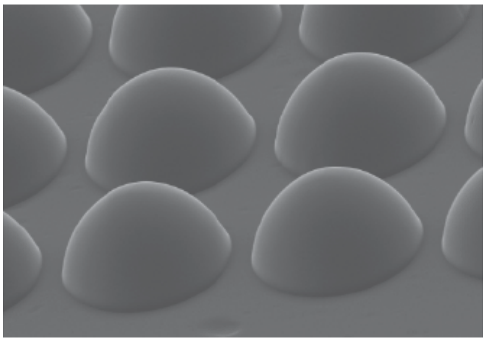

Fig.1 Microphotograph of plano-convex lens of the 32x32-element array, 50-µm pitch, 46-µm diameter fabricated by polymer mold

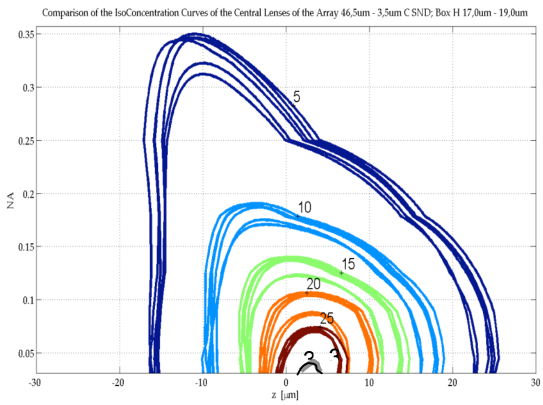

Fig.2 Five samples of iso-concentration curves plotted on a NA-z (numerical aperture vs distance) diagram for the plano-convex lens array. The parameter is the concentration factor C. Horizontal scale is 10 µm /div, vertical scale 0.05/division.

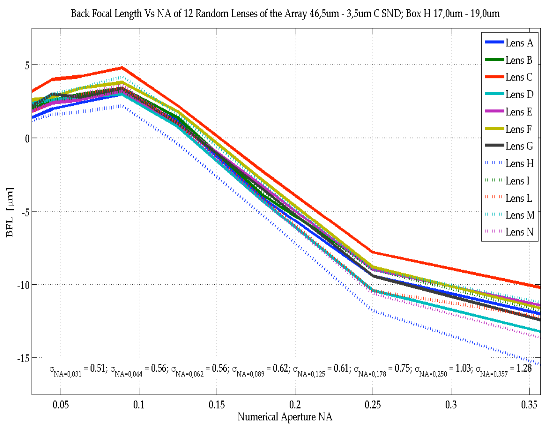

Fig.3 (see left) A sample of back-focal-length deviation curves plotted as a function of numerical aperture. Horizontal scale is 0.05 /div, vertical scale 2.5µm/division.